Risk and Consequence Analysis Focused on Biota Transfers Potentially Associated with Surface Water Diversions Between the Missouri River and Red River Basins

Written, edited, and compiled by Greg Linder, Ed Little, Bruce Peacock, Heather Goeddeke, Lynne Johnson, and Chad Vishy

Executive Summary

Under the auspices of the Dakota Water Resources Act (DWRA) of 2000, the Secretary of the Interior has been directed to conduct a comprehensive study of the water quality and quantity needs of the Red River Valley and the options for meeting those needs. As such, the Bureau of Reclamation (Reclamation) requested technical support from the U.S. Geological Survey (USGS) Columbia Environmental Research Center (CERC) for an evaluation of the risks and economic consequences of biota transfers potentially associated with interbasin water transfers that might occur between the Upper Missouri River and the Red River of the North (Red River) basins. This project report summarizes the technical findings of CERC staff and their Department of the Interior (DOI) partners in the National Park Service (NPS) with respect to these concerns regarding interbasin biota transfer. This technical report consists of six sections with accompanying appendices. Section 1 provides a brief overview of the project and the historic context for this evaluation focused on potential biota transfers. Section 2 summarizes the technical tools applied to the analysis of risks and economic consequences that are summarized in Section 3. Section 4 characterizes the risks potentially associated with biota transfers directly resulting from interbasin water transfers and competing pathways, while the economic consequences that are derivatives of those risks are considered in Section 5. Section 6 presents a summary of risks and economic consequences detailed in the report. A series of appendices provides detailed technical materials that support the analysis of risks, economic consequences, and their attendant uncertainties.

Section 1 provides a brief overview of the project, including a cursory summary of the history of the "Garrison Diversion" and how that history relates to this work focused on the analysis of risks and consequences potentially associated with interbasin biota transfers. The present study was initiated under the auspices of the Dakota Water Resources Act (DWRA) of 2000, which directed the Secretary of the Interior to conduct a comprehensive study of the water quality and quantity needs of the Red River Valley and the options for meeting those needs. As such, the Bureau of Reclamation (Reclamation) requested technical support from the U.S. Geological Survey (USGS) Columbia Environmental Research Center (CERC) for an evaluation of the risks and economic consequences of biota transfers potentially associated with interbasin water transfers that might occur between the Upper Missouri River and the Red River of the North (Red River) basins. Pursuant to guidance from National Academy of Sciences, National Invasive Species Council, regulatory agencies (e.g., US Environmental Protection Agency), and nongovernmental organizations such as The Nature Conservancy and awardees of Sea Grant program support, USGS/CERC entered into an iterative risk-assessment process with stakeholders interested in the biota transfer issue. Section 1 summarizes the implementation of the stepwise risk assessment process, with the primary outcomes of the section detailed in the problem formulation phase of the USGS technical support project. Outcomes of problem formulation were focused on identifying biota of concern (Table ES1) and related issues associated with interbasin biota transfers, pathways potentially linking Missouri River and Red River basins, and the potential confounding factors that might influence the interpretation of cause-effect relationships predicated on biota transfers, if these events did occur in the future.

Section 2 summarizes the tools applied to this desk-top analysis of risks associated with interbasin biota transfers regardless of the roles played by potential diversions of Missouri River source waters to Red River basin. Predicated on the outcomes of problem formulation, e.g., conceptual models, measurement and assessment endpoints were characterized and linked to the primary tool–habitat equivalency analysis–for evaluating consequences. Terminology critical to the evaluation of risks of biota transfer was characterized, including project-specific definitions for "introduction," "native," "alien," and "invasive." Data-mining techniques were applied to open literature searches initiated for compiling existing data and information on biota of concern. Outcomes of those searches are detailed and summarized. Potential pathways directly associated with engineered interbasin water diversions were considered as one of many competing pathways linked to human device(s) or natural events (i.e., those not linked to anthropogenic activities). A

Table ES1. Biota of concern identified for analysis focused on biota transfers from Upper Missouri River basin to Red River basin.

Microorganisms and Infectious Diseases	Aquatic invertebrates: Mollusks
Enteric redmouth Infectious hemtopoietic necrosis virus (IHNV) *Escherichia coli* (various serotypes)* *Legionella* spp.* *Salmonella* spp. *(*including, but not limited, to *S. typhi, S. typhmurium,* other *Salmonella* serotypes, and other waterborne infectious diseases*)** **Protozoa and Myxozoa** *Myxosoma cerebralis (Myxobolus cerebralis)* *Polypodium hydriforme* *Cryptosporidium parvum** *Giardia lamblia** **Cyanobacteria** *Anabaena flos-aquae** *Microcystis aeruginosa** *Aphanizomenon flos-aquae** **Vascular plants** Hydrilla (*Hydrilla verticillata*) Eurasian water-milfoil (*Myriophyllum spicatum*) Water hyacinth (*Eichhornia crassipes*) Purple loosestrife (*Lythrum salicaria*) Salt cedar (*Tamarix* spp.; at least eight species have been listed as introduced into the U.S. and Canada)	Zebra mussel (*Dreissena polymorpha*) Asian clam (*Corbicula fluminea*) New Zealand mudsnail (*Potamopyrgus antipodarum*) **Aquatic invertebrates: Crustaceans** Spiny water flea (*Bythotrephes cederstroemi*) **Aquatic vertebrates: Fishes** Gizzard shad (*Dorosoma cepedianum*) Rainbow smelt (*Osmerus mordax*) Paddlefish (*Polyodon spathula*) "Asian carp"† Pallid sturgeon (*Scaphirhynchus albus*) Utah chub (*Gila atraria*) Zander (*Sander* [*Stizostedion*] *lucioperca*) **Invasive biota associated with sludge disposal and indirect pathways associated with interbasin water transfers, including:** Potential transfer of plant and disease organisms (plant, wildlife, and human) Potential transfer of genetically manipulated organisms Potential biota transfers derived from sludge disposal

* Reclamation and Technical Team acknowledged the potential for interbasin water diversions to influence existing local populations in Missouri River and Red River basins. Species that currently occupy both basins were included on the list of biota of concern, since their potential interbasin water transfer may have adverse impact on fish and wildlife or human health.

† Composite grouping of species of carp originally entering North America from source areas in Asia; species include bighead carp (*Hypophthalmichthys* [*Aristichthys*] *nobilis*), silver carp (*Hypophthalmichthys molitrix*), and black carp (*Mylopharyngodon piceus*).

series of nested fault-probability trees (FPTs) were built to graphically illustrate the biota transfer process potentially captured by interbasin water diversions and competing pathways linked to anthropogenic or natural (not aided by human devices or activity) processes. Tools applied to the analysis of risks are characterized, including categorical and spatiotemporal tools employing traditional dot maps to characterize current distributions of biota of concern, and genetic algorithms focused on ecological-niche models to project potential distributions for these species.

Section 3 summarizes the outcomes of the risk analysis completed for the biota transfer project. The analysis of risks associated with potential biota transfers yielded multiple, complimentary outcomes stemming from the range of analytical tools applied to the evaluation of risks. Outcomes of the analysis of risks resulted from qualitative evaluations, largely based on narrative analyses dependent upon existing information on past and current distributions and life-history attributes potentially associated with future species incursions that might result in successful invasions or shifts in metapopulations. Quantitative evaluations based on categorical analysis considered life-history attributes and assigned numerical scores to each biota of concern, yielding a priority list of species likely to be problematic, if biota transfers occurred in the future. Outcomes of categorical analysis suggested that potential transfers of species already occurring in both Missouri River and Red River basins may occur in the future, since existing multiple competing pathways may link these basins regardless of whether designed water diversions are realized. Whether transfers of species already occurring in both basins would be associated with a measurable shift in metapopulations is unclear, given the relatively sparse data available for the analysis. While georeferenced distribution data were not sufficient for characterizing potential species distributions for all biota of concern, when sufficient data were available, spatiotemporal analysis considered biota transfers and prediction of species distributions through an ecological-niche based model algorithm. Illustrative projections of potential distributions for representative aquatic nuisance species, such as Zebra mussel, New Zealand mudsnail and riparian plants, such as tamarisk, were incorporated into the quantitative analysis as available and suggested that some biota of concern may become invasive in the future, although these species invasions are not uniquely linked to interbasin water diversion, because of multiple pathways available for incursion.

Section 4 focuses on the synthesis and integration of results from risk analysis which is the primary output for risk characterization. The analysis of risks supports management decisions regarding water resources in the northern Great Plains. When completed in parallel with an analysis of uncertainties associated with those risks, risk managers are better positioned to develop and implement resource management practices, e.g., technically evaluate alternatives as

management options to reduce risks (see Wittenberg and Cock 2001; Downes et al. 2002). Characterizing risks associated with a specific management activity such as water diversions moves us toward weighing potential consequences of an event—here, a species invasion or shift in metapopulation dynamics of an organism—relative to a specific pathway and designing and implementing options to address those risks and associated consequences. The integration of ecological consequences potentially linked to future invasions or shifts in metapopluations was considered relative to the adverse effects that organisms might cause, and served as our "risk input" for subsequent economic analysis. Economic consequences were focused on biological and ecological effects, and in Section 5 these associated economic outcomes have been captured through an evaluation that focused on habitat equivalency analysis and collateral measures of economic effects. While categorical and quantitative estimates of risk were developed in Section 3 and are characterized with respect to their attendant uncertainties in this section, a narrative analysis of pathways and their potential risk derivatives has also been considered, with a particular focus on biota of concern lacking data sufficient to more quantitative estimates of risks.

Overall, risks of biota transfers varied across representative species of concern and followed a priority risk ranking as

Fishes << Aquatic invertebrates $\leq$ Aquatic and terrestrial-wetland plants < Waterborne disease agents $\leq$ Cyanobacteria

suggesting interbasin transfers of fishes would be least likely to occur; hence, risks would be very low. In contrast, transfers of waterborne disease agents and cyanobacteria (or their toxins) would be associated with greater risks, particularly if control systems were not incorporated into water diversion processes and infrastructure. Risks were greatest when interbasin water diversions were envisioned as being implemented via open conveyance and only slightly reduced if untreated waters were piped from exporting to importing basin. Greatest risk reduction was achieved when source waters were treated (e.g., using combined control technologies such as conventional water treatment and pressure-driven membrane filtration) within the exporting basin then transferred via closed conveyance (e.g., piped transfer) to importing basin.

Section 5 summarizes economic analyses that estimated the potential consequences associated with interbasin water transfers between the Upper Missouri River and Red River basins. Two economic approaches were used to estimate these consequences. Habitat equivalency analysis was used to estimate consequences throughout the assessment area including the Red River and Lake Winnipeg. That analysis indicated risk consequences ranging from 0.6 to 3.1

river-miles of offsetting restoration on the Red River and from 1.9 to 27,750 acres of offsetting restoration on Lake Winnipeg. While those results suggest potentially significant consequences for Lake Winnipeg, their interpretation depends on the feasibility and availability of appropriate restoration measures.

Since the feasibility and availability of those restoration measures is not clear at this time, a second economic approach was used to focus the consequence analysis on Lake Winnipeg. Regional economic impact analysis was used to estimate the impacts on output (sales revenue) and employment in the Lake Winnipeg commercial fishery. The invasion scenarios with the largest consequences (slow and fast invasions given a jump dispersal event) indicated a total expected present value between $33,000 and $136,000 in direct and indirect output impacts for all Canadian provinces. All other invasion scenarios indicated smaller output impacts. Expected employment impacts in the very high-risk category (i.e., certainty) reach 331 full-time equivalent (FTE) jobs. The average expected employment impacts weighted by the percent outcomes of respective risk categories is 0 FTE for all invasion scenarios.

Given the quantitative results from the habitat equivalency analysis and the regional economic impact analysis, the following three conclusions can be drawn. First, the overall results are sensitive to the distribution of probabilistic outcomes from the risk characterization. Consequence levels for the individual risk categories vary substantially. That variance reflects the different probabilities of successful invasion. A different distribution of probabilistic outcomes would change the weighted averages of the consequence levels. Therefore, this consequence analysis is sensitive to the results of the risk analysis. In this particular case, the weighted average consequences are heavily weighted toward the lowest risk category (87% of outcomes in the very low-risk category). A distribution more heavily weighted toward the higher-risk categories would yield substantially higher-weighted averages of consequences.

The second conclusion of this consequence analysis is that the speed of invasion significantly affects the quantitative results. As many as four orders of magnitude difference in offsetting restoration levels exist between the two invasions' speeds assumed in this analysis, and one order of magnitude difference is captured by output impacts. A much more detailed analysis would match individually estimated invasion speeds to respective organisms and then aggregate the indicated consequence levels over the species of concern. However, the information regarding species-specific invasion speeds was not available to conduct that level of analysis. Therefore, this

analysis indicates not only the significance of this analytic factor but also the need for additional research in this area.

This consequence analysis also concludes that the anticipated distribution of the method and number of dispersal events substantially affects the quantitative results. This analysis considered only a limited set of potential dispersal scenarios. No information was available to inform the distribution of these scenarios to include in the analysis. However, the limited number of potential dispersal scenarios analyzed here indicated as many as four orders of magnitude difference in offsetting restoration levels between them. Similar to the conclusion regarding the speed of biotic invasion, this analysis indicates a significant analytic factor and a need for further research.

In Section 6, technical findings are summarized. In this report the analysis of risks and consequences are predicated on the assumption that water from the Missouri River will be transferred to the Red River basin. At times policy perspectives on water resource management are in conflict, e.g., precautionary measures vary with respect to implementation when encountering contrary views held with equal conviction. Resolution of these conflicting views, or rather the interpretation of how these policies should be implemented, is not a technical problem even if technical solutions are sought. This technical report can only hope to bring an analytical perspective to the discussion of risks and consequences associated with biota transfers potentially occurring consequent to an interbasin water diversion. If the water diversion is realized, the risks of biota transfers range from “highly likely to occur” to “highly unlikely to occur,” depending on how the diversion is realized. Economic consequences match these technical findings focused on risk.

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Abstract. Section 1 provides a brief overview of the project, including a cursory summary of the history of the "Garrison Diversion" and how that history relates to this work focused on the analysis of risks and consequences potentially associated with interbasin biota transfers. The present study was initiated under the auspices of the Dakota Water Resources Act (DWRA) of 2000, which directed the Secretary of the Interior to conduct a comprehensive study of the water quality and quantity needs of the Red River Valley and the options for meeting those needs. As such, the Bureau of Reclamation (Reclamation) requested technical support from the U.S. Geological Survey (USGS) Columbia Environmental Research Center (CERC) for an evaluation of the risks and economic consequences of biota transfers potentially associated with interbasin water transfers that might occur between the Upper Missouri River and the Red River of the North (Red River) basins. Pursuant to guidance from National Academy of Sciences, National Invasive Species Council, regulatory agencies (e.g., US Environmental Protection Agency), and nongovernmental organizations such as The Nature Conservancy and awardees of Sea Grant program support, USGS/CERC entered into an iterative risk-assessment process with stakeholders interested in the biota transfer issue. Section 1 summarizes the implementation of the stepwise risk-assessment process, with the primary outcomes of the section detailed in the problem formulation phase of the USGS technical support project. Outcomes of problem formulation were focused on identifying biota of concern and related issues associated with interbasin biota transfers, pathways potentially linking Missouri River and Red River basins, and the potential confounding factors that might influence the interpretation of cause-effect relationships predicated on biota transfers, if these events did occur in the future.

1.0 Biota Transfer Project Overview

Under the auspices of the Dakota Water Resources Act (DWRA) of 2000, the Secretary of the Interior has been directed to conduct a comprehensive study of the water quality and quantity needs of the Red River Valley and the options for meeting those needs. As such, the

Bureau of Reclamation (Reclamation) requested technical support from the U.S. Geological Survey (USGS) Columbia Environmental Research Center (CERC) for an evaluation of the risks and economic consequences of biota transfers potentially associated with interbasin water transfers that might occur between the Upper Missouri River and the Red River of the North (Red River) basins. This project report summarizes the technical findings of CERC staff and their Department of the Interior (DOI) partners in the National Park Service (NPS) with respect to these concerns regarding interbasin biota transfer. As part of the risk analysis and assessment process, staff from the Reclamation Dakota Area Office (DAO) and stakeholders helped focus this technical support activity through a series of Technical Team meetings convened in Fargo, North Dakota in 2002 and 2003 (September 9 and 10, 2002; March 27, 2003; October 28, 2003) and through comments received consequent to those meetings.

This technical report consists of six sections with accompanying appendices. Section 1 provides a brief overview of the project and the historic context for this evaluation focused on potential biota transfers. Section 2 summarizes the technical tools applied to the analysis of risks and economic consequences that are summarized in Section 3. Section 4 characterizes the risks potentially associated with biota transfers directly resulting from interbasin water transfers and competing pathways, while the economic consequences that are derivatives of those risks are considered in Section 5. Section 6 presents a summary of risks and economic consequences detailed in the report. A series of appendices provides detailed technical materials that support the analysis of risks, economic consequences, and their attendant uncertainties.

1.1 Overview of Garrison Diversion

Past accounts from various perspectives (e.g,, WPA 1939; Bell 1963; Bureau of Reclamation 1974; Souris River Study Board 1978; Thorson 1994; Carrels 1999) and public domain summaries mirroring a similar diversity of perspectives (e.g., http://www.rrvwsp.com/; http://www.savethesheyenne.org/; http://www.dnr.mo.gov/ riverissues/riverissues.htm; http://www.gov.mb.ca/waterstewardship/transboundary/ positions/index.html; http://www.canadianembassy.org/environment/garrison-en.asp) provide the reader with background on the Garrison Diversion and the historic context of the current work concerning potential biota transfers between the Missouri River and the Red River basins. Additionally, other recent studies have addressed the interrelated environmental management issues associated with the Missouri River and its watershed (e.g., NRC, 2002), and the Red River and its watershed (e.g., USGS, numerous citations available at http://mn.water.usgs.gov/ redn/biblio.html).

The historic literature is rich with respect to the issues generated by the Garrison Diversion as it was originally envisioned under the Pick-Sloan Missouri Basin Program of 1944 (also referred to as the Missouri River Basin Project, or Pick-Sloan) as initially authorized by the Flood Control Act of December 22, 1944. As a comprehensive plan for the conservation, control,

and use of water resources in the entire Missouri River Basin, Pick-Sloan was subsequently modified as the Garrison Diversion Unit in response to sociopolitical comments and technical inputs regarding the original plan's feasibility (see http://www.garrisondiv.org; US Congress, 1975; IJC, 1976a-f, and references cited therein). The Dakota Water Resources Act[1] and the Northwest Area Water Supply (NAWS)[2] project in North Dakota (http://www.swc.state.nd.us/projects/nwwatsup.html; http://www.gov.mb.ca/waterstewardship/transboundary/pdf/sfxded.pdf) currently face similar scrutiny in response to various perspectives related to the water needs of the region. During the development of this report, technical issues concerning interbasin water diversions were defined through discussions with the Technical Team and Reclamation. As with most contemporary environmental issues, the immediate questions guiding the technical aspects of this project are easily linked to public needs (e.g., WPA 1939) that predate the signing of the Pick-Sloan legislation as it was captured in the Flood Act of 1944, which is the original point of departure for this technical report. Historic accounts that lead to Pick-Sloan, as well as early biological survey work that provided baseline information regarding the biological resources issues associated with each of the river basins in question were considered in this report (e.g., Young, 1924 and other citations; see Section 4).

Numerous government reports on the Red River basin of North Dakota written prior to Pick-Sloan and contemporary legislation acknowledged environmental management issues of the day. For example, the North Dakota State Planning Board under the auspices of the Works Progress Administration (1939) recommended in part that future work "concentrate on the water problem . . . to include construction of facilities for rural water supplies, regulating the flow in various streams and supplementing the flow in the Red River" and "reduce stream pollution"—recommendations that are similar to issues motivating the current investigation on biota transfer. Although reducing stream pollution was an insightful recommendation for its day, the focus at that time was on "traditional chemical pollution" such as nutrient enrichment from return irrigation flows that were then, and still remain, problematic throughout the western states. Today's version of "reduce stream pollution" also reflects heightened concerns for introduction of species foreign to the Red River basin; hence, the current work's focus may be seen as responsive not only to contemporary concerns of biota transfer but also as a continued response to those concerns of stream pollution voiced over 60 years ago. Observations since Pick-Sloan regarding water needs in the Red River and other drainages of North Dakota continually mark the path toward the DWRA.

Regardless of the water needs—irrigation, hydroelectric power, municipal, or industrial—that historically motivated proposals for water diversions from the Missouri River to

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[1]DWRA is a reauthorization of the 1986 Reformulation Act which was a reauthorization of the 1965 Act (see §1.2 for additional background and references focused on historic setting).

[2]NAWS is a component of the Garrison Diversion Unit (GDU) Municipal, Rural, and Industrial (MR&I) Grants Program.

the Souris River-Red River systems, the interrelationships between the potential source of water exports (the Missouri River) and the system currently proposed for water imports (Red River) reflect the spatial and temporal attributes of water quality and quantity reflected in contemporary debates associated with stakeholder concerns. For example, from a Canadian perspective, early interagency provincial studies such as the Souris River Basin Study Report (1978) reflected concerns including those of biota transfers that were in part captured by U.S. congressional testimonies of the 1970s (e.g., US Congress, 1975). From early studies of potential problems associated with interbasin water transfers (see IJC 1976a-f; IJC 1977), the current study was developed to address species of concern as well as engineering alternatives to reduce risks associated with biota transfers resulting from such water diversions.

1.2 Pick-Sloan and Beyond: Path to USGS/NPS Biota Transfer Project

Pick-Sloan as embedded in the Flood Control Act was authorized by Congress in late December 1944. Originally developed as two plans, one from the U.S. Army Corps of Engineers (Pick Plan) and another from Reclamation (Sloan Plan), Pick-Sloan reflected a joining of these independent water management projects, in part because of similar infrastructure needs and river management issues that politically justified their union. Pick-Sloan as realized with passage of the Flood Control Act of 1944 responded to the issues of flood control, river navigation, irrigation, and hydroelectric power with six main stem dams on the Missouri River between 1933 and 1966. Today Fort Peck, Garrison, Oahe, Big Bend, Fort Randall, and Gavins Point dams[3] are managed by the US Army Corps of Engineers in cooperation with the Bureau of Reclamation (see Figure 1).

As summarized in various public domain sources (e.g., http://www.garrisondiv.org/; http://www.rrvwsp.com/; http://www.savethesheyenne.org/; http://www.dnr.mo.gov/ riverissues/riverissues.htm; http://www.gov.mb.ca/waterstewardship/transboundary/ positions/index.html; http://www.canadianembassy.org/environment/ garrison-en.asp) and contemporary retrospectives (see NRC 1992; Thorson 1994; Licht 1997; Carrels 1999; Silberman and Gudmundson 2002), the irrigation component of Pick-Sloan originally intended to deliver irrigation water to more than 5 million acres of land in seven different states within the Missouri River basin. One project funded under Pick-Sloan, the Missouri-Souris Project, was originally intended to bring water from the Missouri River to North Dakota through a diversion from Fort Peck Reservoir in eastern Montana. The target lands for irrigation in northwest North Dakota, however, were not amenable to irrigated agriculture due to their poor drainage

[3]Authorized and completed as follows: Fort Peck (authorized under the Works Progress Administration in 1933 with construction completed in 1940), Garrison (authorized in 1944 with construction initiated in 1947 and completed in 1953), Oahe (authorized in 1944 with construction initiated in 1948 and hydroelectric generation facility completed in 1962), Big Bend (authorized in 1944 with hydroelectric generation facility completed in 1966), Fort Randall (authorized in 1944 and completed in 1956), and Gavins Point (authorized in 1944 and completed in 1957).

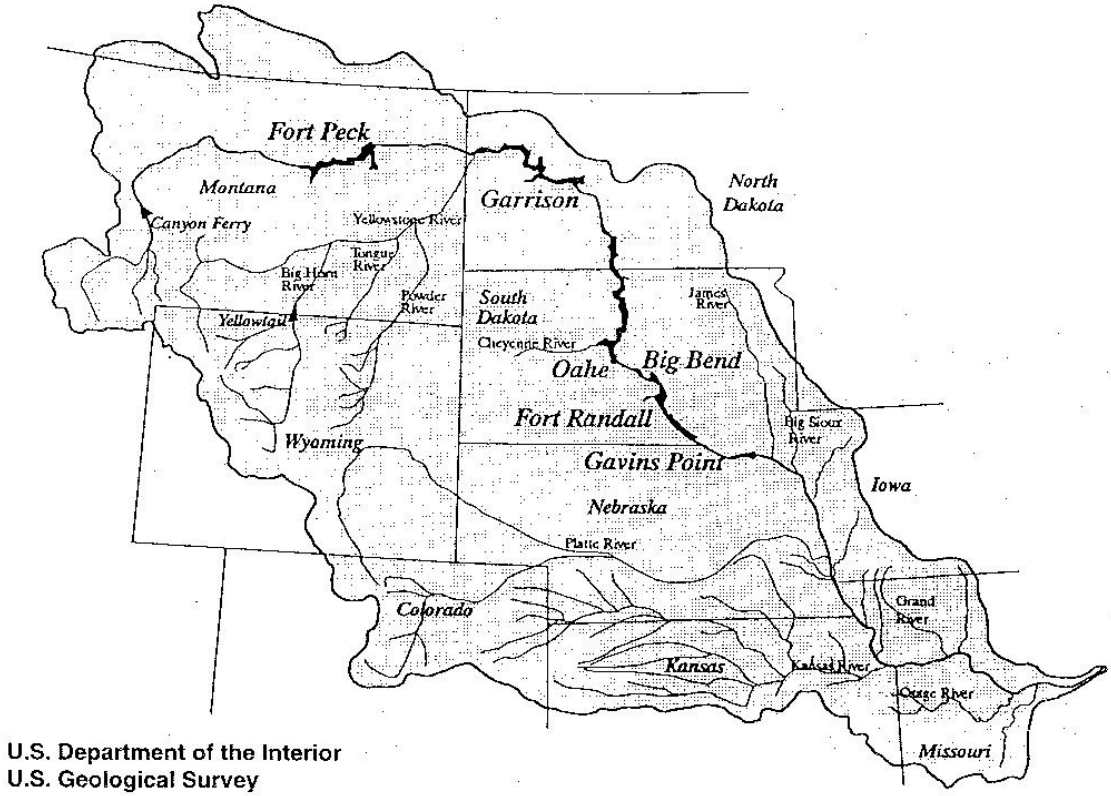

Figure 1. Dams along the main stem of the Missouri River, with diversions from waters behind Garrison Dam providing potential sources for interbasin biota transfers to the Red River system (Burke, et al. 1997).

properties reflecting their glacial origins. Given these soil limitations, the original Missouri-Souris Project was revised by Reclamation in 1957 wherein water from Garrison Reservoir was tabbed to irrigate lands in north-central and eastern North Dakota. The redesigned project was named the Garrison Diversion, and legislative support and appropriations were gained when Congress enacted and funded the Garrison Diversion in 1965. As realized under the 1965 congressional action, Garrison Diversion was focused on municipal and industrial water needs, development or enhancement of fish and wildlife resources, recreation, flood control, and irrigation, although the role of irrigation in the redesigned plans was considerably reduced compared with the Missouri-Souris Project of Pick-Sloan.

The Garrison Diversion Project was funded throughout the 1970s, 1980s, and 1990s. Under the Carter, Reagan, George H.W. Bush, and Clinton administrations, the project was reviewed by public and private stakeholders and government agencies. In part, the increased level of review and comment by stakeholders stemmed from the passage of the National Environmental Policy Act (NEPA) during the Nixon administration early in 1970. Under NEPA, the environmental impact statement (EIS) became a requirement for all “major construction activities,” and EIS requirements under NEPA afforded opportunity for interested parties to comment on the ongoing efforts to develop the Garrison Diversion. The government of Canada, both provincial and federal, while always aware of water projects on shared water resources, became active in commenting on plans envisioned for Garrison. Under the auspices of the Boundary Waters Treaty of 1909, the Canadian government requested that plans for the Garrison

Diversion be discontinued until issues presented by the International Joint Commission were addressed. The International Joint Commission (IJC) had been commissioned under the auspices of the Carter Administration to study the proposed Garrison Diversion and had issued a report in 1977 (IJC, 1976a-f; IJC, 1977) that identified the possibility that return flows from irrigated fields in North Dakota would likely reach Canada (hence, source waters from the Missouri River would be discharged as irrigation drainage to surface waters in the watershed connected to the Hudson Bay). The IJC had also identified that biota, for example, fish, fish eggs, and pathogens, might also be introduced into waters destined for Hudson Bay with a particular focus on the fisheries of the region, for example, Lake Winnipeg. While concerns regarding reduced water quality associated with return flows of irrigation drain water were ultimately addressed by eliminating plans for irrigation in the Souris River watershed, concerns about biota transfer remained.

This evaluation of potential biota transfers between the Missouri River basin and the Red River basin are a direct outgrowth of the DWRA of 2000. DWRA amended the Garrison Diversion Reformulation Act of 1986 and was authorized by Congress in order to evaluate water quality and quantity needs of the Red River valley and the options for meeting those needs, including alternatives that might bring water from the Missouri River to the Red River valley for water programs intended for municipal and rural communities, industrial projects, and tribal needs. Given the history of the Garrison Diversion, it is not surprising that DWRA has again rekindled the biota transfer issue.

Even this brief summary of the current project's development suggests that the political history of the Garrison Diversion is rich, spanning 60 years under various program and project pseudonyms. Presently, the technical activities completed here under the auspices of DWRA may be viewed as an ongoing collaborative process intended to address the water needs of the region which, not surprisingly, are characterized at times by conflicting stakeholder views. The current work's focus on the biota transfer issue can be viewed as complementary to past efforts that focused on the interrelationships between the Missouri River and the Souris-Red rivers, and the evaluation of alternatives for meeting the water supply needs of North Dakota and the Red River Valley.

1.3 Risk Analysis, Risk Assessment and Management Overview

The process commonly pursued during risk assessment, particularly within the context of environmental issues and a multiple stressor approach to cumulative risk assessment, is highly interactive (Figure 2; see EPA 2003; Ferenc and Foran 2000; Foran and Ferenc 1999). The current technical support activity is focused on biota transfers and considered both human and nonhuman receptors as targets of biological agents that will potentially enter the Red River basin as a consequence of water diversion from the Missouri River. Given the focus of the current

analysis of risks and consequences ranges across various levels of biological organization and spatial scales, much of the process and language used in completing the work reflects a dependence on an ecological context for evaluating and characterizing risks potentially associated with biota transfers. However, USGS/CERC did not conduct an ecological risk assessment nor a human health risk assessment as part of this analysis focused on risks and consequences of biota transfers potentially associated with water diversions from the Missouri River or competing pathways for such biological incursions. The present analysis is asymmetric, given our focus on water imports to the Red River basin. Analysis of risks associated with water exports from the Missouri River is limited to the role that water exports have in characterizing uncertainties in our analysis of risks associated with biota imported as a result of water diversions between Missouri River and Red River basins.

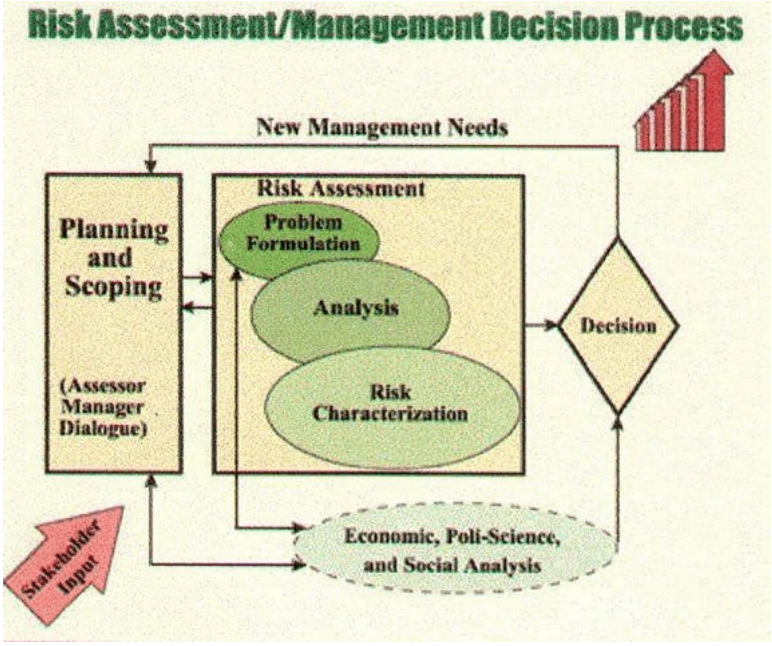

Figure 2. Process for evaluating risks associated with biota transfers potentially associated with interbasin water diversions proposed under DWRA. Figure from EPA 2003.

Figure 2 summarizes the process we have completed and places this report and subsequent work into a larger picture of risks and consequences. Through a series of communications with Reclamation and Technical Team meetings, USGS/CERC identified biota transfer issues that appeared as “drivers” for the technical support request issued from Reclamation. Planning and scoping discussions with Reclamation regarding biota transfer issues were reinforced and additional guidance was gained from Technical Team meetings that were the primary activities during Problem Formulation. As characterized across the various implementation strategies available for the risk assessment process, identification of biota of

concern and pathways linking source and receiving systems were incorporated into conceptual models serving as the primary outcomes to Problem Formulation. The process summarized in Figure 2 is briefly characterized and outcomes from Problem Formulation that provided the foundation for the analysis and characterization of risks are summarized to close the chapter.

1.3.1 Introduction. Risk analysis and the subsequent process of assessing risks and consequences of targeted events has a wide range of applications to evaluations of:

- ecological health,
- accidental events,
- financial concerns, and
- technology issues.

Each of these applications is relevant to the issues that Reclamation faces in its management of water resources across the western US.

In its simplest summary, the analysis, assessment, and management of risks is captured by a stepwise, iterative process wherein (1) questions are formulated, (2) observations or "experiments" are conducted wherein answers are developed to address those questions, and (3) decisions are made given the answers to the questions that initiated the process (EPA 1992, EPA 1998, NRC 1983, NRC 1994; Figure 2). Decisions that result from the initial assessment may (1) yield sufficient management-critical support for a particular management action, or (2) the analysis process may be reiterated to address critical data gaps identified as outcomes of the initial "query-answer routine." For example, answers developed during the first iteration may not be sufficient to support management decisions when the level of uncertainty exceeds the risk-tolerance of the decision-makers. Additionally, if sufficient evidence in support of a management decision is derived following completion of the process, parallel technical support efforts may be conducted as part of an adaptive management program, for example, development of a monitoring program that parallels an on-going management activity (Stahl, et al. 2001).

CERC conducted the technical analysis of risks and consequences associated with biota transfers potentially associated with interbasin water transfers following available guidance (EPA 1992, EPA 1998, NRC 1983, NRC 1994), including that developed for hazard assessment and critical control point analysis for aquatic nuisance species and similar applications (e.g., see Minnesota Sea Grant/Michigan Sea Grant, 2001).

1.3.2 Problem formulation and development of conceptual models. Consistent with the risk assessment process practiced for issues related to environmental and technological interactions such as interbasins water transfers, nested conceptual models were developed to characterize the issues related to biota transfers associated with interbasin water diversions. As part of Problem Formulation, preliminary models were developed in collaboration with

Technical Team members wherein (1) biota of concern (potential and selected representative species) were identified and characterized with respect to their biological and ecological attributes that may promote their transfer and establishment in previously unoccupied areas (e.g., life-history attributes likely to influence invasiveness); (2) pathways that potentially link biota of the Upper Missouri River basin (source area) with the Red River basin (receiving area) were characterized, acknowledging life-history attributes of biota of concern that might enhance the likelihood for invasion and establishment; and (3) ecological receptors likely to be adversely impacted by invasive species were identified. The identification of biota of concern was based on Technical Team input, on the characterization of candidate species, and pathways linking those species to the Red River basin. The selection of representative species of concern captured the range of biota potentially available for emigration from the Upper Missouri River basin (Table 1).

Pathways and potential risks associated with biota transfers were incorporated in the conceptual model, which became a graphical illustration of the environmental conditions critical to the analysis of risks (e.g., potential linkage of sources and receptors via pathways). As such, the conceptual model was developed collaboratively with the Technical Team early during the risk assessment process and was a critical outcome of Problem Formulation.

While many of those representative species included in Table 1 reflect Technical Team's and Reclamation's focus on biota considered exotic or invasive to the receiving system, biota whose current distributions reflect occurrence in both exporting and importing systems were also included in the analysis. Technically, biota transfers of species already occurring in both exporting and importing systems would not constitute an incursion potentially characterized as a "biological invasion." Nonetheless, transfers of these representative species might yield with a shift in metapopulations that could be associated with adverse effects, e.g., increased incidence of disease in the importing system—hence, their inclusion in this analysis.

Collaborative development of nested conceptual models reflected the iterative process characteristic of the risk-assessment process, and helped identify data needs and potential uncertainties. As the primary outcome of Problem Formulation, the nested conceptual models helped identify ecological receptors most likely impacted by exposure to biota potentially transferred to the Red River basin from the Missouri River basin. Additionally, the conceptual models helped identify assessment endpoints potentially of concern when potential adverse effects associated with a biological invasion were considered within the context of risk characterization and evaluation of economic consequences.

Table 1. Biota of concern identified for analysis focused on biota transfers from Upper Missouri River basin to Red River basin.

Microorganisms and Infectious Diseases	Aquatic invertebrates: Mollusks
Enteric redmouth Infectious hemtopoietic necrosis virus (IHNV) *Escherichia coli* (various serotypes)* *Legionella* spp.* *Salmonella* spp. (including, but not limited, to *S. typhi, S. typhmurium,* other *Salmonella* serotypes, and other water-borne infectious diseases)*	Zebra mussel (*Dreissena polymorpha*) Asian clam (*Corbicula fluminea*) New Zealand mudsnail (*Potamopyrgus antipodarum*)
Protozoa and Myxozoa	**Aquatic invertebrates: Crustaceans**
Myxosoma cerebralis (Myxobolus cerebralis) *Polypodium hydriforme* *Cryptosporidium parvum** *Giardia lamblia**	Spiny water flea (*Bythotrephes cederstroemi*)
Cyanobacteria	**Aquatic vertebrates: Fishes**
*Anabaena flos-aquae** *Microcystis aeruginosa** *Aphanizomenon flos-aquae**	Gizzard shad (*Dorosoma cepedianum*) Rainbow smelt (*Osmerus mordax*) Paddlefish (*Polyodon spathula*) "Asian carp"† Pallid sturgeon (*Scaphirhynchus albus*) Utah chub (*Gila atraria*) Zander (*Sander* [*Stizostedion*] *lucioperca*)
Vascular plants	**Invasive biota associated with sludge disposal and indirect pathways associated with interbasin water transfers, including:**
Hydrilla (*Hydrilla verticillata*) Eurasian water-milfoil (*Myriophyllum spicatum*) Water hyacinth (*Eichhornia crassipes*) Purple loosestrife (*Lythrum salicaria*) Salt cedar (*Tamarix* spp.; at least eight species have been listed as introduced into the U.S. and Canada)	Potential transfer of plant and disease organisms (plant, wildlife, and human) Potential transfer of genetically manipulated organisms Potential biota transfers derived from sludge disposal

* Reclamation and Technical Team acknowledged the potential for interbasin water diversions to influence existing local populations in Missouri River and Red River basins. Species that currently occupy both basins were included on the list of biota of concern, since their potential interbasin water transfer may have adverse impact on fish and wildlife or human health.

† Composite grouping of species of carp originally entering North America from source areas in Asia; species include bighead carp (*Hypophthalmichthys* [*Aristichthys*] *nobilis*), silver carp (*Hypophthalmichthys molitrix*), and black carp (*Mylopharyngodon piceus*).

1.3.3 Initial characterization of conceptual model(s) for interbasin water transfers. As discussed earlier, interbasin water transfers may be associated with biota originating in any of various spatially-linked river or lake basins (Figure 3). Pathways linking Red River basin with surrounding watersheds are numerous, and the number of species potentially capable of being transferred among basins through natural (i.e., not aided by human intervention) or anthropogenic means is practically limitless, being bound only by the species occurrence in source areas. Within a landscape-level setting, however, the issue driving the analysis is focused on species expanding their distributions from Upper Missouri River basin to the Red River basin.

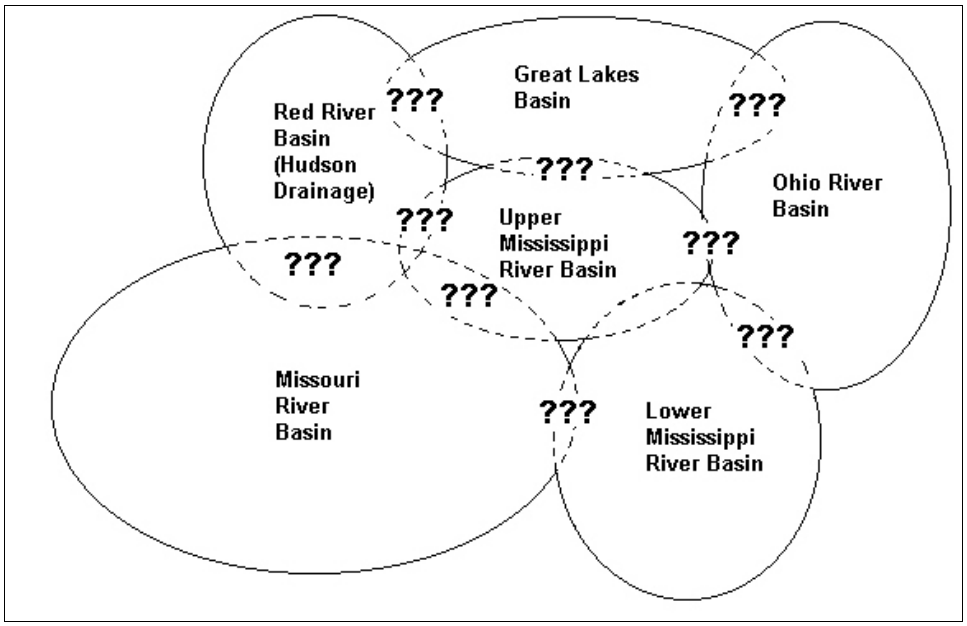

Figure 3. Interrelated river and lake basins ("???" reflect uncertain status of current state of species exchange among watersheds).

Conceptually, the areas surrounding the basins of concern—Upper Missouri River and Red River basins—fit into those regions defined by aquatic resources and used by various environmental management agencies in characterizing the resources for which they are responsible. As presented in Figure 4a and Figure 4b, hydrological unit codes (HUCs) have been assigned to subdivisions of the US by USGS (e.g., Figure 4a) to show major and minor river basins. Each river basin has a numeric code. Major river basins have a 2-digit HUC boundary code, while smaller subbasins nested within a particular 2-digit HUC have 4-, 6-, and 8-digit codes. For example, the Missouri River and Red River basins have 2-digit HUC codes of 010 and 09, respectively, while smaller subbasins within a particular zone would have 4-digit HUCs of 1001, 1002, etc., depending upon the number of topographic basins in the region (here, the Upper Missouri River basin). Subbasins may be further subdivided by using HUC6 and HUC8 identifiers (e.g., NRC 1999).

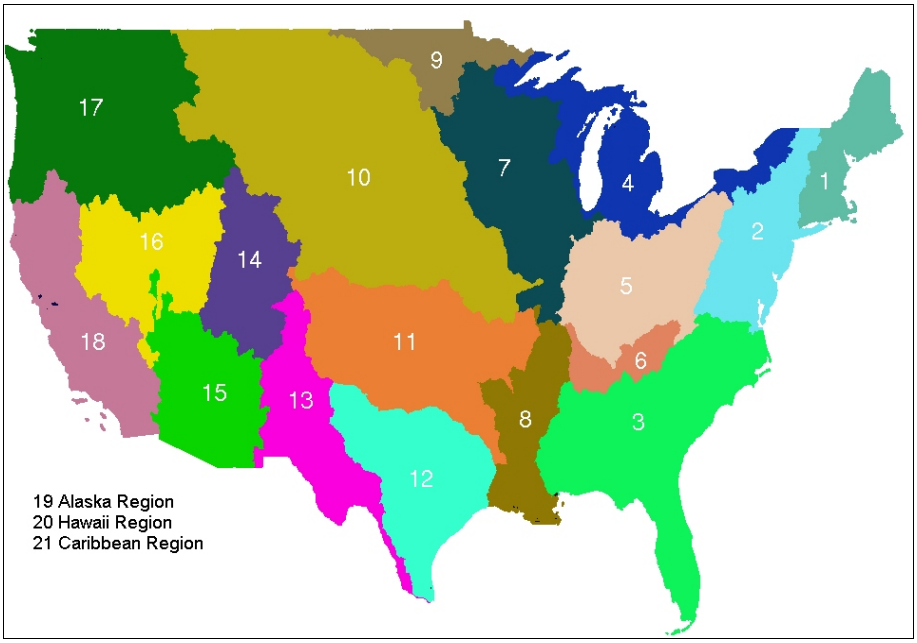

Figure 4a. River basins of the US defined by 2-digit HUCs (hydrological unit codes) of USGS.

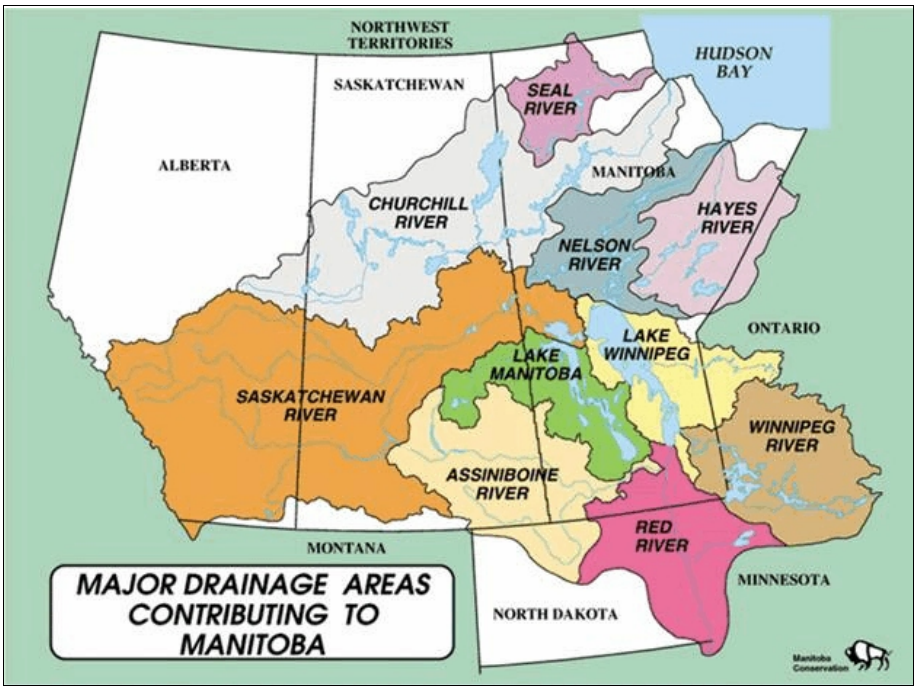

Figure 4b. River basins within the northern Great Plains of US and Prairie Provinces of Canada lying north of Missouri River basin (HUC 10).

HUCs provide a long-practiced technical foundation for the characterization of aquatic regions across the United States, with boundaries and numeric codes being characterized for 21 regions and 222 subregions. Within each region, river basins are specified for drainages of greater than 700 square miles (NRC 1999). While the resolution of available data, e.g., species lists and other information, are not necessarily available for these finer-resolution identifiers, the spatial interrelationships between 4-, 6-, and 8-digit HUCs potentially influence the analysis of biota transfers between the 2-digit HUCs of primary interest, Missouri River (10) and Red River (09) basins. Figure 4 clearly identifies the unique landscape signatures of the Upper Missouri River and Red River basins within the boundaries of the United States, as well as those surrounding basins which bring other potential "biological invaders" to our discussion. Major river and lake basins across continental United States (and North America; see NRC 1999; Abell, et al. 2000) are identified by their 2-digit HUCs. For the current study, Appendix 1 lists 4-digit HUCs within Missouri River (HUC 10) and Souris River-Red River-Rainy River (HUC 09), and Appendix 2 displays aquatic ecoregions of North America with the latter's map illustrating the potential transboundary setting for questions focused on biota transfer.

In setting the stage for the characterization of tools used in the analysis (Section 2) and results of the analysis of risks (Section 3), Figure 3 and Figure 4 illustrate nested landscape-level conceptual models primarily focused on water resources bound by major river and lake basins, which define the spatial context of the analysis in this report. Complementary to these conceptual settings, the nested model(s) that follow are focused on (1) pathways linking those invasive species as emigrants to the Red River basin from the Upper Missouri River basin and (2) "biological agents" or biota of concern, given the regional context for the analysis of biota transfers between Upper Missouri River and Red River basins (i.e., target species presumptively representative of unknown agents potentially subject to interbasin transfer).

1.3.4 Identification of potentially complete pathways. Within the aquatic habitats characteristic of the Upper Missouri River and the Red River, pathways exist that potentially provide "safe passage" from one basin to the other. Pathways are those focused on species potentially associated with interbasin water transfers, with examples being summarized in Figure 5 where broad categories of potential pathways are listed. While expansion of species distributions may occur as a consequence of natural processes that occur in the absence of human intervention, the main focus of the present analysis resides in those anthropogenic events (accidental or intentional) likely to promote a biota transfer either linked to movement of water from one basin to the other or linked to a species' emigration that could be interpreted as a biota transfer mistakenly associated with interbasin water transfers. The misinterpretation of causal linkage(s) between basins will mostly likely result from outcomes that are derivative of competing pathways. While Figure 5 simply lists a single entry for expansion of species distribution in the absence of human intervention, the evaluation of biota transfers mediated by mechanisms other than those associated with anthropogenic activities will be discussed with a particular focus on how such transfers may serve to confound causal linkages characterizing the

transfer process (Section 3; see also Appendix 3A and Appendix 3B). For example, biotic factors other than human-aided transfer (accidental or intentional) will be identified such as vertebrate and invertebrate phoresy (animal transport). Abiotic factors such as wind dispersal will also be noted, again with a particular focus on the role that these alternative mechanisms may play in confounding the characterization of risks associated with interbasin water transfer. Also, factors that are listed as being associated with human intervention, e.g., biological control, may actually represent a combination of mediating factors that are associated with dispersal of invasive organisms or movement of biota from one basin to another. For example, biological control agents such as nonnative predators of pest species may be used in adaptive management programs, and their release, although intentional, may ultimately be recognized as an "invasion," if unintended negative outcomes are realized and their role as control agents is overshadowed by their invasiveness.

Pathways for species invasions:
Red River Basin

+ Species distribution expansion without human intervention (intentional or accidental)
+ Intentional
+ Accidental
  - Associated with interbasin water transfers
  - Aquaculture (e.g., aquatic invertebrates, aquatic plants)
  - Aquarium trade and unintentional releases
  - Biological control
  - Transfer from boat, ship, and barge
    - Commercial
    - Recreational
  - Canals, locks, channels
  - Live bait and releases from recreational/commercial fisheries
  - Releases associated with other sources (e.g., food business)

Figure 5. Pathways providing routes between Upper Missouri River and Red River basins (and other biota transfers potential confounding source and receiving water characterizations in this report). Expansion of species distributions associated with factors other than human intervention (accidental or intentional) will consider biotic and abiotic factors directly or indirectly related to the biota transfer process, e.g., animal transport.

1.3.5 Pathways: Linking source and receiving systems. Efforts to characterize the process of linking source areas for biological invasions with receiving areas (e.g., see http://www.invasivespecies.gov/vectors/main.shtml) apply common themes to their analysis and discussion of pathways. Here, an evaluation of biological invasions follows a process consistent

with that reflected in the current effort where two complementary tasks: a life-history characterization task and a pathways task were considered. Given stakeholder input during Problem Formulation, selection of biota of concern was a collaborative effort in this iteration of the evaluation of risks. Subsequent iterations of the risk-assessment process could incorporate "screening" tasks in order to rank representative biota with respect to their risk as invasives.

As a derivative of the biota of concern selection process, the evaluation of economic consequences of biota transfers potentially associated with water diversions from the Missouri River basin to the Red River basin will focus on case study analyses supported by data sufficient to the analysis. As such, the selection of biota of concern captured a wide range of potential biota of concern which are intended as representative species that present life-history attributes amenable to generalizations regarding the invasiveness of other biota characterized by similar life-history attributes. The nearly limitless variety of life-forms potentially acting as biological invaders precludes a simple "one model suits all" analysis, an analysis option that would highly likely yield uncertainties that merit technical scrutiny.

Complementary to the collaborative effort undertaken with the Technical Team to develop a list of biota of concern, a pathways analysis was pursued, in part because of the multiple exchange venues and mechanisms that are characteristic of complex adaptive systems such as those of the northern Great Plains. While the primary focus of the current analysis resides with biota transfers between the Missouri River and Red River basins directly related to water-diversion structures or processes, a larger spatial scale must be incorporated into the analysis of pathways, since these alternative pathways potentially serve as confounding factors in the characterization of risks.

Ideally, a proactive analysis of pathways helps to reduce risk of unintentional or accidental introductions of species that would expand their distributions, if they become established in the Red River basin. Introductions of plants, animals, and other biota may be accepted within the context of the current investigation, but these acceptable "imports" to the Red River basin (e.g., as species expansions that have been ongoing since the northern Great Plains was released from Laurentian glaciations) potentially act as confounding, coincidental linkages between source, or exporting, region (Missouri River, HUC10) and receiving, or importing, region (Red River, HUC09). Also, organisms characterized as "acceptable" introductions (for example, for commercial or recreational purposes) are likely confounding agents in the characterization risk, since pathways for these accepted introductions may affect the subsequent importation of associated, but unintended organisms, including insects, other invertebrates, aquatic animals, terrestrial vertebrates, disease pathogens, and plant seeds and propagules.

The outcomes of Problem Formulation, and in particular the (1) biota of concern, (2) pathways of concern (both water diversion and potentially confounding alternative pathways for

biota transfer), (3) spatial interrelationships between Missouri River basin and Red River basin, and (4) spatial interrelationships among these basins and other lake and river basins adjacent to the basins of concern, guided the development of the technical support structure summarized in the Section 2 and influenced the tools selected for the analysis of risks and economic consequences.

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2.0 Data Mining and Tools for Desktop Analysis of Risks

Abstract. Section 2 summarizes the tools applied to this desk-top analysis of risks associated with interbasin biota transfers regardless of the roles played by potential diversions of Missouri River source waters to Red River basin. Predicated on the outcomes of problem formulation, e.g., conceptual models, measurement and assessment endpoints were characterized and linked to the primary tool—habitat equivalency analysis—for evaluating consequences. Terminology critical to the evaluation of risks of biota transfer was characterized, including project-specific definitions for "introduction," "native," "alien," and "invasive." Data-mining techniques were applied to open literature searches initiated for compiling existing data and information on biota of concern. Outcomes of those searches are detailed and summarized. Potential pathways directly associated with engineered interbasin water diversions were considered as one of many competing pathways linked to human device(s) or natural events (i.e., those not linked to anthropogenic activities). A series of nested fault-probability trees (FPTs) were built to graphically illustrate the biota transfer process potentially captured by interbasin water diversions and competing pathways linked to anthropogenic or natural (not aided by human devices or activity) processes. Tools applied to the analysis of risks are characterized, including categorical and spatiotemporal tools employing traditional dot maps to characterize current distributions of biota of concern, and genetic algorithms focused on ecological-niche models to project potential distributions for these species.

2.0 Tools and Data-Mining Overview

Risk analysis may be conducted with various levels of effort and tap into a variety of data and information available to the analyst. From a technical perspective, there are three varieties of risk analysis that potentially serve natural resource managers in their efforts to manage risks in the face of various levels of uncertainty (see ASTM 2004; EPA 2003, 1998, 1992; Foran and Ferenc 1999). While terminology varies from author to author, the analysis of risks can be implemented through (1) "desktop" efforts reliant on available information (e.g., open-source, peer-reviewed technical literature) and existing data sources, (2) screening efforts that are implemented along a spectrum of designed or observational studies, and (3) comprehensive efforts that are generally phased interrelated studies resulting from previously completed desktop and screening level efforts. While these categories may be conventionally characterized as discrete forms, a desktop analysis may be implemented with various levels of effort, ranging from a "preassessment" activity that provides analysis and commentary sufficient to support decisions regarding the need for further study (e.g., NOAA 1997) to comprehensive studies that are variously implemented as data mining or integrated field-laboratory efforts involving designed studies to address environmental or engineering issues (see Downes et al. 2002; Doppelt et al. 1993; Margoluis and Salafsky 1998).

The current investigation is a focused desktop-level analysis that was designed to address questions fielded from Reclamation and Technical Team and reflected in the regional conceptual model in Section 1 (see Section 1, Figure 3). As a desktop analysis of risks, the current work was

implemented through a comprehensive literature survey targeted on the list of biota of concern (Table 1) developed in collaboration with Reclamation and Technical Team. The literature survey yielded existing information, largely peer-reviewed literature and data compilations (see Appendix 3A and Appendix 3B), that was evaluated using available data analysis tools as briefly summarized in the following text and Appendix 4.

2.1 Terminology and Identification of Biota of Concern

For purposes of the present study focused on biological invasions potentially associated with interbasin water transfers, definitions of terms were critical to the analysis. Four terms in particular must be clearly understood: introduction, native species, alien species, and invasive species. We have followed the terminology of the National Invasive Species Council (NISC) as specified in Executive Order 13112 in this report (Office of the President, Executive Order 13112, 1999).

An "introduction" means the intentional or unintentional escape, release, dissemination, or placement of a species into an ecosystem as a result of human activity. "Native species" are those that, other than as a result of an introduction, historically occurred or currently occurs in a specific region. An "alien species" means, with respect to a particular ecosystem, any species, including its seeds, eggs, spores, or other biological material capable of propagating that species that is not native to that ecosystem. In contrast, our definition of "invasive species" follows as an alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health. Although not alien or invasive species, a limited focus of the current analysis also fell on biota transfers between regions that merely reflected a movement of species across basin boundaries; that is, the species presently occurs in each region but the interbasin transfer of water expedites movements of subpopulations between regions. Although not invasions by definition, biota of concern in the present analysis included selected species that are present in each basin regardless of population levels and current distributions, and are potentially associated with adverse impacts on the receiving system.

In identifying biota of concern, species lists for Upper Missouri River and Red River basins were initially referenced with respect to the compilation of candidate species of concern. Then, given Technical Team input, species selected as biota of concern (Section 1, Table 1) were characterized as being widely characterized as invasive species (see http://www.invasivespecies.gov/; http://anstaskforce.gov/; http://www.nrcs.usda.gov/technical/invasive.html; http://plants.usda.gov/) and were considered as species likely to emigrate from Upper Missouri River basin to Red River basin. In addition to those invasive species identified as representatives of a larger pool of candidate species, selected species occurring in both Missouri River and Red River basins were also included as biota of concern, because interbasin water transfers were considered potential links between basins that might be associated with shifts in metapopulations, resulting in an increased occurrence of a species in the receiving basin, e.g.,

waterborne disease agents could potentially be transferred consequent to interbasin water diversion (see Embrey et al. 2002; Greenblatt and Spigelman 2003; http://www.phac-aspc.gc.ca/new_e.html; http://www.cdc.gov/mmwr/distrnds.html; http://wildfishsurvey.fws.gov/). Within the context of risk analysis and the process of developing a technical analysis suited to the risk-management needs of stakeholders, the selection of species as biota of concern was influenced by the emigrant's attributes of invasiveness (e.g., see Elton 1958; Ehrlich 1976; FAO 2002 for overview; Johnson and Carlton 1996; Moyle and Light 1996; Ricciardi and Rasmussen 1998; Kolar and Lodge 2002 for aquatic nuisance species; Goodwin et al 1998; Higgins et al. 1999; NRC 2002; Rejmánek and Richardson 1996; Rejmánek 2000 for invasive plants) and its role as a "representaive species" in the crafting of a risk characterization focused on an analysis that must be generalized to anticipate invasions by species that present unique species signatures, yet possess attributes that are common to invasive species as a general category of species of concern.

In combination with these attributes of invasiveness, inclusion of a species as biota of concern also focused on the likely ecological receptors, or those species in Red River basin, that would likely be adversely affected if a given species invaded from the Upper Missouri River basin. Any given biota of concern may adversely impact single or multiple species in their role as ecological receptors. The species identified as "likely to emigrate" were identified as biota of concern and their selection was influenced by those species "likely to be adversely affected" as ecological receptors adversely impacted as a consequence of invasion, e.g., unionid mussels were ecological receptors likely to be adversely affected by invasions by zebra mussel. Criteria for inclusion on this list of biota of concern were:

- Organisms identified as biota of concern were included on lists of invasive species previously compiled by the NISC or similar organizations (Invasive Species Specialist Groups, ISSG of the Global Invasive Species Program, GISP), with a particular emphasis on lists having geographic ties to the northern Great Plains and Great Lakes regions.
- Organisms identified as biota of concern were cited by Centers for Disease Control and Prevention and resource management agencies (e.g., US Fish & Wildlife Service, state agencies) as causative agents of waterborne disease in the states of the northern Great Plains and adjacent areas in both United States and Canada.
- Organisms identified as biota of concern have been reported as disease-causing agents in fish, wildlife, or domestic livestock and are directly linked to surface water pathways.
- Initial literature surveys suggested that these species might be supported by data previously published or available for analysis, which would enhance their role as species representative of the broader general focus on the wide range of invasive species that might be critical to evaluations of risks associated with biota transfers in the future.

In our current application, ecological receptors in the Red River basin were considered as those native species most likely adversely affected by a successful biological invasion. For example, zebra mussel (e.g., Johnson and Padilla 1996, Johnson and Carlton 1996, Johnson et al. 2001) are well characterized with respect to their competitive advantage over native bivalves. Similarly, the displacement of native species of mollusks and other aquatic invertebrates is clearly indicated subsequent to invasions by the New Zealand mudsnail (e.g., Richards et al. 2001; see http://www.esg.montana.edu/aim/mollusca/nzms/), and invasions by spiny water flea (e.g., Yan et al. 2001) have adverse effects on ecological receptors in the Great Lakes region where the species has adversely affected aquatic invertebrates and fishes.

Emerging diseases, although not a primary focus of the current effort, do potentially represent species invasions or exchanges of disease agents between the Upper Missouri River and Red River basins. For example, an emerging disease that would represent a species invasion for the Red River basin would be whirling disease caused by *Myxosoma cerebralis* (*Myxobolus cerebralis*). Salmonids (especially, strains of rainbow trout, *Oncorhynchus mykiss*) are potential ecological receptors adversely affected by a successful invasion of *M. cerebralis* (Noga 1996; Bartholomew and Wilson 2002). Similarly, while not invasive species by our definition, disease agents of fish, wildlife, and human populations represent biota potentially subject to interbasin transfer through water diversions from the Missouri River to the Red River basins (e.g., serotypes of *Escherichia coli* and various species of *Salmonella* as those relate to waterborne disease). Representative biota listed in Table 1 have been considered within the current investigations purview at the request of Reclamation and Technical Team, and screening of candidate species was limited. As detailed in the analysis of risks (Section 3) and the characterization of risks (Section 4), the economic consequences (Section 5) associated with invasions of these biota of concern and the adverse effects associated with the most likely impacted ecological receptors are considered in the text of this report, with the bulk of summarized technical materials associated with these species contained in appendices supporting the main body of the report.

2.2 Derivation of Initial Conceptual Model for Biological Invasions of Red River Basin from Upper Missouri River Basin

The iterative process characteristic of the current practice of risk assessment (see Section 1) yielded a draft conceptual model (Figure 6) initially developed from the regional conceptual model (see Section 1, Figure 3), and subsequently modified to yield an operational conceptual model given Reclamation and Technical Team inputs during problem formulation (Figure 7). The operational conceptual model that guided the work summarized in this current report incorporates

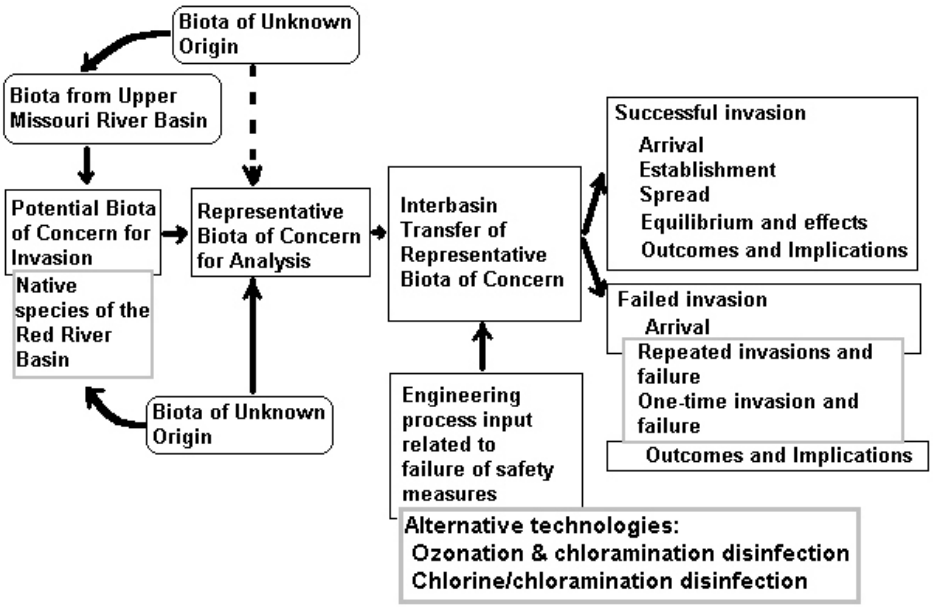


Figure 6. Preliminary conceptual model that guided early discussions with Reclamation and Technical Team to address the analysis, characterization, and interpretation of risks associated with biota transfers consequent to water diversions from HUC10 to HUC09.

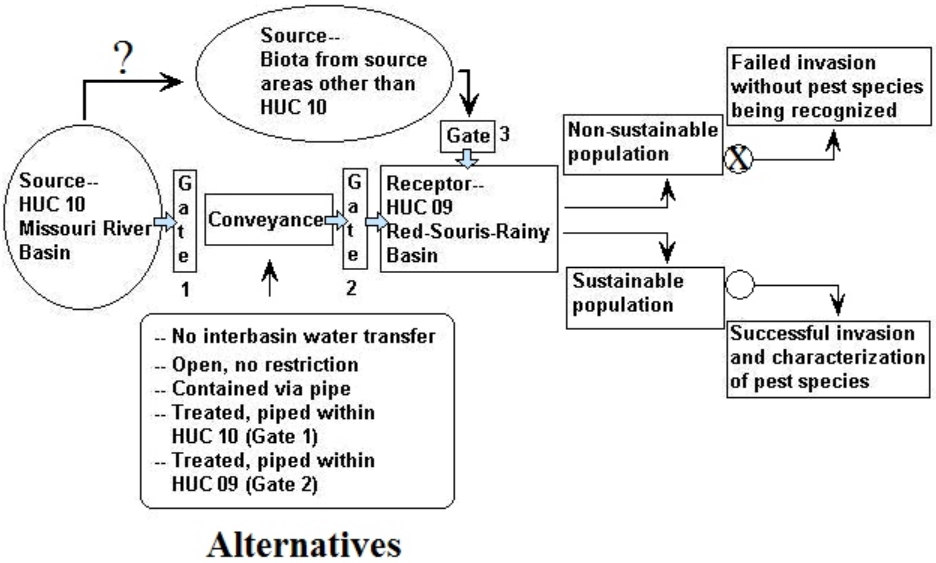


Figure 7. Revised conceptual model which became the operational linkage between the draft conceptual model developed early in the study with those elements of the project that were subsequently identified as critical to Reclamation and Technical Team needs for evaluating of risks and consequences (e.g., alternatives) potentially associated with interbasin water transfers.

sources of invasive species from the Upper Missouri River basin emigrating to the receiving Red River basin through various pathways, including those (1) directly reflecting interbasin water transfers reflected diversions from the Missouri River, (2) other invasions mediated by alternate routes of invasion dependent on human intervention (but not Garrison-related) pathways, or (3) invasions independent of anthropogenic activities.

2.3 Assessment Endpoints

Within the risk assessment process, and in particular during problem formulation, discussions with risk managers yield guidance for technical support activities such as in this current effort. Within an ecological context, assessment endpoints are selected for risk assessment during problem formulation. In this current investigation, assessment endpoints were globally identified as valued ecosystem components to be protected, in this instance, populations of ecological receptors and habitats potentially adversely impacted by species invasions consequent to biota transfers linked to water diversions between basins. While a range of professional opinion is evident in the identification and characterization of assessment endpoints and valued ecosystem components, the identification of global assessment endpoints reflects the systems-level bearing of the Technical Team (see Appendix 17 for listing of Technical Team membership). Technical support developed subsequent to that input reflects biota of concern being viewed within an ecological context, with the primary focus for evaluating consequences resolving on habitat equivalency analysis (HEA; see Section 5). For developing risk scenarios that reflected complete or potentially complete exposure pathways identified during preliminary problem formulation, this initial analysis identified biota of concern that could be relatively easily linked to assessment endpoints captured through HEA that were ecologically relevant, measurable or predictable, and susceptible to biological stressors such as invasive species. By integrating an analysis of economic consequences using HEA at this early stage of technical support, our technical analysis should better support Reclamation and Technical Team's needs related to environmental management and policy decisions. Given the economic analysis tool of choice—habitat equivalency analysis—the integration of global assessment endpoints that guided the technical analysis through the selected biota of concern as "measurement endpoints" (Suter 1993) closely linked to global assessment endpoints summarized in Table 2.

These global assessment endpoints reflected concerns conveyed by Reclamation and Technical Team, particularly as those regional concerns were captured by the selected biota of concern. Although the technical analysis focused on measurement endpoints at the species level of organization, assessment endpoints characterized in part through HEA were considered representatives of the much larger body of "receptors" potentially at risk to species invasions, including adverse affects at the community and ecosystem levels of organization, environmental (both ecological and public) health, and potentially measurable population-level effects. During the development of these assessment endpoints, ecological relevance was an important consideration in selecting appropriate ecological receptors representing these assessment

endpoints. From ecological perspectives, relevant conditions considered in the process of identifying global assessment endpoints included:

- Effects associated with the absence of a species normally expected to occur
- Effects associated with reduction in population size
- Effects associated with altered in community structure
- Habitat degradation or loss
- Diminished or reduced ecological function

Table 2. Global assessment endpoints linking species-specific analysis on selected biota of concern with habitat equivalency analysis supporting analysis of potential economic consequences associated with interbasin water transfers

Population-level	Community-level	Ecosystem-level
♦ Extinction ♦ Abundance ♦ Yield or production ♦ Changed age or size-class (demographic structure) ♦ Disease occurrence (changes in mortality or morbidity)	♦ Market or sport value ♦ Recreational quality ♦ Habitat alteration to less useful or desired type ♦ Changed community structure	♦ Productive capacity

2.4 Measures of Adverse Effects

Measurements of adverse effects, traditionally identified as measurement endpoints (see Suter 1993; EPA 2003, 1998, 1992), were used to quantify adverse effects associated with completed pathways in evaluating alternatives and in characterizing risks likely to occur subsequent to a species invasion. The primary measures of adverse effects are captured by the selected biota of concern, their selection in part determined by the ecological receptors most likely adversely affected by a particular species invasion, e.g., zebra mussels displacing native unionid mussels, and tamarisk displacing native cottonwoods and willow in riparian zones. Good measurement endpoints are intended to correspond to or are predictive of the selected assessment endpoints with the conceptual model establishing links between assessment endpoints and measurement endpoints. For the present study, our focus on invasive species or species having otherwise adversely impacted receptors expedites the identification of measures of adverse effects, and their linkage to assessment endpoints ensures a technically founded transition between risk and economic consequence analysis.

2.5 Pathway Analysis

The pathways analysis conducted as part of the current study reflects guidance from NISC (2001; see http://www.invasivespecies.gov/), with the analysis of pathways focused on both spatial and temporal distributions of biota of concern in source areas of the Missouri River and receptors in the Red River basin most likely responsive to species invasions, if they occur. As part of problem formulation, a brief but illustrative listing of pathways in Figure 5 (see Section 1) clearly suggested the modes of transit that potentially serve the operational conceptual model of Figure 7. In part, the interbasin transfer scenarios that follow in Section 3 are straightforward derivatives of these graphical summary of issues voiced by Reclamation and Technical Team. Distinguishing between invasions linked to intentional transfers from those linked to unintentional and largely accidental transfers is critical to the analysis of risks, the characterization of uncertainty associated with that analysis, and the evaluation of economic consequences of biota transfers.

The root cause of biota transfers in the current investigation is focused on potential water diversions from the Missouri River to the Red River basin. But alternative and competing pathways were critically evaluated within the risk analysis, given the role that these alternate pathways play in linking, or potentially linking, the areas of concern and their intuitively high likelihood for serving as confounding factors in the analysis of risks. For example, intentional and unintentional importation of animals or plants (e.g., commercial- or transportation-linked dispersal mechanisms) represents important pathways for the introduction of biota by direct means or coincidentally, e.g., as hitchhiking organisms.

Pathways analysis is a critical element to the multifaceted process of dispersal regardless of whether anthropogenic or natural mechanisms (or combinations thereof) are the primary linkage between source areas and receiving areas. NISC (2001; see http://www.invasivespecies.gov/) devoted much time and effort to the characterization of pathways that is critical to our current investigation, and we presently rely on its lead in characterizing pathways that potentially mediate biota transfers, whether they were directly linked to interbasin water transfers or not. Similarly, we follow the lead of NISC (2001; see http://www.invasivespecies.gov/) with respect to its focus on uncertainty as an explicit component of the analysis that complements an evaluation of pathways, e.g., a pathway may be identified as being associated with “high risk” but characterized by significant uncertainties with respect to its role in any given invasion process.

Given the list of representative species as biota of concern (Section 1, Table 1) and the task of identifying and characterizing pathways as factors contributing significantly to invasion risks, the current investigation again followed the lead of NISC (2001; see http://www.invasivespecies.gov/) in evaluating pathways directly related to potential interbasin water diversions and competing pathways potentially confounding the characterization of risk. As

suggested by NISC (2001; see http://www.invasivespecies.gov/), pathways were categorized "depending on whether they influenced the probability of introduction or the consequences of the introduction" and were evaluated in conjunction with an "explicit analysis of the degree of uncertainty in the data" available for analysis. Graphically, pathways considered in the current work are captured in Annex, Figure 1 through Annex, Figure 5, which are referred to as "fault-probability trees" (FPTs) and will guide the derivation of quantitative estimates of risk (see Section 3). Fault-probability trees represent a melding of tools common to systems analysis (e.g., analysis of ecosystems or engineering systems) and probability estimation (see Barlow 1998; Bartlett 1960; Bedford and Cooke 2001; Blischke and Parbhakar Murthy 2000; Borgelt and Kruse 2002; Fielding 1999; Haupt and Haupt 2004, 1998; Huzurbazar 2005; Li 1981; Peterson et al. 2002a-d; Peterson and Vieglais 2001; Puccia and Levins 1985; Salthe 1985; Shigesada and Kawasaki 1997; Stockwell and Noble 1991, 1992; Williamson 1996).

Following the lead of NISC (2001; see http://www.invasivespecies.gov/), the current investigation considered pathways as (1) the physical process (e.g., a device or mode of transit, a specific route or course of invasion) that links source and receiving areas and (2) an integrated concept that melds physical processes linking source and receiving areas with attributes of the transferred biota itself (e.g., invasive species may have reproductive mechanisms that favor their migration and establishment in a receiving area). As such, pathway analysis in the current investigation considered a number of attributes that influenced the probability estimates (either quantitative or qualitative) associated with particular biota of concern and the pathways that provide an avenue for dispersal of the species into the Red River basin. These attributes of pathways illustrate the integrated physicochemical and biological characteristics of the invasion process that were critical to the current analysis of risks:

- **Pathway magnitude**: the absolute or relative contribution of a given pathway as a linkage between Missouri River sources and receiving areas in the Red River basin. The magnitude of any particular pathway would reflect, for example, the numbers of species potentially relying on the pathway for transit; the propagule pressure associated with a particular pathway which captures the interrelated factors of inoculation strength (i.e., how propagules characterize each biota transfer or invasion event, also referred to as a "trial") and frequency (i.e., how often to events or trials occur); and the diversity of species that is carried by a particular pathway.

- **Propagule survival**: survival of propagules during transit or their viability and sustainability following transfer reflect the potentially variable ability of a transferred organism to successfully migrate from Missouri River source to the receiving Red River basin throughout the organism's life cycle, e.g., transfer may occur at any time during a species' life history (as adult or larval stages), and some development stages may be more amenable to invasiveness than others.

- **Varying detection probabilities**: a pathway may be characterized by different likelihoods (quantitative or qualitative) for a particular species transfer, e.g., a species may be difficult to manage in transit, or for observing a species during or following its transfer, e.g., a species "presence" or "absence" may be difficult to measure during the transfer process.

- **Habitat similarity between source and receiving areas**: biota transfers, and more likely, species invasions will be highly dependent upon habitat availability and habitat quality in the receiving basin, e.g., successful biota transfers may not be fully realized if habitats in the receiving areas of the Red River basin are not comparable to those in the Missouri River source areas.

- **Likelihoods of establishing a sustainable population and continued dispersal in receiving systems will vary**: regardless of the means of transfer between Missouri River sources and the receiving areas of the Red River basin, biological attributes of a transferred organism will influence its capacity to attain sustainable populations, e.g., whether the species continues to increase its distribution in the receiving system will depend in part on its reproductive fitness in the receiving area and other factors such as habitat interconnectness that might facilitate its spread within and beyond that immediately invaded region.

- **Difficulty in managing a species, if it becomes established**: biota transfers, particularly those that are truly invasions according to our current definitions, may be exacerbated if biological attributes of the invader confer robust invasiveness potential to the species, e.g., although potentially influenced by habitat, management technologies for controlling or potentially eliminating the species may lessen the risks associated with the species transfer.

Each of these attributes may serve as potential risk management tools to control species dispersal. Or if dispersal has already occurred, the species' attributes may be critical in the control of spread and other mitigation issues, e.g., if propagules successfully breach basin boundaries through a completed pathway, do propagule's arrive at the receiving environment in good health and potentially capable of establishing a sustainable population?

Life-history summaries, including presence data, current status, and distribution data for biota of concern, were collected as available from a variety of sources (see Appendix 3A and Appendix 3B). Species-specific data of particular interest in the analysis of aquatic biota included: trophic status, parental care (fishes and aquatic invertebrates only), maximum body size, size of species native range, physiological tolerance, distance from nearest native source, prior invasion success, fecundity, and propagule pressure. These attributes were assigned values in discrete categories based on a survey of current literature (see Appendix 3A and Appendix 3B). Only the variable "prior invasion success" was continuously distributed; otherwise, variables were categorical and ordinal measures which were selected over continuous measures given the

relatively limited reliable quantitative data for the majority of biota of concern (see Appendix 4 regarding details of categorical data, measurement data, and related terminology used in Section 2). Categorical scores for each variable were considered as specified below:

- **Trophic status**: categories for trophic status were designated: (1) parasites, (2) carnivores and herbivores, (3) omnivores, (4) filter-feeders on zooplankton or phytoplankton, including detritivores, (5) autotrophs (primarily cyanobacteria and vascular plants) based on life-history characteristics of biota of concern.

- **Parental investment in offspring (fishes and aquatic invertebrates only)**: for fishes and aquatic invertebrates, parental care categories (scored 1–4) were based on species life histories and included: (1) livebearers including ovoviviparous fishes, (2) biota of concern confer protection of propagules, e.g., fish may protect their embryos or larvae, (3) modes of spawning reflect limitations in propagule release by parents; e.g., for fish, fertilized eggs may be hidden but no additional parental care is apparent, or for aquatic plants, seeds or vegetative reproductive structures have limited unaided dispersal potential, (4) water-column spawners with no parental care (e.g., mollusks and fishes that scatter their eggs in the environment).

- **Maximum adult size (fishes only)**: this category is the maximum length individuals achieved, scored as 3 for "large," 2 for "intermediate," and 1 for "small."

- **Size of native range**: georeferenced data were not available for all biota of concern; hence, using the available presence and distribution data, biota of concern were categorically assigned a score of 1 to 5 based on presence data in North America (and in the instance of carp, worldwide distribution). These categorical scores were: (1) range occupies <5% of one zoogeographic subregion, e.g., local endemics, (2) range occupies 5–50% of one zoogeographic subregion; 3) range occupies >50% of one zoogeographic subregion, (4) range occupies more than one zoogeographic subregion. If biota of concern presented sufficient data for characterizing their current and predicted distributions, these were also reflected in their categorical assignments.

- **Physiological tolerance**: this variable represents tolerance to changes in water quality (usually temperature, dissolved oxygen, turbidity, and salinity) or to extreme conditions in water quality, based on Halliwell et al. (1999) for aquatic vertebrates and extended for our current application, with the addition of an extremely tolerant category: (1) intolerant: biota have low physiological tolerance to changes or extremes in water quality. (2) moderately tolerant biota capable of living in water with moderately high variability in water quality, (3) tolerant biota capable of living in waters in which water quality often reaches their limits of physiological tolerance for short periods, (4) extremely tolerant

biota capable of living in waters with water quality that excludes most other members of the taxon.

- **Distance from nearest native source**: because dispersal distances are infrequently characterized and reflect retrospective estimates, categories were used to characterize distances from source to receiving areas that historically have been observed for biota of concern: (1) <150 km, or within HUC or current distribution suggested movements across HUC boundaries are not likely events unless presence data suggest current distribution reflects occurrence near HUC boundary, (2) 150–1000 km, or within HUCs and diffusive dispersal not unlikely at HUC boundaries; 3) 1000–3000 km, or within North America outside above areas; 4) >3000 km or dispersal from other continents beyond HUC boundaries for either Missouri River or Red River basin.

- **Prior invasion success**: a category that reflects past performance of the biota of concern as an invasive species. This score ranged from 1 to 4 as defined: (1) invasion potential limited unless mitigating factors such as human-assisted introductions occur (e.g., introductions of species greater than 1000 km from current distribution), (2) invasion potential restricted due to limiting life-history attributes (e.g., species is physiologically limited by low temperatures) or limited means of self-dispersal (e.g., propagules such as seeds are not disperse by wind), (3) species is opportunistic given translocation to receiving areas is amply supported by physical or biological means (e.g., species may have limited means to self-disperse but is a highly capable "hitchhiker" and relatively tolerant of widely varying environmental conditions), (4) species is highly mobile and has a widespread distribution, but presents life-history attributes that require relatively invariant environmental conditions to assure sustainable populations develop in receiving areas, (5) invasion highly likely given the species life-history attributes (e.g., propagules easily dispersed and highly tolerant of widely varying environmental conditions).

- **Fecundity and propagule pressure**: propagule pressure is the number of propagules (at any stage of life-history) that historically represents sufficient numbers to successfully establish a self-sustaining population in areas being invaded. Categories ranged from 1 to 4 and represented logarithmically spaced estimates as single events or multiple events that are effectively linked in any given cohort's common life history: (1) less than 10 individuals released, (2) greater than 10 but less than 100 individuals, (3) greater than 100 but less than 1000 individuals, (3) greater than 1000 but less than 10,000 individuals released, and (4) greater than 10000 individuals released. Categories were applied to this analysis, since measured counts of propagule pressure are infrequently recorded in the literature and when available are frequently rough estimates based on the most likely scenarios for the introduction.

In the current investigation, we have incorporated a categorical analysis for characterizing risk and used a rank-categorical approach (see Campbell and Kreisch 2003; Agresti 2002; NISC 2001) to evaluate each of the biota of concern listed in Table 1 by adapting a set of categorical assignments suggested by Campbell and Kreisch (2003), Kolar and Lodge (2002) and Marchetti et al (2004) among others (Ashton and Mitchell 1989; Rejmánek and Richardson 1996; Rejmánek 2000, e.g., for invasive plants) to evaluate those attributes identified for each biota of concern.

As suggested by Marchetti et al. (2004), we used the following general analytical approach based on Burnham and Anderson (2002) to assess the influence of species characteristics on three stages of the invasion process. First, we gathered existing data and information on species presence, characteristics, spread, and abundance (see Appendix 3A and Appendix 3B), then completed a spatial analysis that was focused on predicting the potential distribution of each biota of concern. Depending on the available life history, past records of invasiveness, and the current and predicted distributions of biota of concern, we then characterized risk as a function of the categorical evaluation of potential risk and predicted distributions of biota of concern.

Quantitatively, two techniques were applied to the analysis and characterization of risk in Section 3 and Section 4, respectively. Various information measures such as Akaike's Information Criterion (see Arndt 2001) and statistical tools such as chi-square analysis of goodness of fit (see Zar 1999) are applicable to identifying "best fit" spatial projections of potential species' distribution (see Appendix 4). In our current work, the latter tool was applied to our spatial analysis. When data were sufficient, categorical and spatial analyses were completed for quantitative evaluations of risk; however, not all biota of concern presented sufficient data to warrant quantitative analysis, and risks were characterized qualitatively through a narrative characterization (see Section 4).

Categorical assignments of risks were also applied to estimates of risk derived from the evaluation of simple FPTs (Figure 8 through Figure 12) that captured the stepwise invasion process that practically linked pathways analysis with our operational conceptual model (Figure 7). The melding of categorical and quantitative estimates of risk assured that differences in data availability from one biota of concern to another would not adversely influence characterization of risks associated with biota of concern but would reinforce the importance of uncertainty in the interpretation of risk and the development of risk management practices available to manage data insufficiency.

2.6 Tools to Characterize Risk and Economic Consequences

The primary task that characterizes this objective of the current study focuses on the derivation of estimates of risk and the consequences potentially associated with those risks. Although oversimplified for our present purposes (and highly dependent on data sufficient for

implementation), in general the analysis of risks considered conditional probabilities that describe the invasion of the Red River basin by any species originating from the Upper Missouri basin as

$$P(A_i|B) = \frac{P(B|A_i)P(A_i)}{\sum_{j=1} P(B|A_j)P(A_j)}$$

where the event, A*i*, is predicated on B repeatedly over space-time. Such tools are commonly applied to engineering systems (see Bedford and Cook 2001, Serrano 2001) and biological systems, including species invasions (Hayes 1996, Levin 1989, Williamson 1989, Williamson 1996, Paine et al. 1998). Although evaluation of risks conceptually hinged on evaluating conditional probabilities, in our current evaluation, simple probability evaluations were the tool of choice (see Appendix 4). For example, FPTs in Annex, Figure 1 through Annex, Figure 5 reflect the "simple" stepwise constructions supporting a simple probability analysis of the biota transfer and invasion process. Biologically, the generalized top event might be "successful biological invasion of Red River basin by biota originating from Upper Missouri River basin." Here, the success of invasion would be predicated on prior independent events occurring, e.g., (1) "biota transfer successfully completed," (2) "invasive species established a reproductive population," and (3) "a reproductive population attains sustainable numbers to compete against indigenous species," with each prior event amenable to decomposition and more comprehensive characterization as data allow (pathways may be incomplete, biota transfer from source area may not lead to establishment of invasive species population given failure to find suitable habitats or hosts, etc.. in the target area). Ultimately, the statements of probability of invasive species established in the target area (Red River basin) would be developed for each of the biota of concern identified in the conceptual model(s).

Given the conceptual models developed early in discussions and finally revised as the current investigations operation conceptual model to guide scenario development (Figure 7), the development of a series of FPTs reflects a graphical summary of these conditioned events that were the focus of quantitative risk estimation (see Section 3 and Section 4 for analysis and characterization of risks, respectively). Here, we briefly describe the graphic representations of FPTs and characterize the calculations that yield quantitative risk estimates summarized in Section 3. The reader is referred to Appendix 4 for greater detail on the preliminary derivations of probability estimates for biota transfers as depicted in Annex, Figure 1 through Annex, Figure 5. Each FPT captures one pathway or a series of interrelated pathways that potentially link biota from the Missouri River basin with the Red River basin. For example, FPT 1 is the primary depiction of pathways directly linked to water diversions proposed under the DWRA, and subsequent fault-probability trees (Annex, Figure 1 thorugh Annex, Figure 5) reflect alternative transfer and invasion pathways.

Consequence analysis was fully integrated with the analysis of risk, and as identified during problem formulation (see Section 1), the analysis of economic consequences relied upon tools commonly applied to the evaluation of restoration and compensatory costs in Natural Resource Damage Assessments (NRDA). Invasion of habitats by nonnative species and the subsequent displacement of native species from those habitats clearly suggest that HEA is appropriate as a tool to evaluate economic consequences potentially associated with interbasin biota transfers. Section 5 summarizes the HEA process which focused on the costs of compensatory measures that offset the loss of wildlife habitat function associated with invasive species. Outputs of risk characterization provide inputs to the HEA process, and the subsequent integration of risk and costs provide insights to the consequences associated with biota transfers as captured by the supporting conceptual model. Also, tools available to the natural resource and environmental economist have been applied to resource valuation, including those tools applied to nonmarket valuation and characterization of nonuse, option, and existence values.

Confidence in the conclusions of risk characterization may be increased by using several lines of evidence to interpret and compare risk estimates, including an evaluation of the relevance of evidence to the assessment endpoints, the relevance of evidence to the conceptual model, the sufficiency and quality of existing data, the strength of cause and effect relationships noted in comparative studies, and the relative uncertainty associated with each line of evidence and the concordance (or absence of concordance) across various lines of evidence.

2.6.1 Focus on ecological adversity. Risk characterization discusses whether ecological receptors are exposed to invasive species capable of causing adverse effects to the overall ecosystem or to the particular valued species within that ecosystem (assessment endpoint), including a focus on whether ecological receptors may be adversely affected in the future (see Section 1; EPA 1992, EPA 1998, Suter 1993, Minnesota Sea Grant/Michigan Sea Grant, 2001).

The nature and intensity of effects were evaluated to distinguish adverse effects from effects occurring within the normal pattern of variability. Spatial and temporal scales were also considered in assessing adverse effects. The spatial dimension involves both the extent and pattern of adverse effects, as well as the context of the effects within the ecosystem. Factors to consider include the absolute area affected, the extent of sensitive habitats affected compared with a larger area of interest, and the current and future land and water use within the ecosystem. The temporal scale of adverse effects for ecosystems can vary from short term (e.g., seconds to minutes to days for altered photosynthesis yielding advantages to invasives for establishing sustainable populations) to long term (e.g., decades to centuries for adverse effects reflected in changes in biodiversity). Risk assessors should recognize that the time scale of adverse effects operate within the context of multiple natural time scales. For example, visible changes in the productivity of an aquatic system may not become evident for many years after initial biological invasion. The potential for recovery of a system was also considered in assessing ecological adversity. Recovery is the rate and extent of return of a population or community to a condition that existed before the

introduction of invasive species. Examples include reestablishment of a species to a specified density or recolonization during recovery following removal of a biological invader.

2.6.2 Uncertainty analysis. A discussion of uncertainties or the lack of relevant information is a necessary part in an even-handed characterization of risks associated with a biological invasion. Sources of uncertainty contribute to possible overestimated or underestimated ecological risks. The objective of uncertainty analysis was to describe and quantify, where possible, what is known and not known about effects and linkage between source and receiving areas. Uncertainty analysis increases assessment credibility by quantitatively or categorically characterizing the magnitude of uncertainties and their relationship to risk characterization.

Uncertainties may be addressed and their effects minimized for any risk assessment, with the results of uncertainty analysis being used to identify data gaps and direct data collection activities. For the evaluation of biota transfers and the biological invasions subsequent to water transfers between the Upper Missouri basin and Red River, species distributions will be critical data to the risk analysis. Additionally, and as available, the risk analysis will depend on data that reflect a quantitative basis for evaluating the transfer and establishment of invasive species, the spread and development of equilibrium populations of invasive species and the effects and potential implications of invasive species. For example, although data may not be sufficient for each biota of concern, demographic data related to life-table analysis would ideally be applied to the analysis wherein survivorship and maternity functions and reproductive rates would be considered as a basis of analysis. Ecologically, habitat data may be critical to the analysis (e.g., habitats not sufficient to sustain an invading species) as would potential environmental or engineering data that suggest limitations to successful invasions (e.g., ambient temperature extremes or water treatment may limit success). Similarly, data critical to a fully developed consequence analysis would encompass biological data (e.g., species distributions, functions key to life-table analysis) and economic data essential to an analysis of the impacts of invasive species and the determination of compensatory measures sufficient to offset those impacts.

The methodological approach applied in the current analysis was observational and relied on existing data or information in the form of peer-reviewed literature or government documents. Analytically and statistically as possible, these encountered data were reviewed for data quality. When possible, primary data sources were used in developing the risk and consequence analysis. Tools selected for the analysis reflected the contingencies predicated by available data, and as such, those tools commonly applied to encountered data analysis (see Appendix 4). In the absence of primary data, peer-reviewed literature from open sources was relied upon, as well as government documents that have met data quality objectives for the project reports being reviewed (see data quality discussions for the Heinz Center (2002) reports such as http://www.heinzctr.org/ecosystems/report.html, and related technical appendices available at http://www.heinzctr.org/ecosystems/pdf_files/sotne_tech_notes.pdf, and http://www.heinzctr.org/ecosystems/fr_water_technotes/fr_water_non_ntv_spec.shtml).

2.6.3 Data quality evaluation. The derivation of probabilities for interbasin transfers of biota of concern will only be as good as the data used in their calculation, which necessarily means the characterization of risks must be completed in parallel with an evaluation of data quantity and data quality. As a source of uncertainty, data quality and quantity are critical to the interpretation of species invasion probabilities. Also, uncertainty will vary from one species to the next, depending on the available data; hence, risks dependent on probability estimates have been characterized in light of their associated uncertainty. For this investigation, existing literature and available data used as inputs for the derivation of quantitative estimates of risk were obtained from the peer-reviewed literature, from open-source data compilations having documented quality assurance practices, and from USGS-reviewed data compilations. In addition, as available, other Department of the Interior (DOI) sources (e.g., US Fish and Wildlife Service, National Park Service) provided data and available literature with documented quality assurance practices (see http://www.epa.gov/nerlesd1/gqc/courses/qa.htm; http://geography.usgs.gov/standards/).

2.7 Implementing Data Search and Retrieval

Natural resource managers frequently seek technical support for developing practices and policy. The work summarized in this report reflects the technical findings for such a request focused on issues related to biota transfers potentially resulting from water diversions from the Missouri River to the Red River basin. As reflected in Section 1, risk analysis has found increasing application for crafting adaptive resource management practices wherein technical inputs and outputs—realized or potential—to a managed system (e.g., wildlife refuge, agriculture lands) are considered within a “what-if” context focused on potential outcomes that likely influence practices and policy proactively (see Gunderson et al. 1995; Holling 1978; Jensen and Bourgeron 2001; Walters 1986). Regardless of landscape setting, whether it is solely spatial or spatiotemporal, an initial evaluation of risks involved in various management practices available to the manager may be solicited for guidance on which of many management practices might be applied to the specific circumstances. Often, a “desktop” risk analysis is the first step in the characterization of risks and the evaluation of and its dependence on existing data and information directly or indirectly linked to the questions identified in problem formulation.

2.7.1 Encountered data and data mining. Desktop analysis requires working with data and existing information; hence, the analytical tools are more observational than experimental and rely on data-mining search and compilation (see Chen 2001; Wolkenhauer 2001). As such, collection of data in desktop studies is similar to preliminary field investigations in ecological studies, since data in ecological and environmental studies, especially reconnaissance level efforts, are often not collected via an experimental or sampling design but through observational studies. The primary tool in data collection for desktop analysis is data mining, a discipline lying at the interface of statistics, database technology, pattern recognition, and machine learning. Data mining is focused on the secondary analysis of data extracted from the existing literature (e.g., previously published material, compiled databases) in order to characterize relationships among variables typical of new

questions that may be linked to these existing sources of information. Data mining relies on an inductive process and is primarily concerned with secondary data analysis.

2.7.1.1 Literature Search: Collection of existing data and information to evaluate risks associated with biota transfers between Missouri River and Red River basins. The main database providers used included Cambridge Scientific Abstracts (CSA) and OCLC FirstSearch. Databases searched in CSA included Aquatic Sciences and Fisheries Abstracts, Biological Sciences, Environmental Sciences and Pollution Management; and to a lesser extent, AquaLine, Water Resources Abstracts, GeoRef, Biology Digest, Conference Papers Index, Medline and Toxline. Databases in OCLC FirstSearch that were searched included Agricola, ArticleFirst, BasicBiosis, Dissertations, GeoBase, and WorldCat. BioAgIndex, Electronic Collections Online, PapersFirst, and Proceedings. Ingenta database provider was also used for some searches.

Search terms. Searches for identifed biota of concern used the scientific name (at genus or species level), and common names, if applicable. Depending on the number of citations found, additional search terms were added. Terms used would refer to the distribution and spread of the species, its life history and habitat, and its interaction with other species. In some cases, for example, the bacteria, the focus was on the natural occurrence of the biota and risk assessment. Citations related to detection and control measures were generally included. When there were an overwhelming number of citations, the search in some databases was limited to more recent references (within the last 10 years).

2.7.1.2 Search outcomes. Existing literature and data collected from the literature search was dominated by “effects data” derived from past studies—observational and experimental—focused on the effects that a particular biota of concern had on a receiving system and “pathways data” which reflected available literature resources focused on the spatiotemporal linkages between biota of concern and their geographic distributions. Graphically, Figure 8 through Figure 13 summarize citation counts for biota of concern and reflect a relatively wide range in literature and existing data available for the current data-mining effort focused on the biota transfer questions identified during problem formulation.

2.8 Implementing Data Analysis

The following overview provides a summary of analytical tools and the underlying assumptions that are associated with these tools for the data analysis detailed in Section 3 and the characterization of risks in Section 4. Please refer to Aven (2003), Barlow (1998), Blischke and

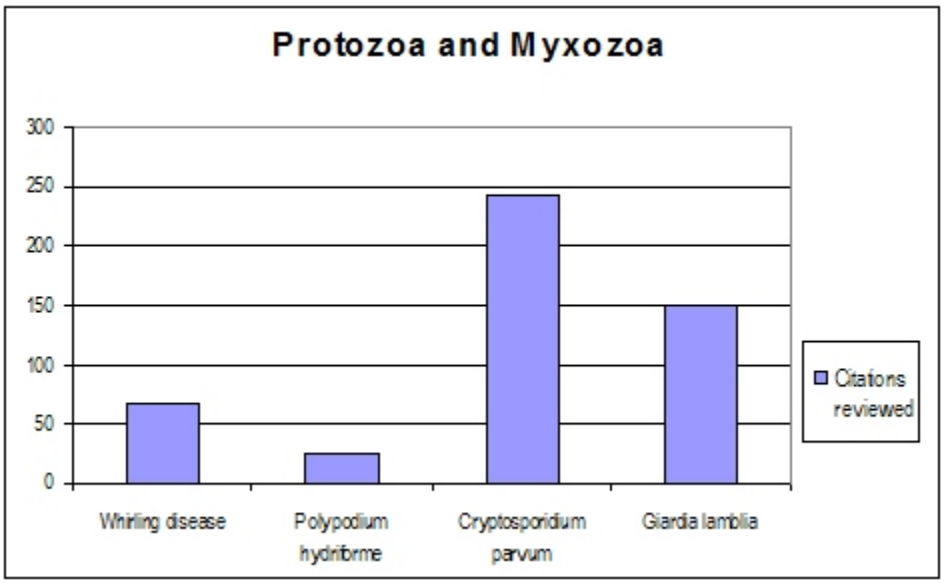


Figure 8. Summary numbers of literature citations collected and subsequently compiled for protozoa and myxozoa (see Appendix 3B).

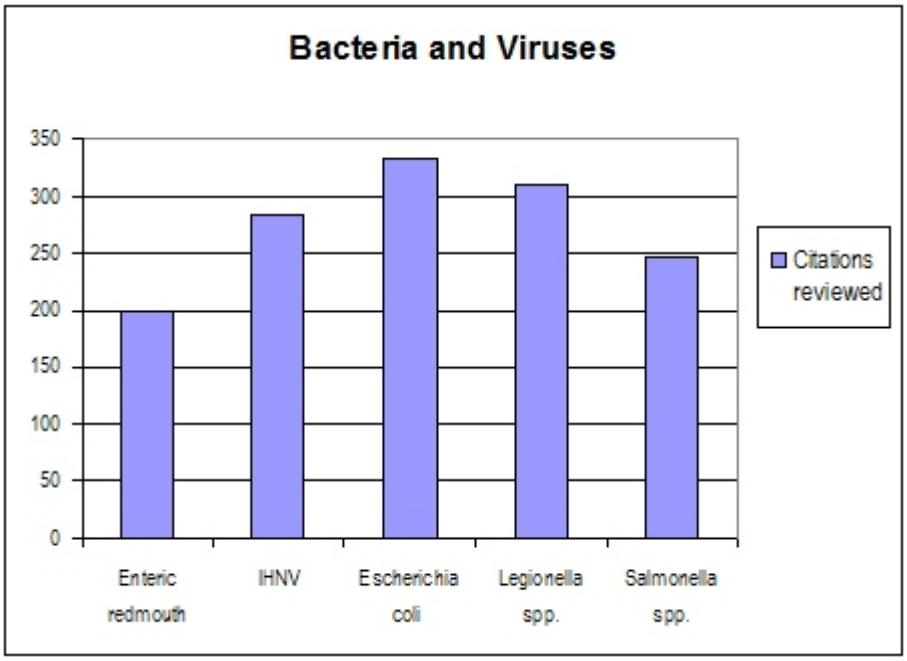


Figure 9. Summary numbers of literature citations collected and subsequently compiled for bacteria and viruses (see Appendix 3B).

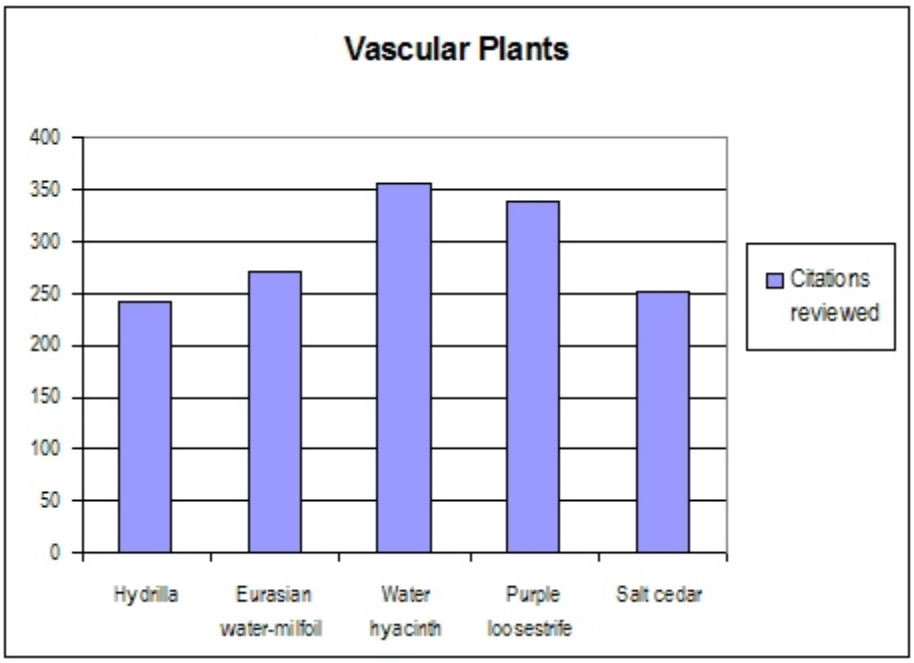


Figure 10. Summary numbers of literature citations collected and subsequently compiled for aquatic vascular plants (see Appendix 3A).

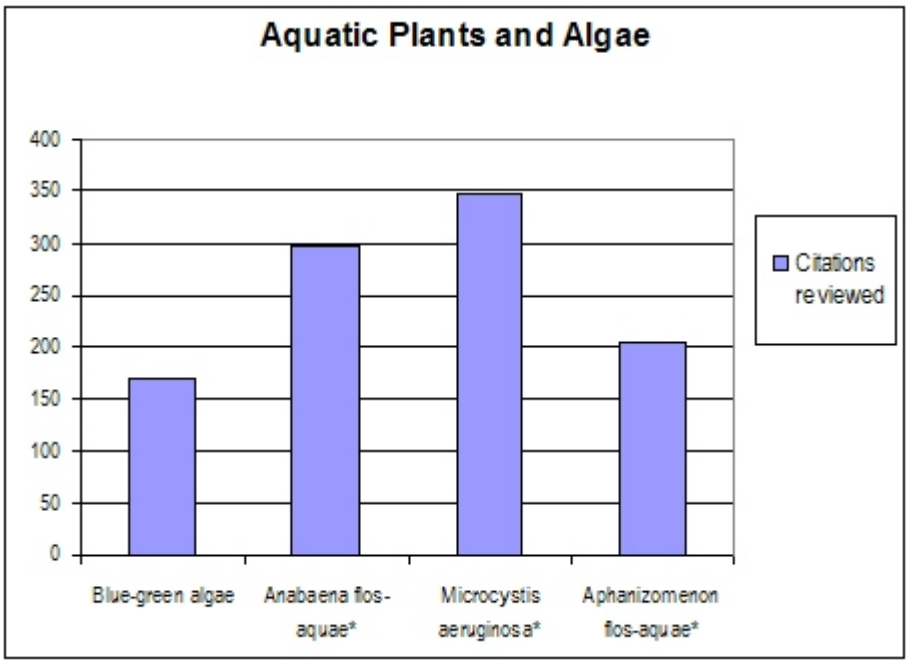


Figure 11. Summary numbers of literature citations collected and subsequently compiled for cyanobacteria (see Appendix 3B).

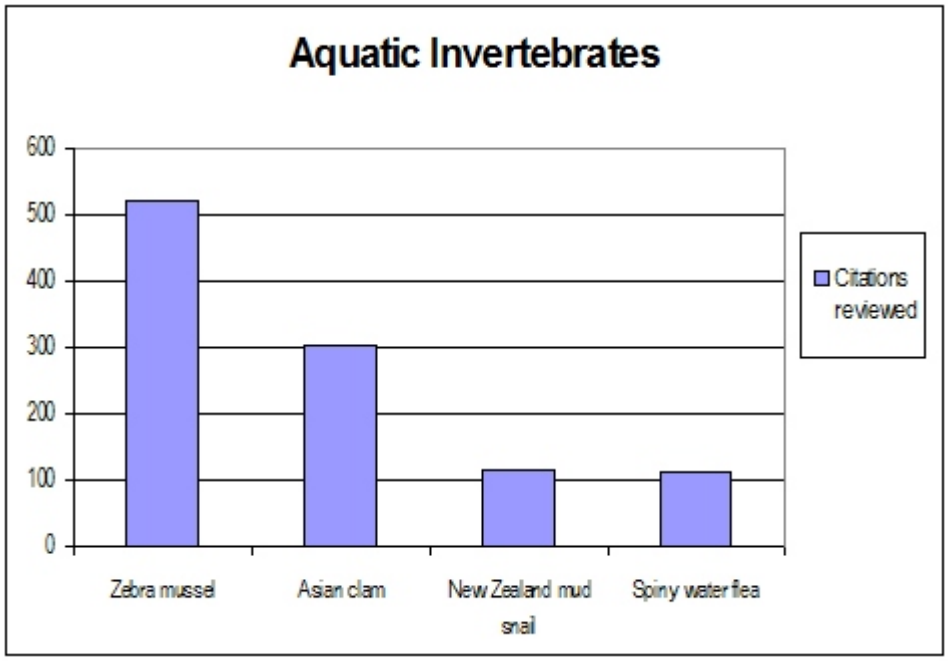


Figure 12. Summary numbers of literature citations collected and subsequently compiled for aquatic invertebrates (see Appendix 3A).

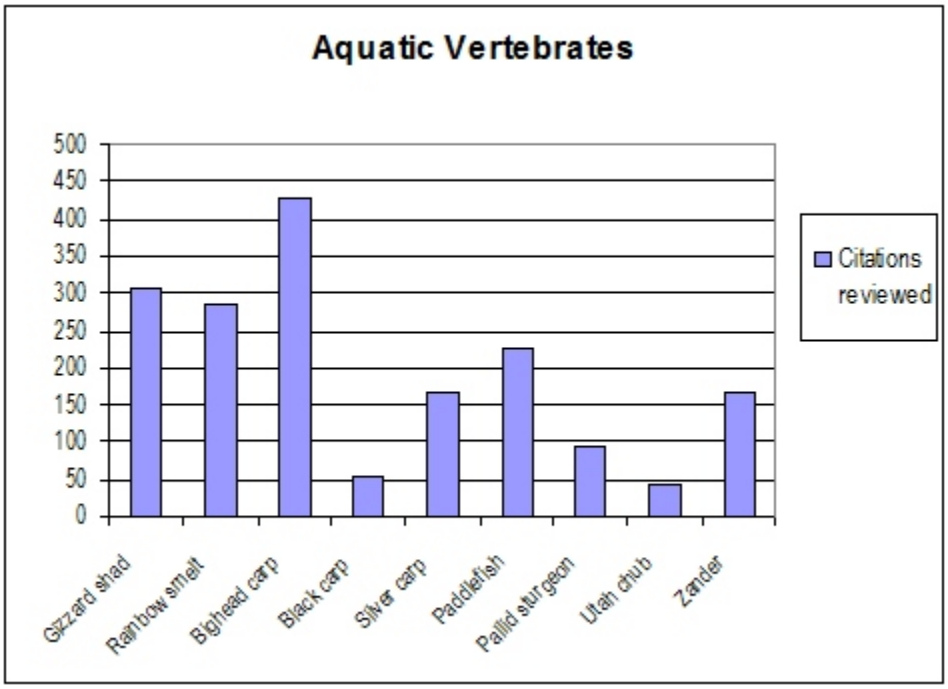


Figure 13. Summary numbers of literature citations collected and subsequently compiled for aquatic vertebrates (i.e., fishes; see Appendix 3A).

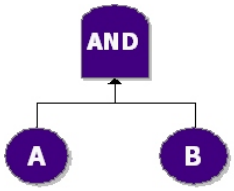
Parbhakar Murthy (2000), Borgelt and Kruse (2002), Huzurbazar (2005), and Appendix 4 as derived in part from NIST/SEMATECH (2004; http://www.itl.nist.gov/div898/handbook/) for background information for supporting data analysis.

2.8.1 Tree diagrams and pathway analysis. Tree diagrams are used to represent probability problems involving multiple events, generally where the events are sequential and independent. The tree diagram consists of a number of branches, where each event in a flow of events has branches characteristic of potential outcomes of trials (see Burgman 2005 for application of these techniques in conservation practice). Probabilities, then, are associated with each of the branches in a flow of events. Construction of a tree diagram continues until the process is fully characterized. In the present work, tree diagrams occur as graphic tools to evaluate (1) probabilities of serial, independent events and (2) potential fault trees associated with a preliminary analysis of control system reliability.

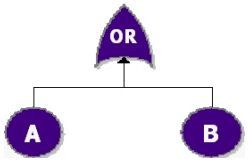
Fault trees are symbolic analytical logic techniques that can be applied to analyze system failure or reliability and related characteristics. A fault-tree diagram follows a structure that represents a graphical model of the pathways within a system that can lead to a potential loss or failure, in our application, a species invasion. The pathways interconnect intermediary events and conditions using standard logic symbols (e.g., AND-gate, OR-gate). Fault-tree diagrams consist of gates and events connected with lines. The AND and OR gates are the two most commonly used gates in a fault tree wherein gates are used to consider two events (called “input events”) that can lead to another event (called the “output event” or “outcome”). If the occurrence of either input event causes the output event to occur, then these input events are connected using an OR gate. Alternatively, if both input events must occur in order for the output event to occur, then they are connected by an AND gate.

2.8.1.1 Basic gates. Gates are the logic symbols that interconnect contributory events and conditions in a fault-tree diagram. The AND, OR gates, and Voting OR gates are the basic types of gates in classical fault-tree analysis that pertain to our present investigation.

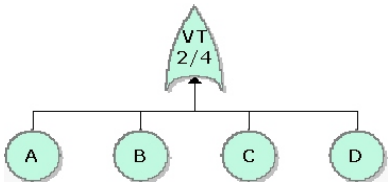
AND Gate. In an AND gate, the output event occurs if all input events occur. In system reliability terms, this implies that all components must fail (input) in order for the system to fail (output) and is conventionally illustrated as:



OR Gate. In an OR gate, the output event occurs if at least one of the input events occurs. In system reliability terms, this implies that if any component fails (input) then the system will fail (output). The illustration below shows a simple fault-tree diagram in which either A or B must occur in order for the output event to occur. In this diagram, the two events are connected to an OR gate. If the output event is system failure and the two input events are component failures, then this fault tree indicates that the failure of A or B causes the system to fail.



Voting OR Gate. In a Voting OR gate, the output event occurs if one or more of the input events occur. In system reliability terms, this implies that if any k-out-of-n components fail (input) then the system will fail (output), e.g., for a sexually reproducing invasive species, at least one of each sex must successfully breach barriers between source and receiving areas. Convention would illustrate a fault-tree diagram with a 2-out-of-4 Voting OR gate as indicated below where the system will fail if any two of its input components fail. The fault tree looks at "k-out-of-n" failures for the system failure.



Combining Basic Gates. Gates within a fault-tree analysis can also be combined to create more complex representations. Regardless of its complexity, a fault-tree diagram is always drawn in a top-down manner and with its lowest item being a basic event block.

Pathway analysis for the current investigation was completed in conjunction with fault-probability tree diagrams and summarized invasion scenarios developed from the conceptual model(s) in problem formulation (see Section 1 and operation conceptual model, Figure 7). Reliability analysis, especially for infrastructures such as those envisioned for implementing interbasin water transfers, has been folded into the pathways analysis, since it is a key component reflected in the developing estimates of risk and evaluation the risk reduction potential of alternative control system technologies. By doing so, alternative controls technologies have also been considered within the context of risk reduction in Section 4.

2.8.1.2 Fault-probability trees and reliability analysis. A graphic depiction of pathways that potentially link biota from source areas in the Missouri River basin with their potential

distribution expansions to the Red River basin are captured in Annex, Figure 1 through Annex, Figure 5. While relatively simple in construction, these FPTs represent an integration of tools from systems analysis that afford us with an opportunity to incorporate alternative control systems into our risk analysis. The reliability of any given control system of interest to Reclamation and Technical Team, be that chemical treatment of source waters (e.g., chlorination, chloramination), use of various water filtration technologies (e.g., microfiltration, ultrafiltration), or combined technologies can be considered within the context of risk reduction when these control systems are contrasted to water transfers in the absence or failure of control systems (see Section 4). As such, the interrelationships between probability characterizations for biota transfer and systems reliability can be graphically summarized for considering various scenarios in the current analysis.

For example, any engineered control system reflects a range in performance that varies with time where a system's quality reflects a snapshot of that system at "time zero," or T_0, or the system's start-up. Reliability, however, is dynamic and captures a system's day-to-day operation. For example, system defects, e.g., in a water treatment system, at time zero likely express mistakes in manufacture of component parts or construction of the system, while reliability defects reflect the aging process of the system and its component parts. To describe reliability defects, a probability model that describes the fraction of failures over time or the system's life distribution model should be known because accurate prediction and control of reliability play important roles in helping a system to meet its performance goals. See Appendix 4 for additional background on reliability analysis as integrated into the analysis of risks for the current investigation.

2.9 Categorical Data and its Analysis: Tools Used in Current Analysis of Encountered Data

A brief review of Appendix 4 provides background on categorical data and measurement data, and in this section we briefly review the primary tools brought to the analysis of risks currently under investigation.

2.9.1 Logistic regression. Logistic regression is instrumental in the analysis of risk, including the development of predicted species distributions for biota of concern (see Hosmer and Lemeshow 2000; see also §4.3.2). As in simple linear regression, logistic regression gives each regressor a coefficient b_1 which measures the regressor's independent contribution to variations in the dependent variable. In evaluating dependent variables that are binary (that is, they result from a Bernoulli process wherein outcomes can only take values of 0 and 1), logistic regression yields estimates of probability (p) of a dependent variable being 1 rather than 0 based upon our knowledge of independent variables, i.e., we are interested in the probability of a biota transfer consequent to a water diversion being successful (value = 1) or not successful (value = 0). Logistic regression requires making a logistic transformation of p, commonly referred to as the

logit of p. Logit(p) is the log (to base e) of the odds or likelihood ratio that the dependent variable is 1, and in symbols is defined as

$$\text{logit}(p) = \log(p/(1-p)).$$

Values of p can only range from 0 to 1, but logit (p) can range from negative infinity to positive infinity with the logit scale being symmetrical around the logit 0.5 (Table 3).

Table 3. The relationship between probability of success (p) and logit(p).

p	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.95	0.99
logit(p)	-0.847	-0.405	0	0.405	0.847	1.386	2.197	2.944	4.595

As indicated by values in this summary table, the differences between extreme probabilities are spread out over a larger interval than mid-range values (e.g., differences of logits between success rates of 0.95 and 0.99 are much greater than logits between 0.5 and 0.7); hence, the logit scale is approximately linear in mid-range and logarithmic at extreme values.

Logistic regression involves fitting an equation of the form to the empirical data available to the analyst; that is,

$$\text{logit}(p) = a + b_1x_1 + b_2x_2 + b_3x_3 + ...$$

Logistic regression finds a “best-fit” equation using a maximum likelihood method in contrast to the simple least-squares methods of linear regression. Hence, the goodness of fit and overall significance statistics used in logistic regression are different from those used in linear regression. Log likelihoods are critical in evaluating logistic regression wherein probability associates with a specified hypothesis, e.g., the null hypothesis that all coefficients in the regression equation take the value zero. Calculations of such a likelihood of observing the exact data we actually did observe under this hypothesis generally yields a very small number. The values are usually transformed to the natural logarithm; hence, a value of log likelihood. Log likelihoods are always negative, since probabilities are nearly always less than one.

2.9.2 Monte Carlo analysis, Markov chain-Monte Carlo analysis, and bootstrap resampling methods. Monte Carlo, Markov Chain-Monte Carlo (MCMC), and bootstrap resampling methods (see Davison and Hinkley 1997; Efron 1982; Gamerman 1997; Manly 1991) were applicable to characterizing quantitative estimates of risk of biota transfers between Missouri River source and Red River basin receiving systems. For example, MCMC is an algorithm that generates a Markov chain of random samples (i.e., each sample is conditionally dependent on the preceding sample) whose stationary distribution is the likelihood function. In contrast, bootstrap resampling relies on assumptions that empirical samples are adequate as representations of

populations and that characterizations of the underlying population may be attained by simply resampling that empirical sample set that is characterized by a statistic, β^{hat}, based on a sample of size, *T*. In bootstrap resampling we assume that the empirical sample of size *T* approximates the entire sampling distribution of β^{hat} by investigating the variation of β^{hat} over a large number of pseudosamples obtained by resampling the same data. For the resampling, we assume the original sample was drawn from a single population and that samples were independent, and a Monte Carlo simulation is used on the available sample values which are drawn randomly with replacement. No underlying assumptions of normality are required in bootstrap resampling. The bootstrap is completed via a large number of resamples (e.g., 1000) of size *T* from the original sample created, with each element of the original sample having the same probability (1/*T*) of being in a sample. The initial idea behind bootstrapping was that a relative frequency distribution of β^{hat}s calculated from the resamples can be a good approximation to its sampling distribution.

2.9.3 Spatial and temporal analysis. Our analysis of risks is largely based on a "snapshot" of species distributions in ecological space-time, yet our intent is projecting future distributions of biota of concern given the dynamic process of species dispersal. In the current investigation the temporal and spatial attributes of species distributions are summarized primarily through dot maps and other qualitative thematic maps (e.g., county maps) for displaying point data and regional count data, respectively. Potential species distributions are predicted using a technique increasingly common in conservation biology and in studies focused on assessing biological diversity (e.g., Peterson and Vieglais 2001; Peterson et al. 2002d).

2.9.3.1 Dot maps. Qualitative and quantitative thematic maps have a long history in the analysis of species distributions and epidemiology (see Lawson et al. 1999; Lawson 2001), especially when data are collected as a result of a point process linked to some geographic feature of the landscape (e.g., some natural or political features that can be projected on a map). Qualitative thematic maps form a variety of maps that differ from general or topographic maps, since they specify distributions of categorical data or nominal data (see Appendix 4) in their simplest forms, e.g. different types of natural features such as soils and vegetation or different types of human cultural attributes such as religions and occupations.

Dot maps are one of the oldest but simplest quantitative thematic maps used to summarize spatial point data. While dot maps provide a quick visual display of point data across some geographic region, it does not project estimates of actual numbers or areal patterns. Simple dot maps, however, do provide a good illustration of distribution and form the basis for the spatial analysis of geographically referenced point data concerned with spatial patterns of species or disease occurrence. In the current investigation dot maps are used to summarize spatial point data when locations of species occurrence are known, or regional count data when location information is limited and the numbers of species occurrences are aggregated for distinctive regions, most often county or state records.

2.9.3.2 Genetic algorithm for rule-set prediction (GARP) and Desktop GARP. There are numerous tools that project spatial point data, e.g., as evident from a simple dot map, to a continuous species distribution where interpolations have been made to account for areas between dots to yield continuously distributed projections (see Cressie 1993; Daly and Gani 1999; Elliot et al. 2000; Lawson et al. 1999; Lawson 2001; Scott et al. 2002). Alternatively, projections of spatial point data may assume disjunct collections of continuous distributions that result from point data that occur as clusters on a simple dot map. In the current investigation, potential species distributions were predicted by using contemporary tools—genetic algorithms and machine learning—increasingly used in conservation biology (see Fielding 1999; Sait and Youssef 1999; Spall 2003; Peterson and Vieglais 2001; Peterson et al. 2002a-d). While simple dot maps are examples of one of our oldest tools for evaluating species distributions, these contemporary tools reflect the development of computer-based analysis of spatial processes and their applications to biological and ecological questions.

Genetic algorithms (GAs) constitute one class of artificial intelligence applications and were inspired by models of genetics and evolution (Holland 1975). They have been applied to various problems not amenable to traditional computational methods because the search space of all possible solutions is too large to search exhaustively in a reasonable amount of time (Stockwell and Noble 1992). Genetic Algorithm for Rule-Set Prediction (GARP) is an expert system, machine-learning approach to predictive modeling (Stockwell and Peters 1999). In general, GA is a machine-learning method (e.g., decision trees, genetic algorithms, rules, and neural nets; Haupt and Haupt 1998, 2004; Fielding 1998), which includes relatively recent techniques previously impractical to implement due to an absence in available computing resources. With the increasing availability of computers sufficient to the prerequisites of GARP and other machine-learning techniques, the range of machine-dependent analytical tools applicable to the addressing problems of natural resource managers has markedly increased, e.g., in evaluating issues related to biological diversity, future land and water use, and the evaluation of alternative environmental management practices (see Scott et al. 2002; Scott et al. 1993). GARP has proven especially successful in predicting species' potential distributions under a wide variety of situations (see Peterson and Cohoon, 1999; Peterson et al. 1999, 2001, 2002a–d; Peterson, 2001; Feria and Peterson 2002; Stockwell and Peters 1999). Chen and Peterson (2000), Peterson and Vieglais (2001), and Anderson et al. (2002) provide general explanations of the GARP modeling process and interpretation of potential distributions; see Stockwell and Noble (1992) and Stockwell and Peters (1999) for technical details.

Developing predicted distributions, as either projections of past distribution or estimates of future species distribution expansion, is an increasingly applied tool in biogeography, evolution, ecology, conservation, invasive-species management, and disease prevention (see contributed papers in Scott el al. 2002; Peterson et al. 1999, 2000; Peterson and Vieglais 2001; Anderson et al. 2002). As illustrated by these and other peer-reviewed publications, these approaches combine presence data with environmental variables (both biotic and abiotic factors, including, e.g.,

temperature, precipitation, elevation, geology, and vegetation) to create a model of the species' distribution based on physical habitat requirements associated with environmental variables. Georeferenced presence data occur as latitude and longitude coordinates for confirmed localities that are characterized by vouchered museum or herbarium specimens or observational accounts (as captures or multiple-observer sightings) collected during designed or opportunistic biological surveys. While presence data are relatively well documented, absence data are infrequently recorded and not necessary for implementation of GARP (Stockwell and Peters 1999; Anderson et al. 2002).

Simple stated, GARP views presence data relative to existing digital maps of biological and physical habitat attributes. Environmental variables typically examined in such modeling efforts encompass include relatively few measures of ecological niche (see often-cited Hutchinson 1957), but available digital environmental coverages provide many variables that commonly influence any given species distributions. Given the analysis of presence data predicated on existing biological and physical habitat attributes, the resulting model is subsequently projected onto a map of the study region, here, the northern Great Plains of North America, wherein the potential distribution of the species of concern is characterized within the context of previously unoccupied space (see Chen and Peterson 2000; Peterson and Vieglais 2001). Models are generally based on the species' fundamental niche (Hutchinson 1957; MacArthur 1968; Wiens 1989), so the spatial projections represent potential areas occupied by a species. In areas currently unoccupied, closely related species may already occur, or the projections may represent potential areas of suitable habitat to which the species has failed to disperse or in which it has previously occupied the area but had been extripated in the near or relatively distant past. Overprediction resulting from the niche-based models, however, allows for comparisons of potential and realized distributions, which may benefit natural resource managers faced with great numbers of potentially invasive species that may be effectively prioritized relative to their varying potentials to successfully invade unoccupied regions (Peterson et al. 1999; Peterson and Vieglais 2001; Anderson et al. 2002).

For the current investigation regarding risks potentially associated with biota transfers between Missouri River and Red River basins, GARP was selected as the predictive tool applied to the evaluation of species distributions potentially expressed by biota of concern when georeferenced data were sufficient to the projection. DesktopGarp is a desktop version of the GARP algorithm and is available as a software package for biodiversity and ecologic research that allows the user to predict and analyze wild species distributions. The genetic algorithm in GARP (http://biodi.sdsc.edu/ and http://beta.lifernapper.org/ desktopgarp/) is a means of generating a set of rules. Each rule, which is a model in itself, is an "if-then" statement used for making inferences about the values of the variable of interest. The sets of rules developed by GARP are more accurately described as inferential models rather than mathematical models, since inferential models are more closely related to logic than mathematics and the basic process is logical inference rather than calculation (see http://biodi.sdsc.edu/ and http://beta.lifernapper.org/

desktopgarp/). GARP presently uses four types of rules: atomic, BIOCLIM rules, range rules, and logit rules.

Atomic rules are the simplest form of rule which uses only values of variables in the precondition of the rule. An atomic rule is most useful for categorical variables such as geological attributes, soil types or geographic features. The atomic rule precondition expresses values of variables, e.g., for categorical variables X and Y: If X = x and Y = y then ... . On the other hand, BIOCLIM rules are based on the form of model used in the BIOCLIM program used by Nix (1986) for predicting the range of a species from the environmental tolerances of a species. The BIOCLIM program develops a model through enclosing the range of the environmental values of the data points where a species occurs in a statistically defined envelope, typically the 95 percentile range. The environmental envelope defined by this range encloses 95% of the data points where the species occurs. The distribution of the species is predicted at those points that fall within that environmental envelope, and absence is predicted outside those points. In GARP, then, a BIOCLIM rule is generated by developing a statistically defined envelope as briefly indicated above. A number of differences between these rules exist:

- The range of the variables is not restricted to climate; variables other than climatic variables can be used.

- The rules are evaluated for significance and accuracy after formation of the range from the percentile range. This permits an accurate estimate of the quality of the rule, which does not necessarily have a relationship to the percentile value.

- The rule can predict presence or absence of a species, but not both.

- The negation of a BIOCLIM rule can be used to predict presence or absence.

The range rule in GARP is a generalization of the BIOCLIM rule. In a range rule a number of variables may be regarded as irrelevant, which is useful when the response of a species has the form of environmental tolerances or limitations. As such, a range rule expresses intervals for each of the variables in the precondition (e.g., If $X \geq x1$ and $X \leq x2$ then ...) which lends these rules good for predicting the distribution of a species with a range of tolerance to climatic variables.

Another family of rules called logit rules is useful when species respond to the environment through environmental gradients. Logit rules are an adaptation of logistic regression models to rules, as previously characterized. As noted, logistic regression is a form of regression equation where the output is transformed into a probability. For example the logistic regression gives the output probability p where:

$$y = a_0 + a_1x_1 + a_2x_2 + \ldots + a_nx_n$$

and,

$$= \quad p \quad \frac{1}{1+e^{-y}} \; .$$

A logistic rule, in the manner of all "if then" rules, appends an outcome (such as presence or absence) to the logistic regression and uses the probability output from the regression to determine if the rule should be applied. Thus a logistic rule produces an outcome Y with a precondition X as the rule, "If p(X) is greater than some parameter, then Y; else rule not applied." A logistic regression, then, is a form of regression equation where the output is transformed into a probability *P* that determines if a rule should be applied.

GARP reduces error in predicted distributions by both significance and predictive accuracy (Stockwell and Peters 1999). The algorithm is largely successful in doing so without overfitting which is especially important when models are based on occurrence data compiled without a fixed study design (Peterson and Cohoon 1999). Because of stochastic elements in the algorithm (such as mutation and crossing over; Holland 1975; Stockwell and Noble 1992), however, no unique solution is produced; indeed, the underdetermination of the system yields multiple solutions holding the same value for the optimization criterion. Hence, the variability among resulting models (typical of most machine-learning problems) requires careful examination of possible sources of error in order to select the most predictive models (see http://beta.lifemapper.org/desktopgarp/).

Overview of GARP implementation. GARP searches for nonrandom associations between environmental characteristics of localities of known occurrence versus those of the overall study region. It works in an iterative process of rule selection, evaluation, testing, and incorporation, or rejection to produce a heterogeneous rule-set characterizing the species' ecological requirements (Peterson et al., 1999). First, a method is chosen from a set of possibilities (e.g., logistic regression, bioclimatic rules), and it is applied to the data. Then, a rule is developed and predictive accuracy is evaluated via training points intrinsically resampled from both the known distribution and from the study region as a whole (Stockwell and Peters 1999). The change in predictive accuracy from one iteration to the next is used to evaluate whether a particular rule should be incorporated into the model (rule-set). As implemented here, the algorithm runs either 2500 iterations or until addition of new rules has no appreciable effect on the intrinsic accuracy measure (convergence). The final rule-set, or ecological-niche model, is then projected onto a digital map as the species' potential geographic distribution, exported as an ASCII raster grid, and imported into ArcView 8.3 (ESRI Corporation, Redlands, California) using the Spatial Analyst Extension for visualization.

The base environmental data comprise a variety of geographic coverages (digitized maps). For our current implementation, we used 21 environmental coverages having a pixel size of 0.04°

x 0.04° (about 4.5 km x 4.5 km). These coverages consisted of georeferenced attributes of elevation, slope, aspect soil conditions, geological ages, geomorphology, coarse potential vegetation zones, and a series of coverages for solar radiation, temperature, and precipitation. For the latter three, separate coverages representing upper and lower bounds of isopleth intervals were included (for mean annual solar radiation, mean annual temperature, mean monthly temperature in January and July, mean annual precipitation, and mean monthly precipitation in January and July). Collection localities were randomly divided into training and test data sets (50% each) for each species. We generated 20 models for each species using their respective training sets; then, the same training set is used to create each of the 20 models for a species. Test points were withheld completely from GARP's model building and internal evaluation process and were used only for evaluating final models in the "best subsets" implementation (see Anderson et al. 2003).

For each model, the elements of the confusion matrix were collected then calculated values of the correct classification rate ((a + d)/(a + b + c + d)), the intrinsic omission error (c/(a + c)) and the intrinsic commission index (b/(b + d)) (Appendix 5). In some models, GARP failed to predict every pixel as either present or absent, and such pixels were categorized as "no data" in the resultant map and reclassified as predicted absence in further geographic analyses. These unpredicted pixels do not enter into the confusion matrix. Following the "best subsets" procedure as detailed in Anderson et al. (2003), a one-tailed χ^2-statistic was applied to test data to evaluate the significance of each model against a null hypothesis of no relationship between the prediction and the test data points. In a best subsets procedure, we test whether test points fell into areas predicted present more often than expected at random, given the overall proportion of pixels predicted present versus predicted absent for that species (modified from Peterson et al. 1999). The χ^2-value represented our extrinsic composite measure of overall model performance (including contributions of both omission and commission; see Anderson et al. 2002, 2003).

As detailed by Anderson et al. (2003), we considered the potential variability of GARP outputs and generated a suite of 20 models to predict the potential distribution rather than a single model, then we subsequently queried those outputs for a consistent signal among those model outputs. The equal-weight approaches, e.g., of Anderson et al. (2002) suggested that summing the 20 models for each species (value of 1 for a pixel of predicted presence; value of 0 for predicted absence) would yield a composite map comprised of pixels with values ranging from 0 to *n*, where *n* represents the number of models of the best subset that predicted the species' presence in the pixel. For visualization of these results, maps showing various thresholds of concordance among models are presented by quartiles. In outputting the prediction of the "best subsets" composite model, a color code was used for display and ease of interpretation. Red was used for predicted presences with 75%–100% of pixel overlay of composite map when overlays were in agreement, orange for 50%–75% agreement of pixel overlay of composite map, pale green for 25%–50% agreement of pixel overlay of composite maps, and green for 0–25% agreement of pixel overlay of composite maps.

Textual output was produced by GARP, including the confusion matrix and measures of predictive accuracy. The confusion matrix tabulates the fraction of results both observed in the data and predicted by the model. The overall predictive accuracy is the accuracy of the model as a whole on an independent test set (see Appendix 5).

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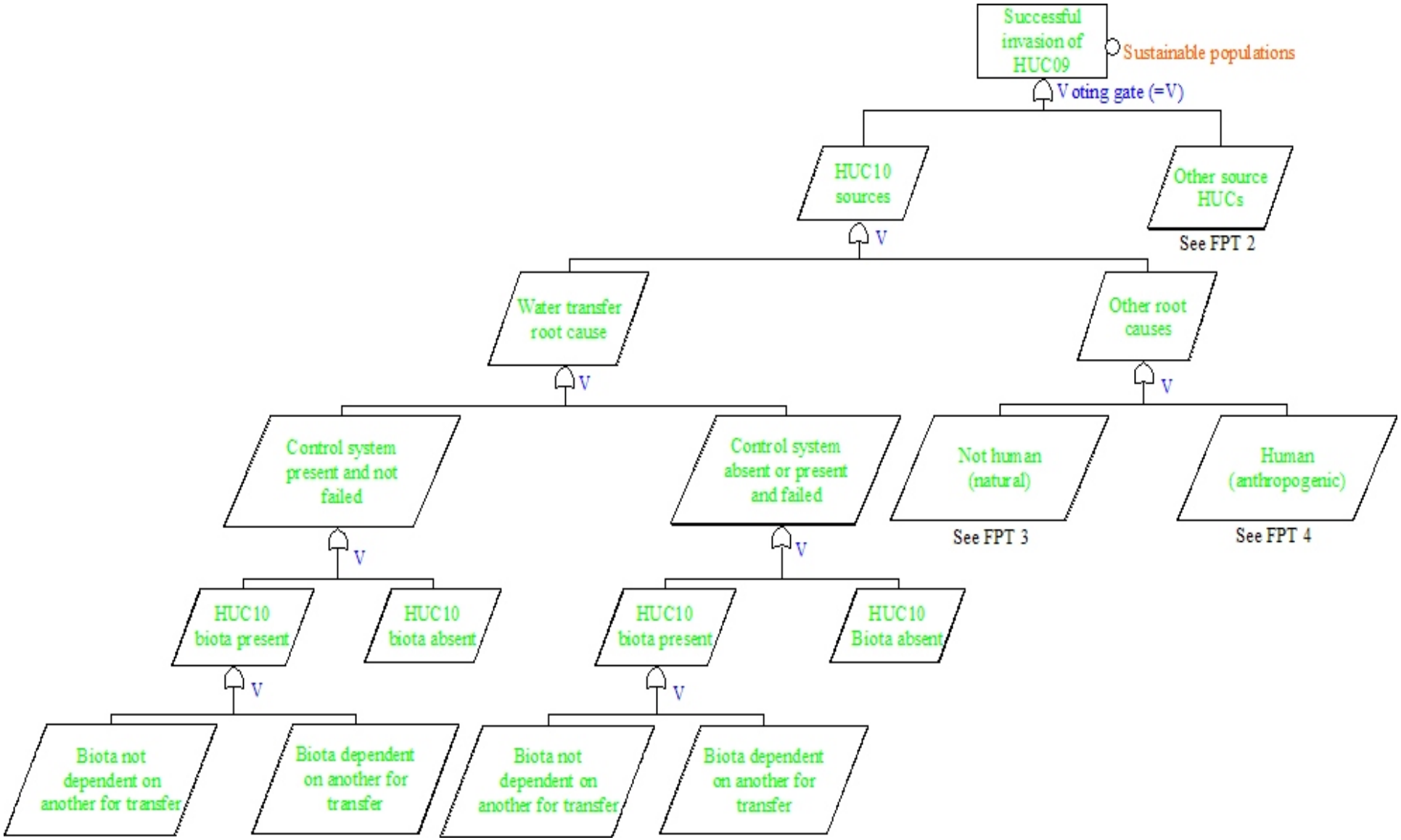
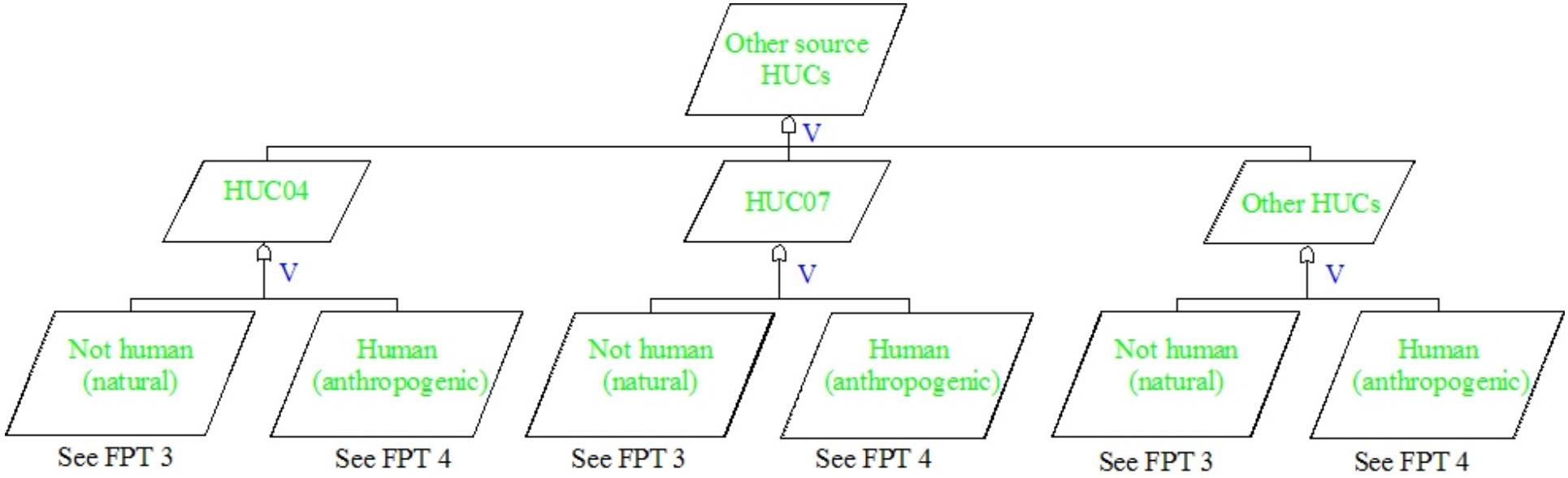
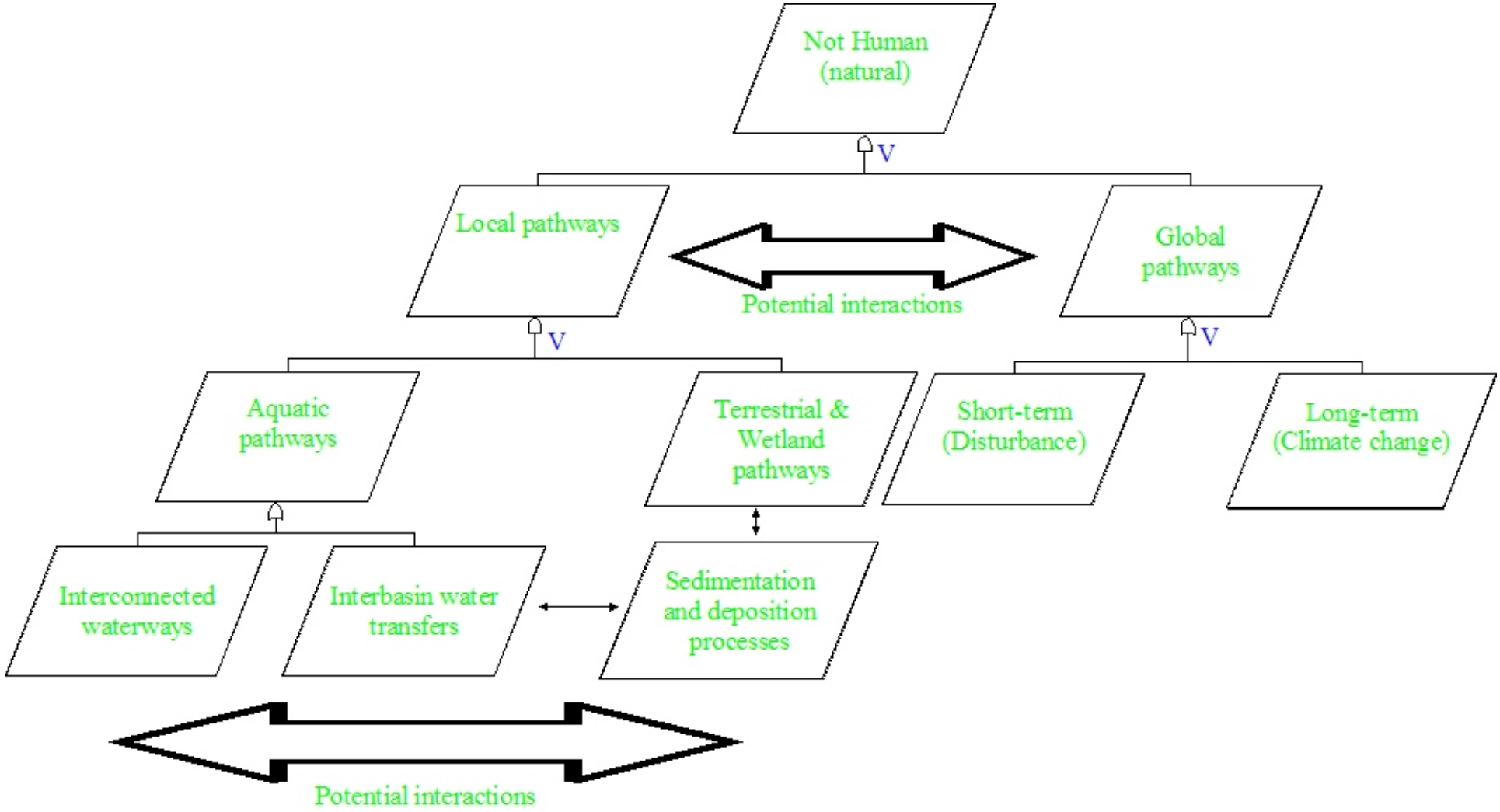
Annex, Figure 1. Fault-probability tree (FPT) 1


Successful invasion of HUC09
Sustainable populations
Voting gate (=V)
HUC10 sources
Other source HUCs
See FPT 2
V
Water transfer root cause
Other root causes
V
V
Control system present and not failed
Control system absent or present and failed
Not human (natural)
Human (anthropogenic)
See FPT 3
See FPT 4
V
V
HUC10 biota present
HUC10 biota absent
HUC10 biota present
HUC10 Biota absent
V
V
Biota not dependent on another for transfer
Biota dependent on another for transfer
Biota not dependent on another for transfer
Biota dependent on another for transfer

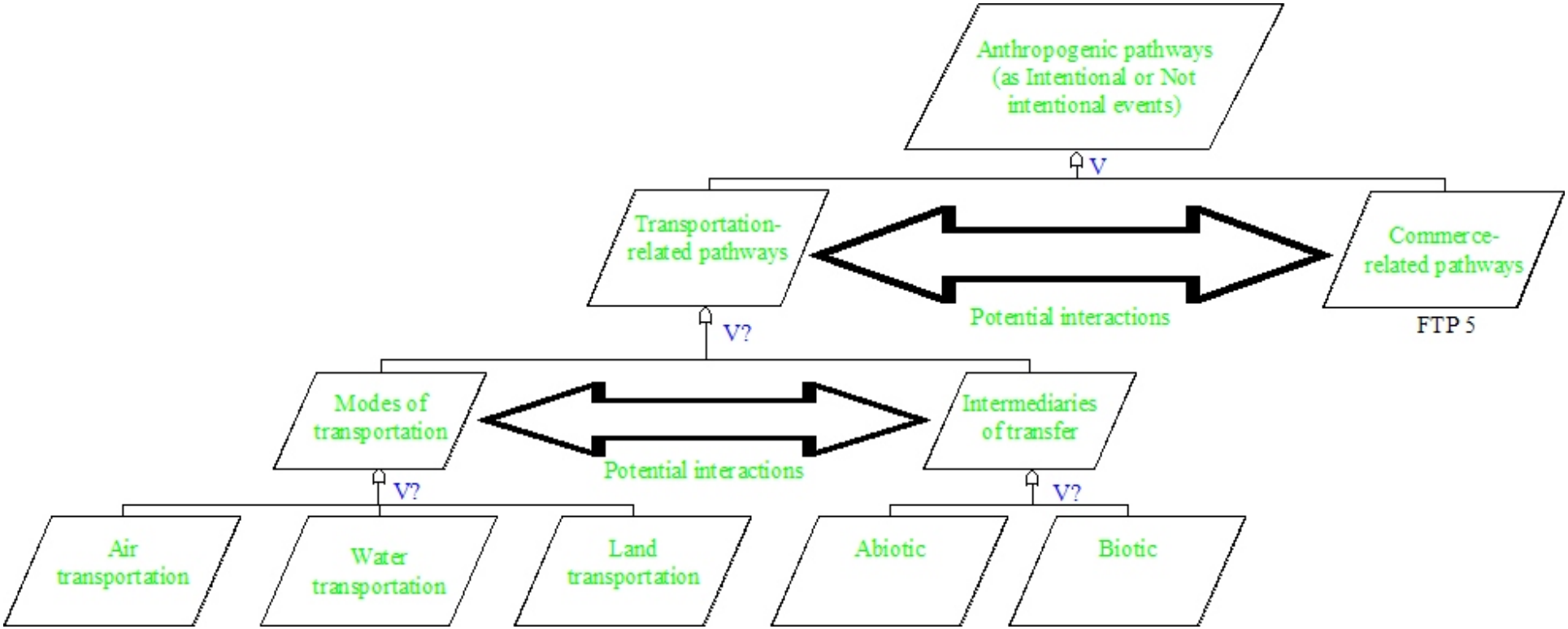
Annex, Figure 2. FPT 2


Other source HUCs
V
HUC04
HUC07
Other HUCs
V
V
V
Not human (natural)
Human (anthropogenic)
Not human (natural)
Human (anthropogenic)
Not human (natural)
Human (anthropogenic)
See FPT 3
See FPT 4
See FPT 3
See FPT 4
See FPT 3
See FPT 4

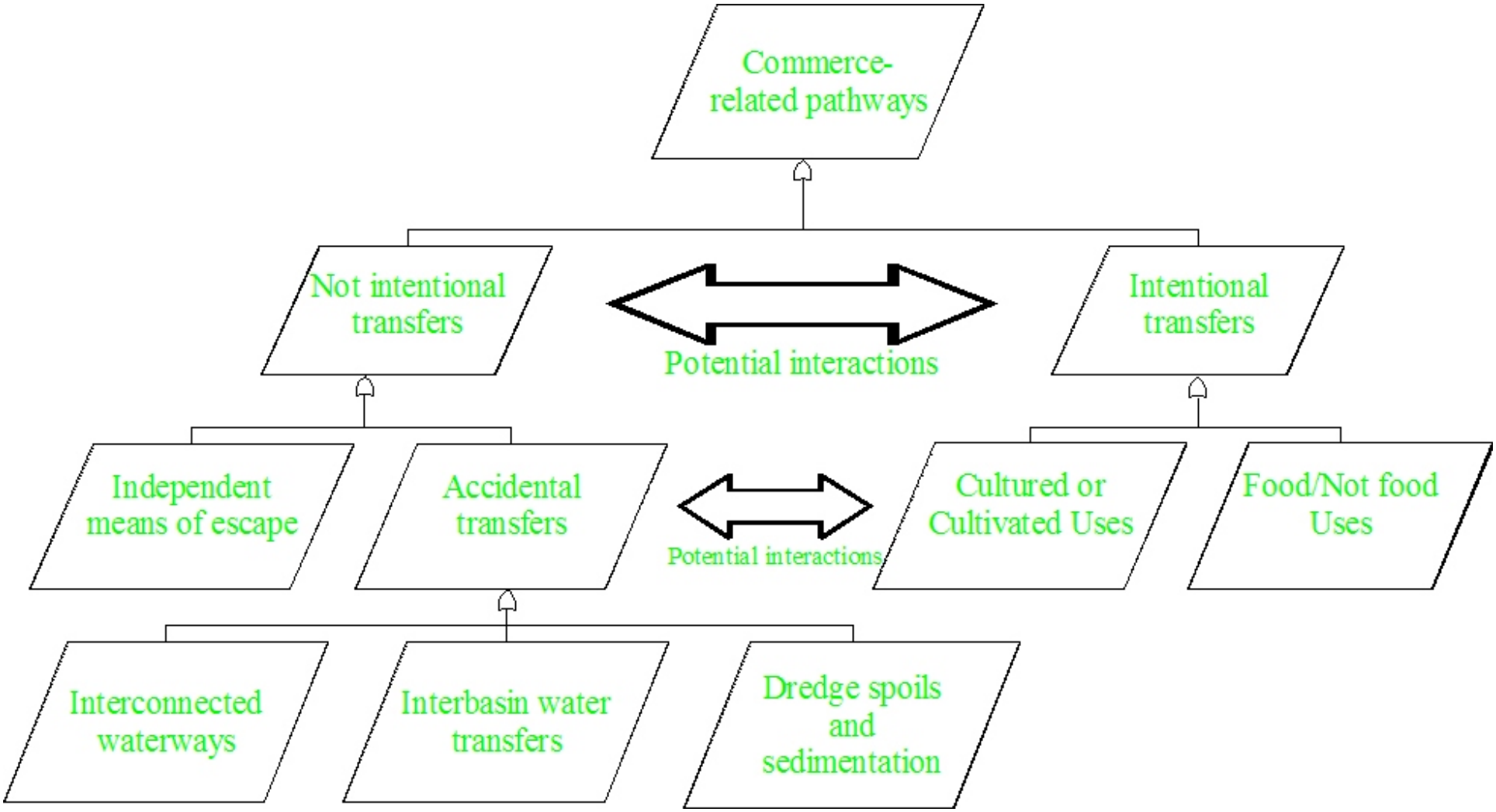
Annex, Figure 3. FPT 3


Not Human
(natural)
V
Local pathways
Potential interactions
Global
pathways
V
V
Aquatic
pathways
Terrestrial &
Wetland
pathways
Short-term
(Disturbance)
Long-term
(Climate change)
Interconnected
waterways
Interbasin water
transfers
Sedimentation
and deposition
processes
Potential interactions

Annex, Figure 4. FPT 4


Anthropogenic pathways (as Intentional or Not intentional events)
V
Transportation-related pathways
Commerce-related pathways
Potential interactions
FTP 5
V?
Modes of transportation
Intermediaries of transfer
Potential interactions
V?
V?
Air transportation
Water transportation
Land transportation
Abiotic
Biotic

Annex, Figure 5. FPT 5


Commerce-related pathways
Not intentional transfers
Potential interactions
Intentional transfers
Independent means of escape
Accidental transfers
Potential interactions
Cultured or Cultivated Uses
Food/Not food Uses
Interconnected waterways
Interbasin water transfers
Dredge spoils and sedimentation

3.0 Risk Analysis of Biota Transfers–Biological Invasions and Shifting Metapopulation Dynamics

Abstract. Section 3 summarizes the outcomes of the risk analysis completed for the biota transfer project. The analysis of risks associated with potential biota transfers yielded multiple, complementary outcomes stemming from the range of analytical tools applied to the evaluation of risks. Outcomes of the analysis of risks resulted from qualitative evaluations, largely based on narrative analyses dependent upon existing information on past and current distributions and life-history attributes potentially associated with future species incursions that might result in successful invasions or shifts in metapopulations. Quantitative evaluations based on categorical analysis considered life-history attributes and assigned numerical scores to each biota of concern, yielding a priority list of species likely to be problematic if biota transfers occurred in the future. Outcomes of categorical analysis suggested that potential transfers of species already occurring in both Missouri River and Red River basins may occur in the future since existing multiple competing pathways may link these basins regardless of whether designed water diversions are realized. Whether transfers of species already occurring in both basins would be associated with a measurable shift in metapopulations is unclear, given the relatively sparse data available for the analysis. While georeferenced distribution data were not sufficient for characterizing potential species distributions for all biota of concern, when sufficient data were available, spatiotemporal analysis considered biota transfers and prediction of species distributions through an ecological-niche-based model algorithm. Illustrative projections of potential distributions for representative aquatic nuisance species such as Zebra mussel, New Zealand mudsnail, and riparian plants such as tamarisk, were incorporated into the quantitative analysis as available and suggested that some biota of concern may become invasive in the future, although these species invasions are not uniquely linked to interbasin water diversion, due to multiple pathways available for incursion.

3.0 Overview of Biological Invasions and Shifting Metapopulation Dynamics

As Sjödin et al. (2004) noted, "[S]implifying assumptions are necessary in order to turn complex biological systems into caricatures that are, on the one hand, simple enough to analyze, and on the other hand, realistic enough to capture key features of the process under investigation." A better characterization of the current investigation's context could not be written. In order to address the questions of Reclamation and Technical Team, we necessarily had to develop models that captured their concerns and helped focus the analysis. Data analysts, whether detailed to scientific or engineering problems, generally look at models as one of three types which are variously identified as conceptual or heuristic models, mathematical or statistical models, or physical models (see Burnham and Anderson 2002). Various authors have characterized models along these or similar lines (see Burnam and Anderson 2002, Jensen and Bard 2002), and all express similar views similar to Puccia and Levins (1985):

> "Every model distorts the system under study in order to simplify it. . . .There are two dangers in model building: one is that the model does not tell us about the world; the other is that is a faithful representation, and therefore we are overwhelmed. Simplification is both legitimate and necessary as long as we are cautious, are willing to change the original underlying assumptions as necessary and build new models, and carefully interpret the model's predictions."

Regardless of the various names and approaches to categorizing models, experienced analysts note that these general types of models are not necessarily independent in their application to complex environmental issues such as those related to water use and land use, as characterized in the various realizations of water diversions envisioned for the Upper Missouri and Red River basins.

Practically speaking, models fit into of one of three groups: (1) those that are accurate, precise, and field validated; (2) those that are useful as analytical tools for evaluating a range of "what-if" scenarios but have not been validated and present varying levels of precision and accuracy; and (3) those that are variously available as largely theoretical abstractions whose value to the risk assessment process is poorly characterized. Models of the first group are lacking in studies such as these of the current investigation (see Scott et al. 2002 for critical review), and tools of the third group have relatively limited value in adaptive management practices where bounds of certainty are critical to the assessment, management, and update process (see Walters 1986). Hence, we have applied a set of analytical tools of the second variety to the evaluation of risks and consequences potentially associated with biota transfers realized as a result of interbasin water diversions. These tools have a long history in applications similar to those of the current investigation (see Scott et al. 2002), and although lacking rigorous field validation, each analytical tool contributes outputs valuable to stakeholders in their decision-making process.

Our primary tools have been detailed in Section 2. As needed, brief presentations of lesser used tools are included in this section to set the stage for results that are limited to a few species of concern, due to sparsely available data (e.g., dispersal analysis following Fisher (1937), Kolmogorov et al. (1937), and Skellam (1951) and more recently extended others such as Clark et al. (2001a,b, 2003)). Depending on the empirical data available for biota of concern, the evaluation of risks followed a three-part analysis as detailed in Section 2: (1) a categorical analysis focused on species' attributes that would influence the ability of a biota of concern to successfully traverse geographic boundaries between Missouri River source waters, (2) a simple probability analysis that characterized risk as outcomes of a multiple-step flow of events linking source system with receiving system (see Section 2, Annex Figure 1 through Annex Figure 5), and (3) a spatial analysis that characterized potential distribution of biota of concern through a preliminary ecological-niche analysis using GARP (see Section 2).

Not all biota of concern were amenable to analysis with each of these three tools, but a narrative analysis of risks was completed for each biota of concern regardless the level of effort devoted to the evaluation of risks associated with biota transfers consequent to water diversion. When data were sufficient for a spatial analysis and metadata included time record sufficient to the task, a spatiotemporal analysis was completed such that output from the investigation considered predicted distribution of biota of concern through time (e.g., zebra mussel and New Zealand mudsnail). While biota of concern identified by stakeholders were not limited to invasive species, the evaluation of effects associated with species invasions as well as potential shifts in metapopulations associated with water diversions were considered using the same categorical and spatial analysis tools.

For a quantitative evaluation of risks, available data must have been amenable to analysis with a wide range of tools (see Appendix 4). Data quantity and quality would not only influence predictions of a particular species invasion (e.g., Will invasion occur, and what expansion of a species' distribution will be realized?), but also strongly influenced the uncertainties associated with risks associated with each prediction of species invasion subsequent to biota transfer (e.g., How certain are these predictions?). Data may have been limited or incomplete, often times reflecting the difficulties in observing or studying the invasion process (see Elton (1958) for a classical perspective or Kolar and Lodge (2001, 2002) for recent updates). Each step of the invasion process varies with respect to its data quality and quantity, and the interrelationships between steps will necessarily reflect these differences in data sources. In the current investigation, effects data (e.g., adverse effects of invasive species on indigenous species) were abundant for nearly all biota of concern, yet each reflected a different level of effort in mining available data for categorical, quantitative (i.e., spatial or spatiotemporal), or narrative analysis. For example, in identifying transfer coefficients to characterize transport from source system to receiving system, data availability varied from species having data sufficient to estimate numerical values (e.g., zebra mussel and New Zealand mudsnail) to those having data sufficient for a categorical evaluation (e.g., tamarisk) to those having little empirical data in the existing literature (e.g., *Polypodium hydriforme* and its hosts). Ranges in data quantity and quality varied for each representative included in the list of biota of concerned identified during problem formulation (Section 1).

As noted in Section 2 and in Appendix 4, in the current investigation the discrimination between species invasions linked to interbasin water transfers and those linked with other pathways was considered within the context of competing risks related to system failure (i.e., biota transfer and successful invasion). From the perspective of competing risks, if a species invasion is considered a failure, then each of k different failure modes or ways a failure can occur (i.e., for species invasions, different pathways may be interpreted as different failure modes) are competing, and underlying each failure mode is a failure mechanism (i.e., for a given pathway, each mode will have one to many different failure mechanisms; see Annex Figure 1 through Annex Figure 5). When data were not sufficient for quantitative estimates of competing risks, a

narrative evaluation of competing risks was completed within the context of the competing risks conceptual model summarized in Annex Figure 1 through Annex Figure 5 of Section 2.

3.1 Categorical Analysis of Species Attributes for Ranking Biota of Concern

Given the early efforts of researchers and especially since Elton's classical publication focused on invasive species (Elton 1958), work has been pursued to establish principles of invasion biology and develop tools for predicting successful invasions (see Carlton 1996 for marine and estuarine habitats; Rejmánek 1996 for invasive plants; Kolar and Lodge 2002a,b for invasive aquatic species). As a consequence of these past efforts, a large body of literature exists that describes general characteristics of invasive species, with some attributes (e.g., related to reproduction) being of apparently greater significance than others when attempting to characterize the "ideal" invasive species (see Ehrlich 1989; Williamson and Fitter 1996; Ricciardi and Rasmussen 1998; McKinney and Lockwood 1999, 2001). For example, successful invaders generally reproduce rapidly (see Elton 1958; Leung et al. 2004; Lodge 1993), are habitat or diet generalists (see Elton 1958; Moyle and Light 1996a, b), or have a broad native range (Lodge 1993; Ricciardi and Rasmussen 1998), these global characterizations fall short with respect to their contributing to a quantitative analysis amenable to developing an initial predictive capability needed for developing management strategies to prevent or limit successful invasions.

Recently, in an effort to develop predictive models of species invasions, many authors have offered observations on the processes involved in biological invasions (see Verimeij 1996; Williamson 1996; Kolar and Lodge 2001; D'Antonio et al. 1992, 1999, 2001). These observations are consistent with anecdotal accounts of species invasions in the older literature (see Elton 1958), and suggest that species invasions reflect a complex process involving five generalized steps: transport, release, establishment, spread, and integration (see Marchetti et al. 2004). Each of these steps, or stages, in the invasion process may be decomposed into constituent events and may be dependent on contingencies reflecting collateral processes required for invasion of specific species, e.g., host-parasite relationships will influence the successful invasion of disease organisms. In part, these steps in the invasion process, but especially those related to transfer and release, are captured in the nested conceptual models summarized in Annex Figure 1 through Annex Figure 5.

3.1.1 Categorical analysis of risks. Given the taxonomic range of the biota of concern identified by Reclamation and stakeholders—bacteria and viruses to aquatic and terrestrial plants to aquatic invertebrates and vertebrates—the current investigation captured a variety of life histories across multiple taxonomic groups that was responsive to suggestions that "predictive understanding of the invasion process can only emerge from taxonomically focused studies" (Lodge 1993). In the current investigation we relied on guidance of Kolar and Lodge (2001) and others (see Elton 1958; Moyle and Light 1996; Verimeij 1996; Williamson and Fitter 1996; Kolar

and Lodge 2001; D'Antonio et al. 1992, 1999, 2001; Marchetti et al. 2004), and considered life-history attributes identical or similar to those Kolar and Lodge (2001; depending on species of concern) for our categorical analysis (see Section 2). For the categorical analysis completed as part of this investigation, biota of concern were scored within groups, based upon life history attributes shared by members of those groups, e.g., plants and microorganisms, and aquatic invertebrates and aquatic vertebrates (fishes).

Tables for the categorical analysis have been included as grouped outputs for biota of concern (Table 1 through Table 7), with a summary table (Table 8) included wherein all biota of concern are considered equally weighted using a simple ratio estimator, i.e., "species score relative to total possible" (Fleiss et al. 2003). Although beyond the scope of the current investigation, future applications of the categorical analysis may extend to Delphi methods of analysis (see Adler and Ziglio 1996; Bernard 1999). Figure 1 plots arcsin-transformed scores (Sokol and Rohlf 1981) and Table 9 lists selected summary statistics for these arcsin transformed scores.

As listed in Table 9, biota of concern presented simple rank scores ranging from 1.0 (e.g., cyanobacteria) to nearly 1.0 (e.g., Eurasian water-milfoil, purple loosestrife, and bacterial and protozoan infectious disease agents) to less than 0.6 (e.g., Utah chub, paddlefish, and pallid sturgeon), which suggests that biota transfers of these representative biota, if realized, would present a range of outcomes reflecting life-history attributes favoring transport and establishment in the receiving area. The majority of those species presenting high rank scores were not candidate invasive species identified by Reclamation and Technical Team as biota of concern. Rather, these high-ranking species were currently present in both the Missouri River and Red River basins and were included as biota of concern because proposed interbasin water transfers could potentially represent sources for shifts in metapopulations between the two basins. In this initial rank categorization, the nine highest-ranking biota of concern presented a widespread occurrence, not only in the Missouri River and Red River basins, but throughout North America. Invasive species potentially of greatest concern, if interbasin water diversions are realized, included numerous representative biota falling into the second and third quartiles, e.g., zebra mussel, New Zealand mudsnail, Asian carp, and others presenting similar scores (see Table 8, Table 9, and Figure 1). Species falling into the first quartile may be reconsidered by stakeholders, if species life-history attributes and current status, e.g., pallid sturgeon, are entered into the selection process in subsequent iterations in the reformulation of lists of biota of concern (see also Appendix 3A and Appendix 3B). Similarly, Reclamation and Technical Team may revisit the list of biota of concern, given the ongoing discussions related to control systems envisioned as part of water diversion infrastructure (see Section 4).

Table 1. Categorical analysis of fishes included as biota of concern.

Attribute	Fishes						
	Gizzard shad	Rainbow smelt	Asian carp†	Paddlefish	Pallid sturgeon	Utah chub	Zander
Trophic status (Score 1–5)	3	3	3	2	2	3	2
Parental investment in offspring (Score 1–4)	3	3	3	2	2	3	3
Maximum adult size (Score 1–3)*	2	2	3	3	3	1	3
Size of native range (Score 1–4)	3	3	4	2	2	2	2
Physiological tolerance (Score 1–4)	3	3	4	3	3	3	3
Distance of native source (Score 1–4)	3	3	4	2	2	3	4
Prior invasion success (Score 1–5)	3	3	3	2	2	3	2
Fecundity and propagule pressure (Score 1–4)	3	3	4	3	3	3	3
Total score (possible 36)	**23**	**23**	**28**	**19**	**19**	**21**	**22**

*relative size within broad categories of "Fishes" with 1 "small-bodied" to 3 "large-bodied"
†composite grouping of bighead carp, silver carp, and black carp (see Appendix 3A)

Table 2. Categorical analysis of aquatic invertebrates included as biota of concern.

Attribute	**Aquatic invertebrates**			
	Dreissena polymorpha	***Corbicula fluminea***	***Potamopyrgus antipodium***	***Bythotrephes cederstroemi***
Trophic status (Score 1–5)	4	4	4	4
Parental investment in offspring (Score 1–4)	4	4	4	4
Maximum adult size (Score 1–3)*	1	1	1	1
Size of native range (Score 1–4)	4	4	4	3
Physiological tolerance (Score 1–4)	3	3	3	3
Distance of native source (Score 1–4)	3	3	3	1
Prior invasion success (Score 1–5)	4	4	4	3
Fecundity and propagule pressure (Score 1–4)	3	3	4	4
Total score (possible 36)	**26**	**26**	**27**	**23**

*relative size within broad categories of "Aquatic Invertebrates" with 1 "small-bodied" to 3 "large-bodied"

Table 3. Categorical analysis of aquatic vascular plants included as biota of concern.

Attribute	**Aquatic vascular plants**		
	Hydrilla verticillata	***Myriophyllum spicatum***	***Eichhornia crassipes***
Trophic status (Score 1–5)	5	5	5
Parental investment in offspring (Score 1–4)	4	4	4
Size of native range (Score 1–4)	2	4	2
Physiological tolerance (Score 1–4)	1	4	2
Distance of native source (Score 1–4)	1	4	1
Prior invasion success (Score 1–5)	3	4	3
Fecundity and propagule pressure (Score 1–4)	4	4	4
Total score (possible 30)	**20**	**29**	**21**

Table 4. Categorical analysis of riparian and wetland vascular plants included as biota of concern.

Attribute	**Riparian and wetland vascular plants**	
	Lythrum salicaria	***Tamarix spp.***
Trophic status (Score 1–5)	5	5
Parental investment in offspring (Score 1–4)	4	4
Size of native range (Score 1–4)	4	4
Physiological tolerance (Score 1–4)	4	4
Distance of native source (Score 1–4)	4	4
Prior invasion success (Score 1–5)	4	5
Fecundity and propagule pressure (Score 1–4)	4	4
Total score (possible 30)	**29**	**30**

Table 5. Categorical analysis of cyanobacteria included as biota of concern.

Attribute	**Cyanobacteria**		
	Anabaena flos-aquae	***Microcystis aeruginosa***	***Aphanizomenon flos-aquae***
Trophic status (score 1–5)	5	5	5
Size of native range (Score 1–4)	4	4	4
Physiological tolerance (Score 1–4)	4	4	4
Distance of native source (Score 1–4)	4	4	4
Prior invasion success (Score 1–5)	5	5	5
Fecundity and propagule pressure (Score 1–4)	4	4	4
Total score (possible 26)	**26**	**26**	**26**

Table 6. Categorical analysis of bacteria and viruses included as biota of concern.

Attribute	**Microorganisms and Disease Agents**				
	IHNV	**ERM**	***E. coli***	***Salmonella spp.***	***Legionella spp.***
Trophic status (score 1–5)	1	1	1	1	1
Size of native range (Score 1–4)	4	4	4	4	4
Physiological tolerance (Score 1–4)	3	3	3	3	3
Distance of native source (Score 1–4)	4	4	4	4	3
Prior invasion success (Score 1–5)	4	4	5	5	5
Fecundity and propagule pressure (Score 1–4)	4	4	4	4	3
Total score (possible 26)	**20**	**20**	**21**	**21**	**19**

Table 7. Categorical analysis of protozoa and myxozoa included as biota of concern.

Attribute	**Protozoa and Myxozoa**			
	Myxosoma cerebralis	***Polypodium hydriforme***	***Cryptosporidium parvum***	***Giardia lamblia***
Trophic status (score 1–5)	1	1	1	1
Size of native range (Score 1–4)	4	4	4	4
Physiological tolerance (Score 1–4)	3	3	3	3
Distance of native source (Score 1–4)	3	3	4	4
Prior invasion success (Score 1–5)	5	4	5	5
Fecundity and propagule pressure (Score 1–4)	3	4	4	4
Total score (possible 26)	**19**	**19**	**21**	**21**

Table 8. Summary scores of biota of concern and their relative rankings from high score to low score.

Biota of concern	Score	Possible score	Simple Rank Score (Score/Possible Score)
Microcystis aeruginosa	26	26	1.000
Anabaena flos-aquae	26	26	1.000
Aphanizomenon flos-aquae	26	26	1.000
Myriophyllum spicatum (Eurasian watermilfoil)	29	30	0.967
Lythrum salicaria (Purple loosestrife)	29	30	0.967
Escerichia coli (primarily O157:H7)	21	26	0.808
Salmonella spp. (various serotypes)	21	26	0.808
Cryptospordium parvum	21	26	0.808
Giardia lamblia	21	26	0.808
“Asian carp”	28	36	0.778
Infectious Hematopoietic Necrosis Virus	20	26	0.769
Yersinia ruckeri (Enteric Redmouth)	20	26	0.769
Potamopyrgus antipodarum (New Zealand mudsnail)	27	36	0.750
Legionella spp.	19	26	0.731
Myxosoma cerebralis	19	26	0.731
Polypodium hydriforme	19	26	0.731
Dreissena polymorpha (zebra mussel)	26	36	0.722
Corbicula flumenia (Asian clam)	26	36	0.722
Eichhornia crassipes (water hyacinth)	21	30	0.700
Hydrilla verticillata	20	30	0.667
Tamarix spp. (tamarisk)	20	30	0.667
Dorosoma cepedianum (gizzard shad)	23	36	0.639
Osmerus mordax (rainbow smelt)	23	36	0.639
Bythotrephes cederstroemi (spiny water flea)	23	36	0.639
Sander [Stizostedion] lucioperca (zander)	22	36	0.611
Gila atraria (Utah chub)	21	36	0.583
Polyodon spathula (paddlefish)	19	36	0.528
Scaphirhynchus albus (pallid sturgeon)	19	36	0.528

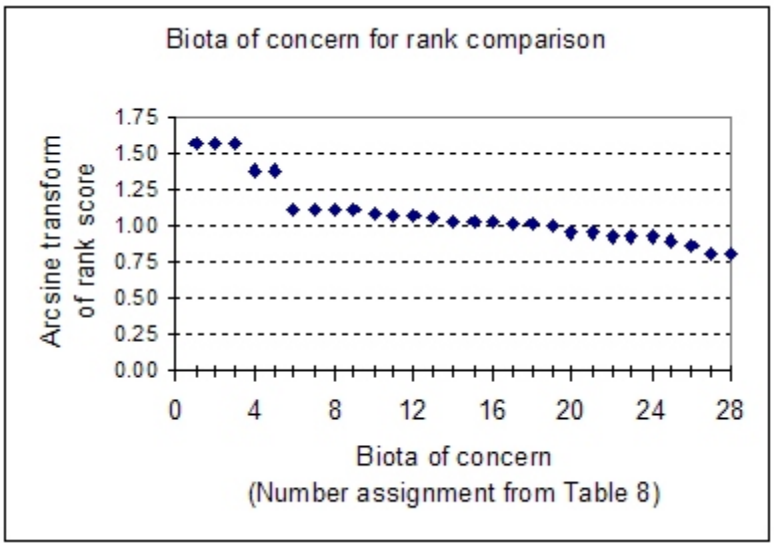


Figure 1. Transformed rank scores plotted from high to low with summary statistics on transformed rank scores listed in Table 9.

Table 9. Selected summary statistics for rank scores listed in Table 8 and plotted "high to low by transformed rank score" in Figure 1.

Sample size (N)	28	Percentiles:	10	0.8635
Minimum	0.8132		25	0.9334
Maximum	1.5708		50	1.0253
Mean	1.0857		75	1.1168
Median	1.0253		90	1.5708
Kurtosis	0.8487			
Coeff kurtosis	3.8487	First quartile:		0.9334
Skewness	1.2632	Second quartile:		1.0253
Coeff skewness	0.6316	Third quartile:		1.1168

3.2 Simple Probability Models and Quantitative Analysis of Risks

In evaluating competing risks, a system's reliability is considered as a "build-up" model based on evaluations of the reliability of each failure mode. As in any analysis of competing risks, three assumptions were specified in the current analysis: (1) each failure mechanism leading to a particular type of failure (i.e., failure mode) proceeds independently of every other mode at least until a failure occurs; (2) a failure event occurs when the first of all the competing failure mechanisms reaches a failed state; and (3) each of the k failure modes has a known life distribution model $F_i(t)$ (see Appendix 4 and Blischke and Parbhakar Murthy, 2000). In the initial analysis

summarized here, the third of these assumptions defaulted to a distribution of failure events that approached normality upon iteration in simulation study (see Appendix 13).

Quantitatively, a focus on competing risks is best applied when all three assumptions hold. If $R_c(t)$, $F_c(t)$, and $h_c(t)$ denote the reliability, cumulative distribution function (CDF), and failure rate for the constituent event, respectively, and $R_i(t)$, $F_i(t)$ and $h_i(t)$ are the reliability, CDF and failure rate for the i-th failure mode, respectively, then the competing risk model formulas are

$$R_c(t) = \prod_{i=1}^{k} R_i(t)$$

$$F_c(t) = 1 - \prod_{i=1}^{k} \{1 - F_i(t)\}$$

$$h_c(t) = \sum_{i=1}^{k} h_i(t) \quad .$$

For evaluating competing risks, we assume that all failure mechanisms are "racing to see which can reach failure first" (NIST/SEMATECH 2004, see Appendix 4), e.g., which competing risk is most likely to yield a species invasion? If the failure mechanisms are assumed independent, then the component reliability is the product of the failure mode reliabilities, and the component failure rate is the sum of the failure rates. Within an engineering context (e.g., analysis of failure in a control system made of multiple components), this algorithm holds for any arbitrary life distribution model, as long as "independence" and "first mechanism failure causes the component to fail" assumptions are not violated. In the field, each of these assumptions may be violated, but the model provided a common tool with a long history in its application to an initial analysis of risks of invasion (see Williamson 1989, 1996).

In our simple probability calculations we relied on an elementary stochastic simulation (see Bartlett 1955, 1960; Thompson 2000; Huzurbazar 2005) to directly evaluate invasion scenarios captured by pathways summarized in the conceptual models in Annex Figure 1 through Annex Figure 5 (see Section 2). Given the range in data quality and quantity across menu of biota of concern, as well as the range in their life-history attributes, the simple probability analysis focused on groups of biological agents potentially involved in interbasin transfers with the representative biota of concern handled as indicated in Table 10 for interpretation.

Table 10. Groups of representative biota of concern targeted in the simple probability analysis.

Grouping of representative biota of concern	Focus of simple probability estimation
Microorganisms and Disease Agents Enteric redmouth (ERM) Infectious hemtopoietic necrosis virus (IHNV) *Legionella* spp. *Escherichia coli* (various serotypes but data focused on O157:H7) *Salmonella* spp. (various species and serotypes including, but not limited to *S. typhi*, *S. typhmurium*) *Anabaena flos-aquae* *Microcystis aeruginosa* *Aphanizomenon flos-aquae* Protozoa and Myxozoa *Cryptosporidium parvum* *Giardia lamblia* *Myxosoma cerebralis* (*Myxobolus cerebralis*) *Polypodium hydriforme*	Interpreted as a single-event type
Aquatic Vascular Plants and Riparian & Wetland plants Hydrilla (*Hydrilla verticillata*) Eurasian water-milfoil (*Myriophyllum spicatum*) Water hyacinth (*Eichhornia crassipes*) Purple loosestrife (*Lythrum salicaria*) Salt cedar (*Tamarix* spp., including *T. rammossima*, *T. chinensis*, *T. aphylla* and others)	Interpreted as a single-event type
Aquatic Invertebrates: Mollusks *Dreissena polymorpha* (zebra mussel) *Corbicula flum*inea (Asian clam) *Potamopyrgus antipodarum* (New Zealand mudsnail) Aquatic Invertebrates: Crustacean *Bythotrephes cederstroemi* (spiny water flea)	Interpreted as a single-event type
Aquatic Vertebrates: Fishes *Dorosoma cepedianum* (gizzard shad) *Osmerus mordax* (rainbow smelt) "Asian carp" *Polyodon spathula* (paddlefish) *Scaphirhynchus albus* (pallid sturgeon) *Gila atraria* (Utah chub) *Sander [Stizostedion] lucioperca* (zander)	Interpreted as a single-event type

Quantitative analysis focused on a simple probability estimate for potential biota transfers associated with water diversions and relied upon available data related to failures in distribution infrastructure (see Deb et al. 1995; Schippers et al. 2004) and dispersal of species of concern recorded in the literature (see Appendix 3A and Appendix 3B) for an interpretative context in Section 4. Empirical data were limited or not available in most cases, and general distribution properties, e.g., assumptions of normality as limiting distribution for Poisson processes (see Appendix 4) or comparative data for related taxonomic groups, were considered within an interpretive context to characterize outcomes of the multiple-step invasion process. Distribution assumptions and reliance on comparative data, however, influenced uncertainties associated with interpretation of these simple probability estimates risk. These uncertainties are subsequently considered in Section 4 focused on risk characterization.

Figure 2 illustrates all outcomes from the simulations completed as part of the stochastic process envisioned as occurring during any of the flows of events depicted in Annex Figure 1 through Annex Figure 5 (Section 2). As such, those simple probability estimates graphically summarized in Figure 1 range from "practically 1.0" to values "practically 0." Appendix 13 lists all outcomes from experiments generated in the iterative process that focused on the train of events required to realize a species invasion (or shift in metapopulation) from biota transfers from the Missouri River to Red River basins.

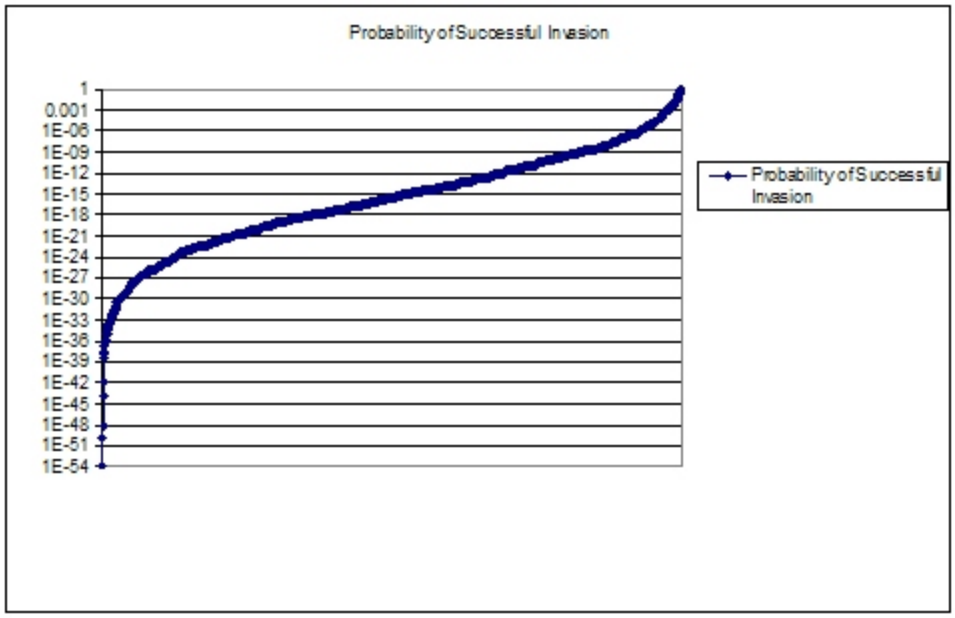


Figure 2. Plot of outcomes from iterative calculation (n=1728) of probability of successful invasion. Outcomes plotted from low risk (left side of panel) to high risk (right side of panel).

In Figure 2, the outcomes of "successful invasion" (or for species currently present in both source and receiving basins, "increased metapopulation in receiving area") are simply plotted from lowest probability outcome to highest probability outcome derived from iterative experiments completed in this investigation. These outcomes of "successful invasion" incorporate various inputs (e.g., probability of biota of concern occurring in source waters transferred to receiving system, probability of control system failure) following a stochastic process, which is amenable to greater resolution as risks are characterized (see Section 4). At this level of simulation, however, no distinction is made regarding biota of concern or whether control systems of any specific type are located at nodes along the flow of events depicted in each of the FPTs in Annex Figure 1 through Annex Figure 3. Instead, the simulation focuses on serial flows of events characterized by nodes other than those presenting sources of interaction between nodes, as illustrated, e.g., in FPTs 3, 4, and 5. Even in these relatively coarse-grained conceptual models, the recognition of interactions between nodes within serial events precludes simple probability analysis as a tool applicable to the current investigation, given these interactions obviate assumptions of independence.

As a prelude to risk characterization in Section 4, an preliminary analysis focused on control systems and their relationships to species invasions (or shifts in metapopulations), which is graphically summarized in Figure 3a,b. Here, an arbitrary probability of control system failure set at 10^{-3} was applied as a filter to the range of "successful invasion" outcomes.[1] When control system performance was associated with probabilities of failure less than 10^{-3}, probabilities of successful invasions ranged between 10^{-4} and 10^{-54} (Figure 3a). In contrast, if a control system was absent and biota transfer occurred as simply a stochastic event, or if the control system failed at probabilities bounded by 10^{0} and 10^{-3} (Figure 3b), then probabilities of successful invasions ranged from near unity to 10^{-34}. Although an exhaustive sensitivity analysis focused on specific control systems (e.g., slow sand filtration, pressure-driven membrane filters) must be deferred until greater specification is identified in infrastructure design, these preliminary results suggested that interbasin water transfers would be amenable to a characterization of risks reflecting different levels of control in the diversion, e.g., "open conveyance," "closed conveyance without treatment," and "closed conveyance with treatment" (see Section 4)

In addition to the varying influences of control systems potentially incorporated into interbasin water diversion infrastructure (e.g., aboveground and buried distribution piping, and water treatment systems as designed), biota of concern are also key elements of the analysis of risks and their subsequent characterization in Section 4, especially within the context of a species'

[1]For these analyses, preliminary values for control system failures were developed after review of Deb et al. 1995; Hughes 2002; Moser 2001; Nayyer 2000; and Schippers et al. 2004, with a particular focus on failures observed in piping and water distribution networks, and a range of chemical treatment and membrane filtration technologies.

potential distribution within the area of concern (see §3.3) and the time course of dispersal and spread of the founding group.

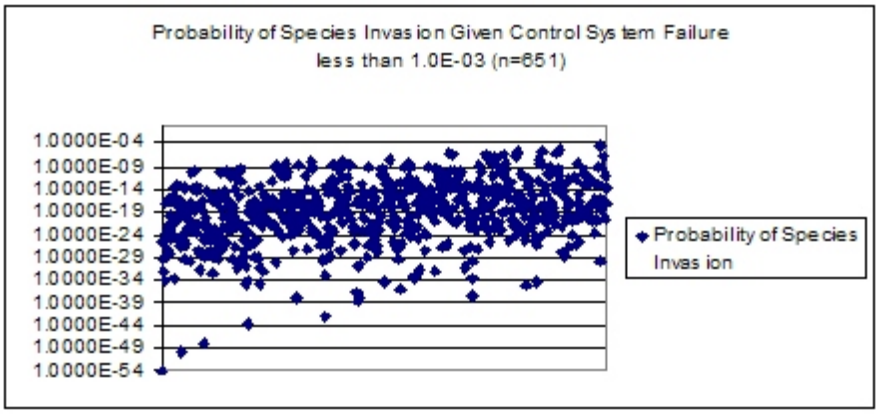


Figure 3a. Probability of species invasions given control system failure less than 10^{-3}.

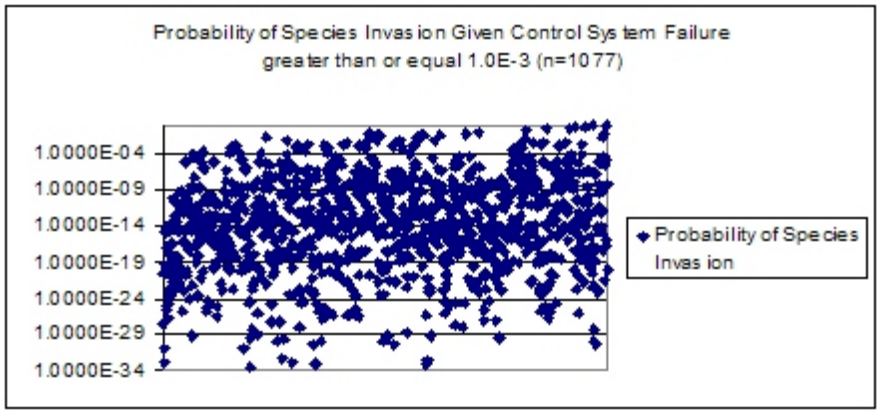


Figure 3b. Probability of species invasion given control system failure greater than or equal to 10^{-3}.

3.2.1 Spatiotemporal analysis. Few biota of concern presented data sufficient for a spatiotemporal analysis. Yet, for zebra mussel and New Zealand mudsnail an initial characterization of the dispersal and growth provided data sufficient to complete an illustrative analysis of the spatiotemporal features of the invasion process. To complete these analyses, methods relied on those originally formulated by Skellam (1951) and subsequently elaborated by Shigesada and Kawasaki (1997), Okubo and Levin (2001), and Cantrell and Cosner (2003).

Once a founding population has emigrated to previously unoccupied, yet suitable habitat, its density typically will increase and individuals will disperse into adjoining areas of suitable habitat. The spread of a species is driven by two processes, population growth and dispersal, and

most models of population spread have focused on these processes. For the current investigation, the simplest and probably the most widely applied model of population spread was used in the analysis. Reaction-diffusion type models combine random diffusion with exponential growth (Skellam 1951):

$$N_{x,t} = \frac{N_{0,0}\ e^{rtx^2/4Dt}}{4\pi Dt}$$

where $N_{x,t}$ = density of organisms at distance, x, from the point of release and at time, t, from the time of release of $N_{0,0}$ organisms at time 0, D is the "diffusivity" or "diffusion coefficient" that measures dispersal, and r is the "intrinsic rate of natural increase" ("birth rate minus death rate" under optimal conditions; e.g., without crowding or resource limitation).

While our focus lies with zebra mussel and New Zealand mudsnail, the dispersal and growth process that characterizes biological invasions is similar, if not identical, to a generalized process reflected in bacterial growth on defined laboratory media (Figure 4) or expansion of vertebrate populations in new habitat (see Okubo and Levin 2001 for examples).

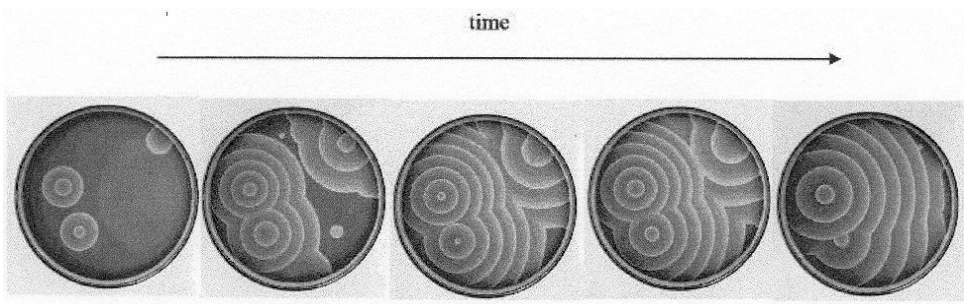


Figure 4. Bacterial growth on laboratory agar plates.

The assumption of random movement in a simple reaction-diffusion model implies that the population will spread radially at an equal rate in all directions (Figure 5). Skellam (1951) originally showed that for any detection threshold, T, such that the infested area at any time t is restricted to points where $N_{x,i} > T$, the expansion velocity of the infested front (radial rate of spread), V, is constant and can be described as

$$V = 2\sqrt{rD}$$

in a simple Skellam equation. There has generally been close congruence between predictions of this model and observed rates of spread of exotic organisms (see Andow et al. 1990), including zebra mussel where data are relatively well characterized (see Appendix 3A).

The simple Skellam model assumes a single, continuous form of dispersal, and it predicts that range expansion should be a smooth, continuous process (Figure 5a). However some species may be able to disperse in at least two ways. If the invasion process reflects both diffusive and jump dispersal, it has been referred to as "stratified dispersal" (see Shigesada and Kawasaki 1997; Kot et al. 1996), and range expansion will proceed through the formation of multiple discrete, isolated colonies established ahead of the infested front. These colonies in turn will expand their ranges and ultimately coalesce (Figure 5b). One consequence of this phenomenon is that range expansion may occur much faster than under a simple diffusion model.

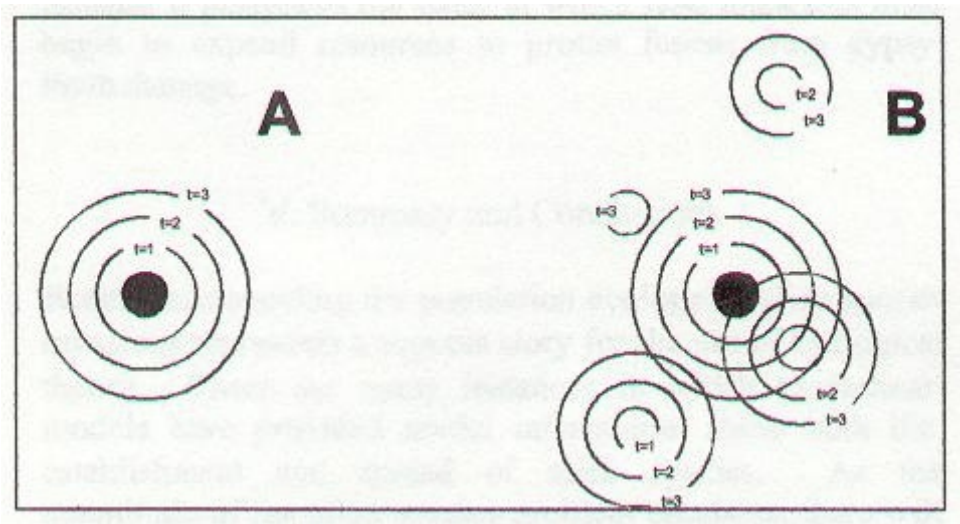


Figure 5. Frame A resolves about a single focus of diffusion, and Frame B illustrates diffusion from multiple foci.

Predicated on published accounts of life history (see Speirs and Gurney 2001; Appendix 3A), values for ***r*** and **D** were applied to the original Skellam equation, and the predicted wavefront for both invasive mollusks (zebra mussel and New Zealand mudsnail) would be nearly 100 kilometers (km) per year. The range about this estimate, however, reflects the variability in the available empirical data (50–250 km/year). More importantly, either species would likely exceed these values given the stratified diffusion that best characterizes the dispersal process currently exhibited by each species. In the absence alteration of preferred habitats and intervention measures, both these mollusks may arrive in the Red River basin within the next 20–25 years, and sooner (e.g., within the next 5 years), if jump events contribute to the stratified dispersal that currently characterizes the invasion process of each species (see Appendix 3A).

3.3 Spatial Analysis: Predicted Distributions for Biota of Concern

While all biota of concern did not present data sufficient for an evaluation of their predicted "potential distributions," georeferenced data were available for some of the fishes

("Asian carp" as a compilation of bighead carp, black carp, and silver carp), gizzard shad and rainbow smelt), zebra mussel, New Zealand mudsnail, and tamarisk (compiled as *Tamarix chinensis*, *T. aphylla*, *T. parviflora*, *T. ramosissima*, and hybrids). Nearly all biota of concern presented occurrence data on a county or state basis (see Appendix 3A and Appendix 3B), but such data collections do not present sufficient resolution for evaluating historic, current, or future distributions using GARP. Preparation of this report precluded incorporation of data sets that are currently being compiled and may become available during 2005 (see also, Section 4).

3.3.1 Asian carp. Current distributions for "Asian carp" are noted in Appendix 3A, and given the similarity in life-history attributes of these species as those relate to their invasiveness, current distribution data were collapsed across species lines to capture the potential distribution of these selected carp species in North America for this preliminary analysis of dispersal and spread. Figure 6 and Figure 7 project the spatial sum of best subsets yielding a predicted "species distribution" for Asian carp world wide and within the area of concern, respectively. Given the current distribution record of those species included in the composite Asian carp, potential distribution of members of the composite group includes the Missouri River, Upper Mississippi River and Great Lakes, with 25% to 50% of the best subsets projections suggesting that Asian carp could potentially expand into the Red River basin, if pathways for founding groups were realized. These projections are not dependent on interbasin water diversion to be realized, but represent experimental outcomes dependent on any pathways potentially serving as conduits for passage between Missouri River and Red River basins. Current North American distributions of carp included in this species compilation are consistent with these projections (see Appendix 3A).

3.3.2 Gizzard shad. Figure 8 and Figure 9 present the potential distribution of gizzard shad throughout North America and within the area of concern, respectively. In contrast to Asian carp, the spatial sum of best subsets suggests that gizzard shad would be successful in the Missouri River, Upper Mississippi, and Great Lakes basins, but with the available georeferenced data characterizing the species' current distribution, the species does not appear to be as great a threat to establishing long-term populations in the Red River basin regardless the pathways that potentially link source areas with receiving waters. Less than 25% of best subsets reflected potential distribution in the Red River basin, as well as other basins within HUC09. As with Asian carp, these projections for gizzard shad are not dependent on interbasin water diversion to be realized but represent experimental outcomes dependent on any pathways potentially serving as conduits for passage between Missouir River and Red River basins. Current distributions of gizzard shad in North America are consistent with these projections (see Appendix 3A).

3.3.3 Rainbow smelt. Figure 10 and Figure 11 present the potential distribution of rainbow smelt in North America and the area of concern, respectively. Since the early 1980s, rainbow smelt have successfully expanded their distribution to HUC09 (see Appendix 3A), which is consistent with spatially summed best subset projections in Figure 11. Based on predicted distribution of rainbow smelt, continued expansion of rainbow smelt in HUC09 is anticipated,

including waters within Red River basin, if pathways are realized that link source areas within HUC09 with receiving waters in the basin of concern. Continued expansion in the surface waters of the Great Lakes and Upper Mississippi basin should continue if management practices do not limit diffusion or stratified diffusion processes from promoting dispersal and spread of the species. On the basis of the spatial sums of best subset projections, rainbow smelt dispersal and spread within the Missouri River basin would appear limited, which is consistent with the species current distribution (see Appendix 3A). As evident from the current distribution, these projections are not dependent on interbasin water diversion to be realized, but represent experimental outcomes dependent on any pathways potentially serving as conduits for passage between Missouri River and Red River basins.

Figure 6. Asian carp predicted distribution projected world wide.

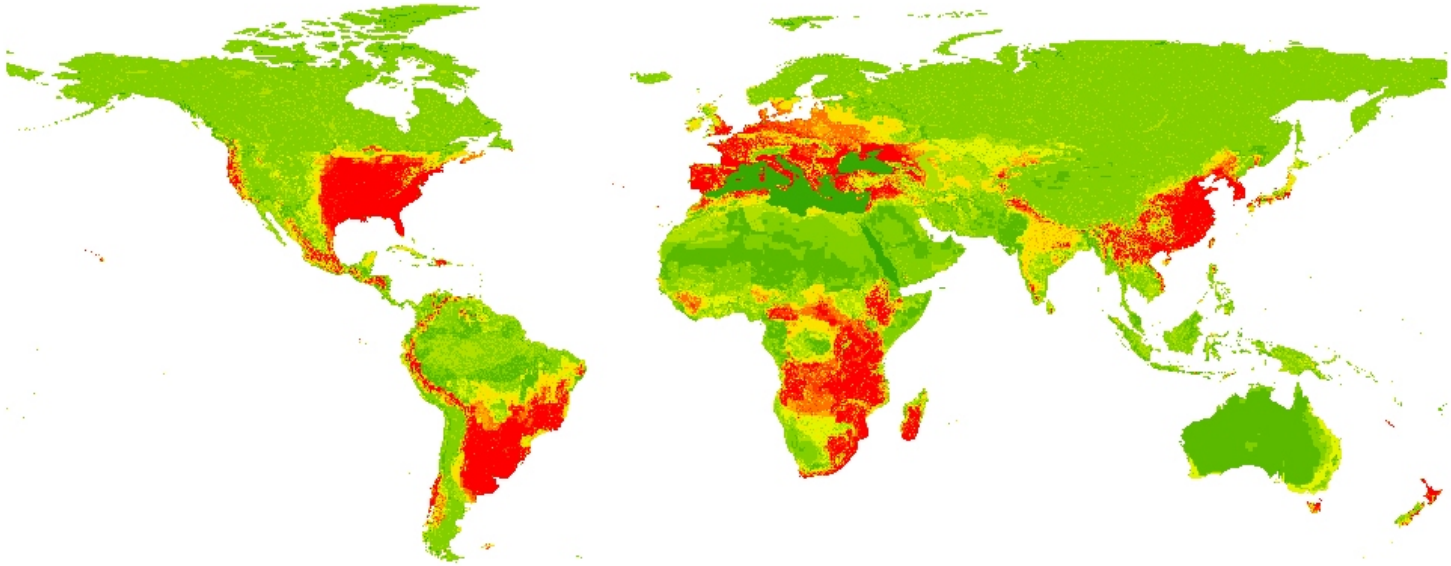


Figure 7. Zoom-scale projection of Asian carp predicted distribution in area of concern.

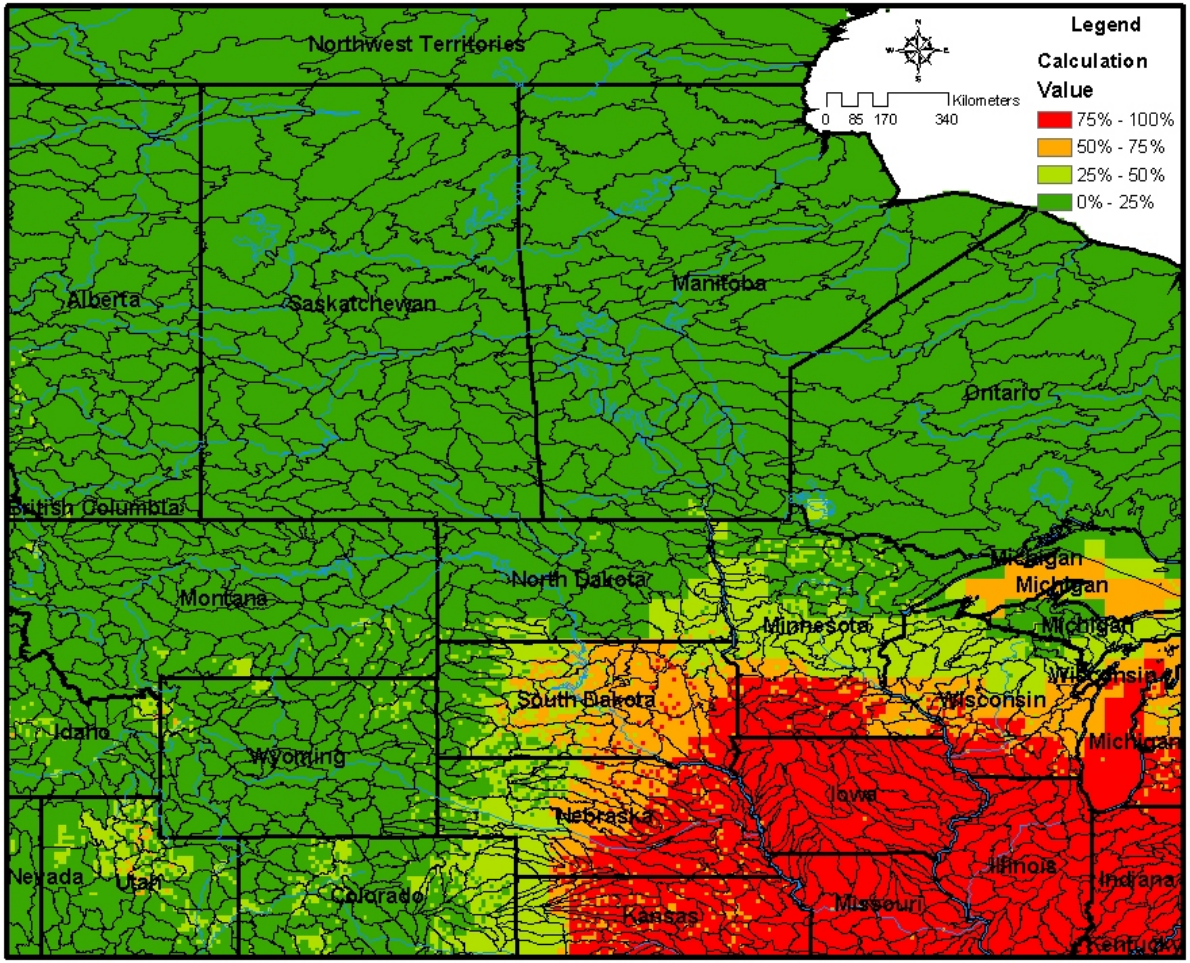


Figure 8. Gizzard shad potential distribution predicted to North America.

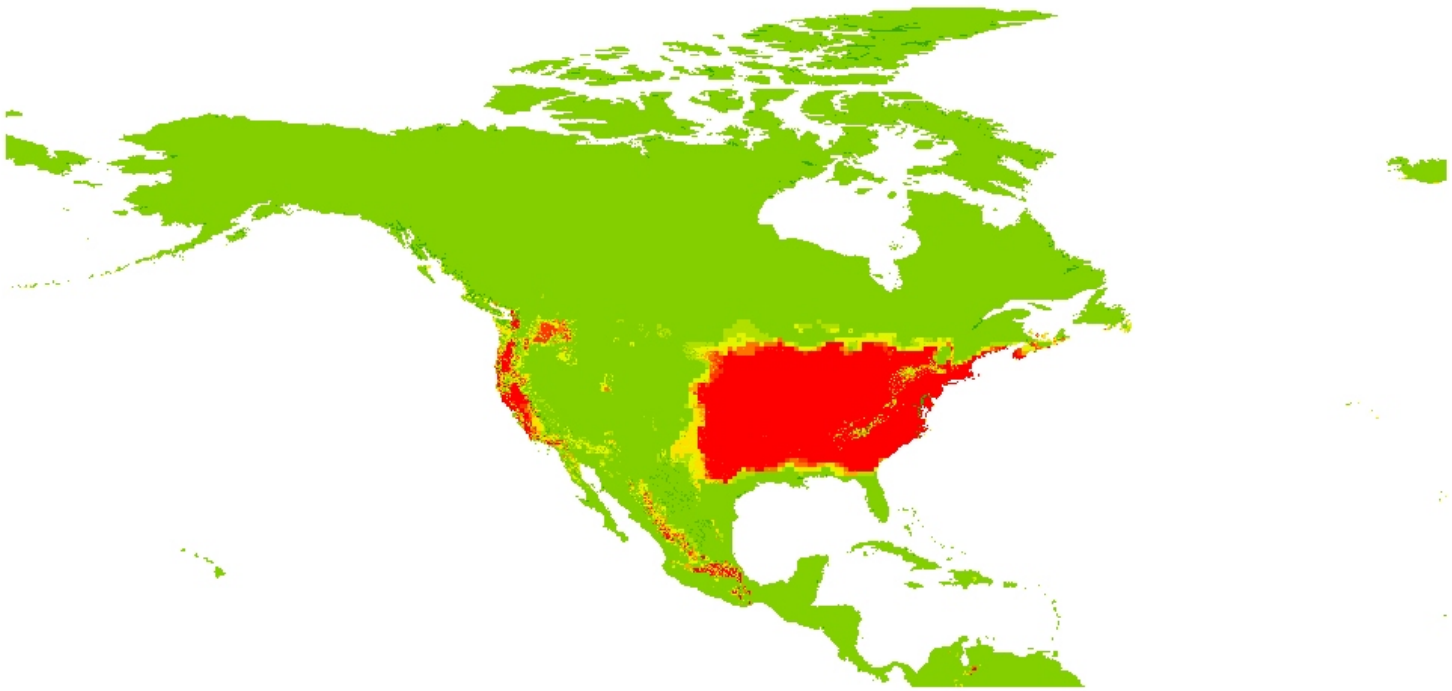


Figure 9. Zoom-scale projection of gizzard shad potential distribution in area of concern.

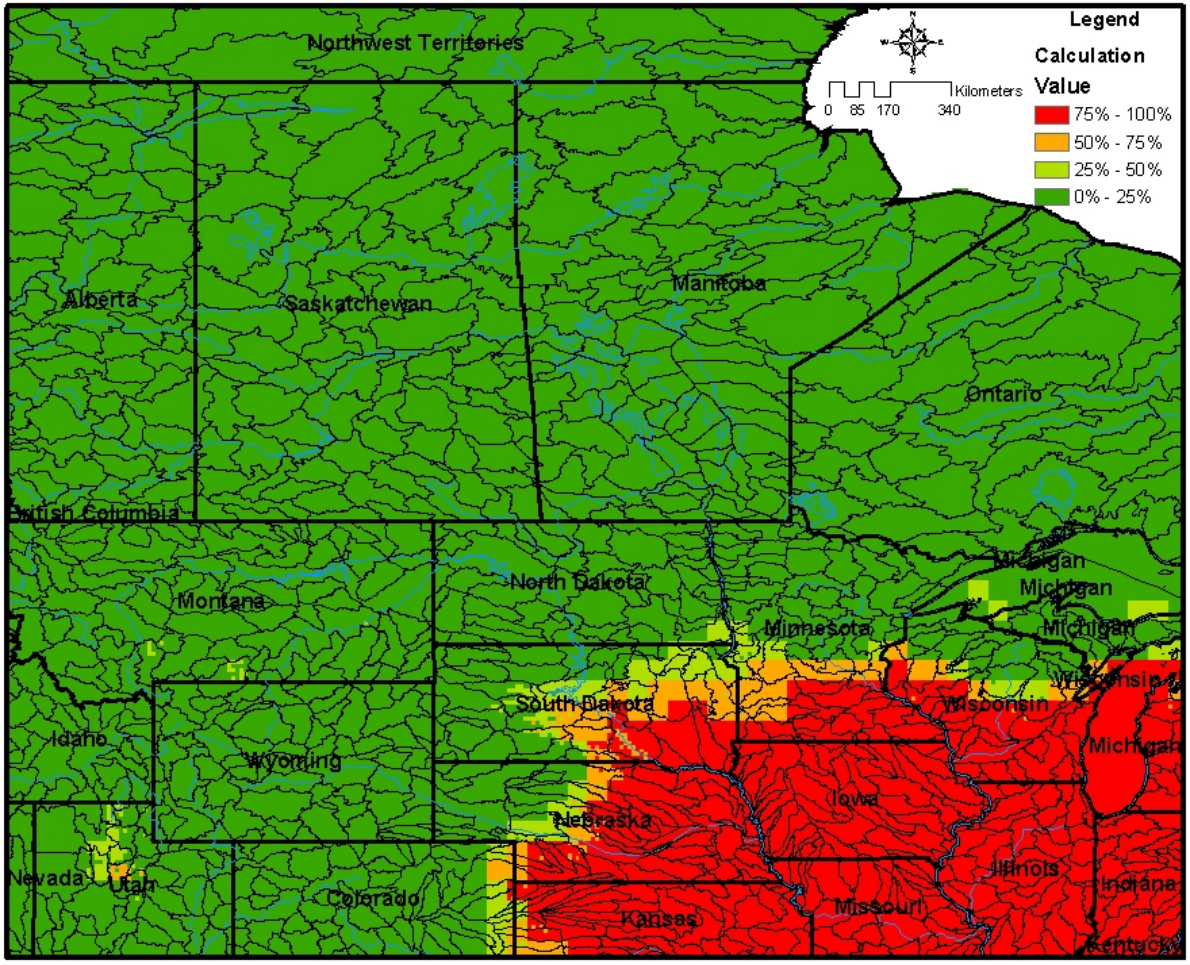


Figure 10. Rainbow smelt predicted distribution projected to North America.

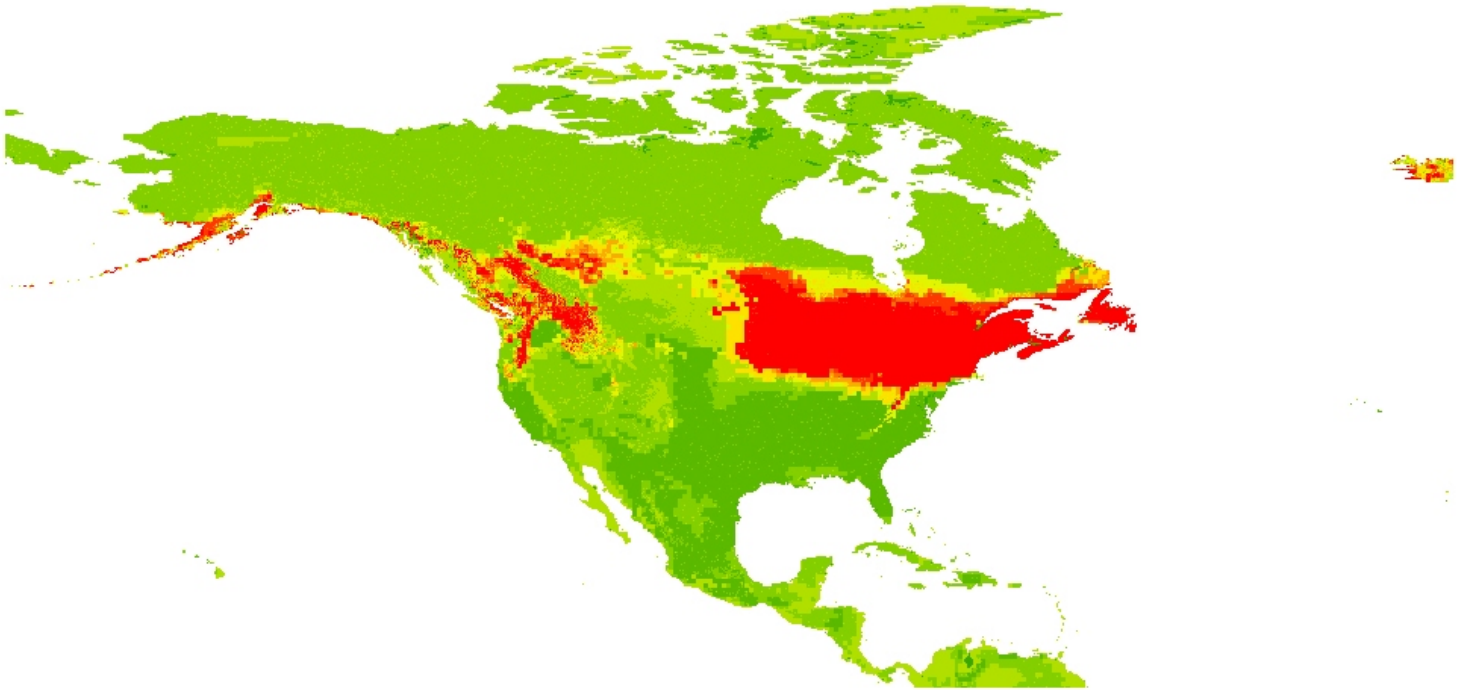
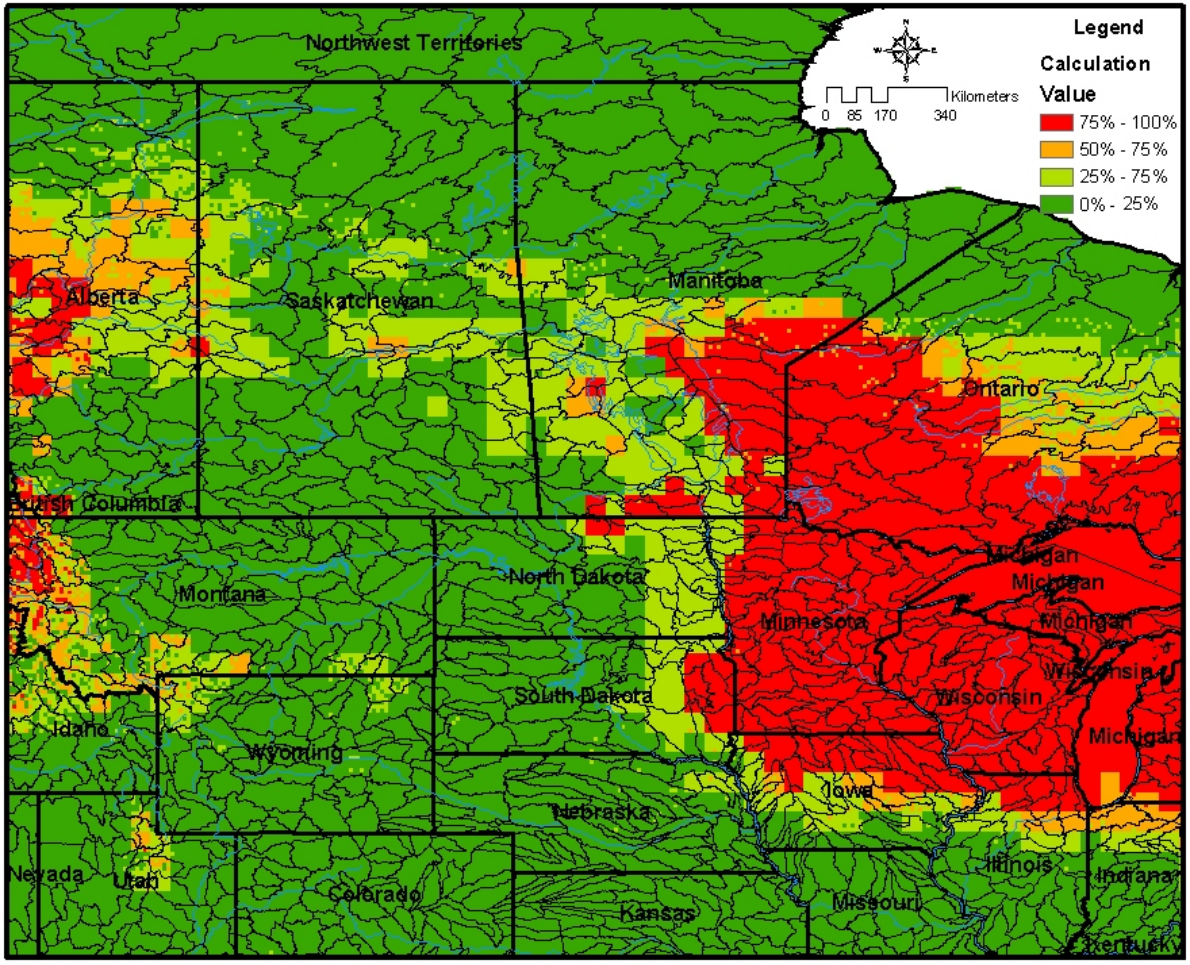


Figure 11. Zoom-scale projection of rainbow smelt predicted distribution in area of concern.



3.3.4 Aquatic invertebrates. Georeferenced data were available for zebra mussel and New Zealand mudsnail and enabled analysis of predicted species distribution using GARP. Appendix 3A summarizes current species distributions state wide and county wide for other aquatic invertebrates whose invasive status should also be considered from an ecological perspective similar to that guiding the analysis focused on zebra mussel and New Zealand mudsnail as representative aquatic invertebrates.

3.3.4.1 Zebra mussel. Zebra mussel presented georeferenced data that afforded an opportunity for a time-series analysis of the species dispersal and spread in surface waters of North America (see Appendix 3A and Section 4, especially related to uncertainty analysis). With the currently available georeferenced data for zebra mussel, predicted distribution of the species in North American is illustrated in Figure 12 and Figure 13 which present spatial sum of best subsets for North America and the area of concern, respectively. In contrast to other spatial analysis using GARP, the potential distribution of zebra mussel clearly fits with the species current distribution (see Appendix 3A), but the species distributions projected as sum of best subsets indicates that dispersal and spread of the species may go beyond the 100th meridian, if pathways linking sources and receiving systems are realized. This observation is drawn in light of the relatively high number of projected distributions (25%–50%, 50%–75%) occurring as outputs from GARP, which is contrasted with other species projections in this spatial analysis of potential distributions where relatively clear limits to species distributions are indicated. Spatial sum of best subsets, however, are influenced by time-related observations, which should be considered in the course of adaptive management focused on prevention and control of zebra mussel in North America (see uncertainty analysis, Section 4).

Current distribution records for zebra mussel are consistent with spatial sum of best subsets, and summed projections indicate that Red River basin affords suitable physical habitat for the dispersal and spread of the species in surface waters of the area of concern. The predicted species distribution in Red River basin is a consistent projection across all possible distributions projected by GARP with 75% to 100% of best subset projections including Red River basin in output projections, suggesting that completed pathways linking source with receiving waters would yield sustainable populations, if completed pathways were realized. These projections are not dependent on interbasin water diversion to be realized but represent experimental outcomes dependent on any pathways potentially serving as conduits for passage between Missouri River and Red River basins. Additionally, given the available time-series data for the dispersal and spread of zebra mussel in the Great Lakes and Upper and Lower Mississippi River basins, these projections could be realized within 20–25 years, and sooner if stratified dispersal occurred between basins of interest.

3.3.4.2 New Zealand mudsnail. Although later in its arrival to North America than Zebra mussel, New Zealand mudsnail presents ample georeferenced data for an analysis of spatial distribution using GARP. Figure 14 and Figure 15 present spatial sum of best subsets from GARP

for New Zealand mudsnail for North America and area of concern, respectively. These projections are consistent with the species' current distribution and suggest that Red River basin presents physical habitat features amenable to species dispersal and spread in the future. Summed best subsets projected from GARP also indicate that surface waters throughout the Missouri River, Mississippi River, and Great Lakes basins provide potential areas for species distribution expansion. Following a pattern similar to zebra mussel, best subset projections derived from spatial analysis completed using GARP suggested that habitats open to invasion and establishment of sustainable populations were potentially widespread throughout North America, given the species' distribution conservatively predicted by 50%–75% of best subset projections.

As noted for zebra mussel, projections of potential distribution for New Zealand mudsnail are not dependent on interbasin water diversion to be realized but represent experimental outcomes dependent on any pathways potentially serving as conduits for passage between Missouri River and Red River basins. And, given the available time-series data for the dispersal and spread of New Zealand mudsnail in the western US, these projections could be realized within 20–25 years and sooner if stratified dispersal occurred between basins of interest (as occurred from the initial observation of New Zealand mudsnails along the Snake River in Idaho, and subsequent sightings at various locations in the Colorado River system; see Appendix 3A).

Figure 12. Zebra mussels' predicted distribution projected to North America.

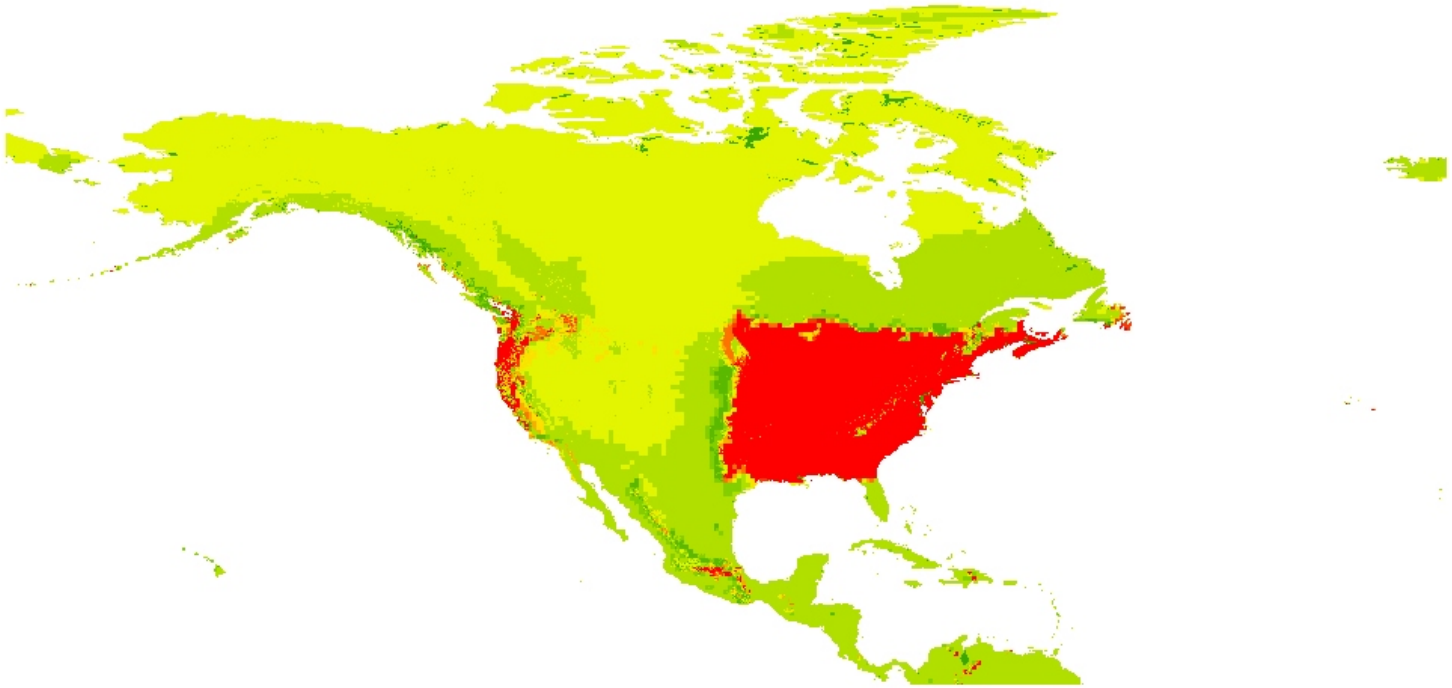


Figure 13. Zoom-scale projection of predicted distribution of zebra mussel in area of concern.

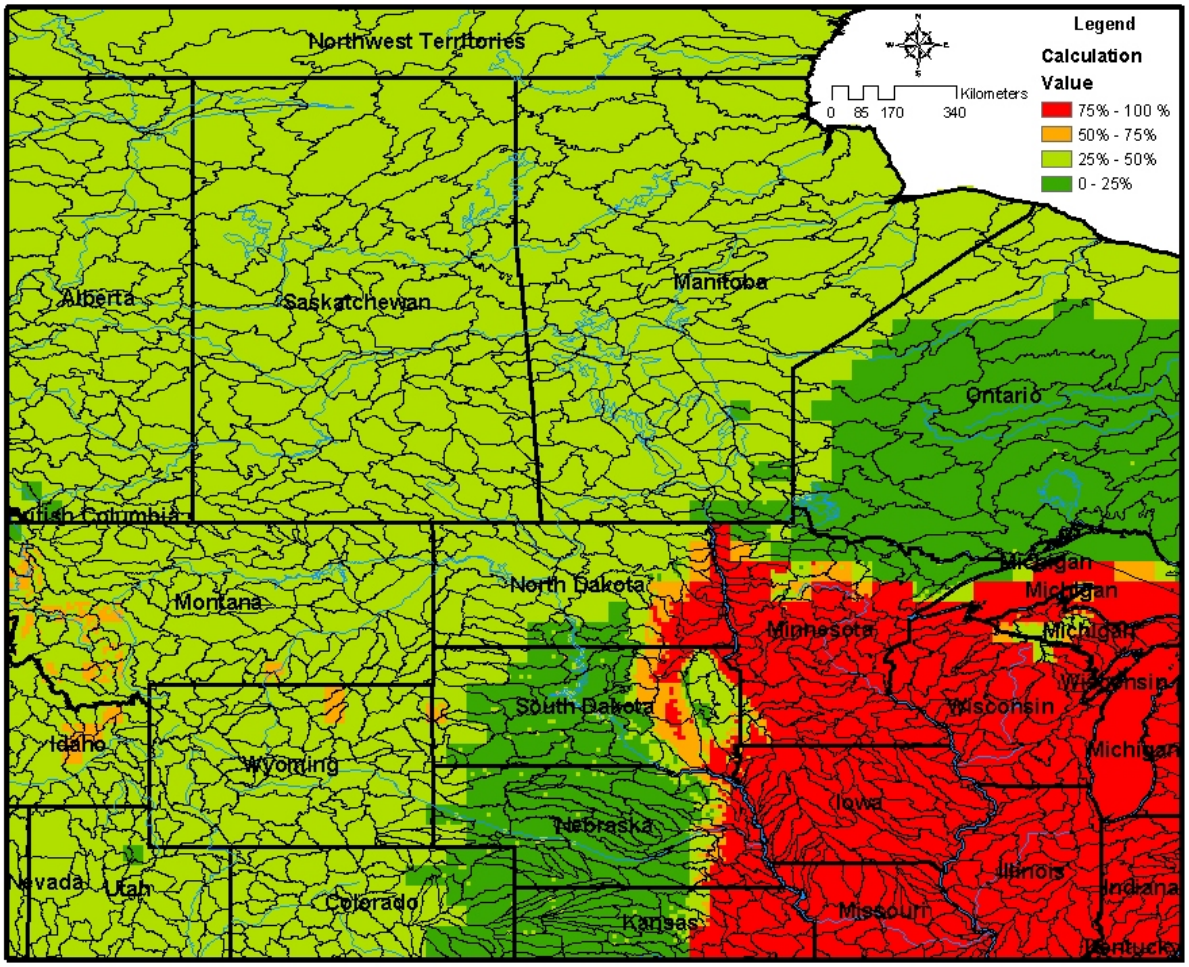


Figure 14. New Zealand mudsnails' predicted distribution projected to North America.

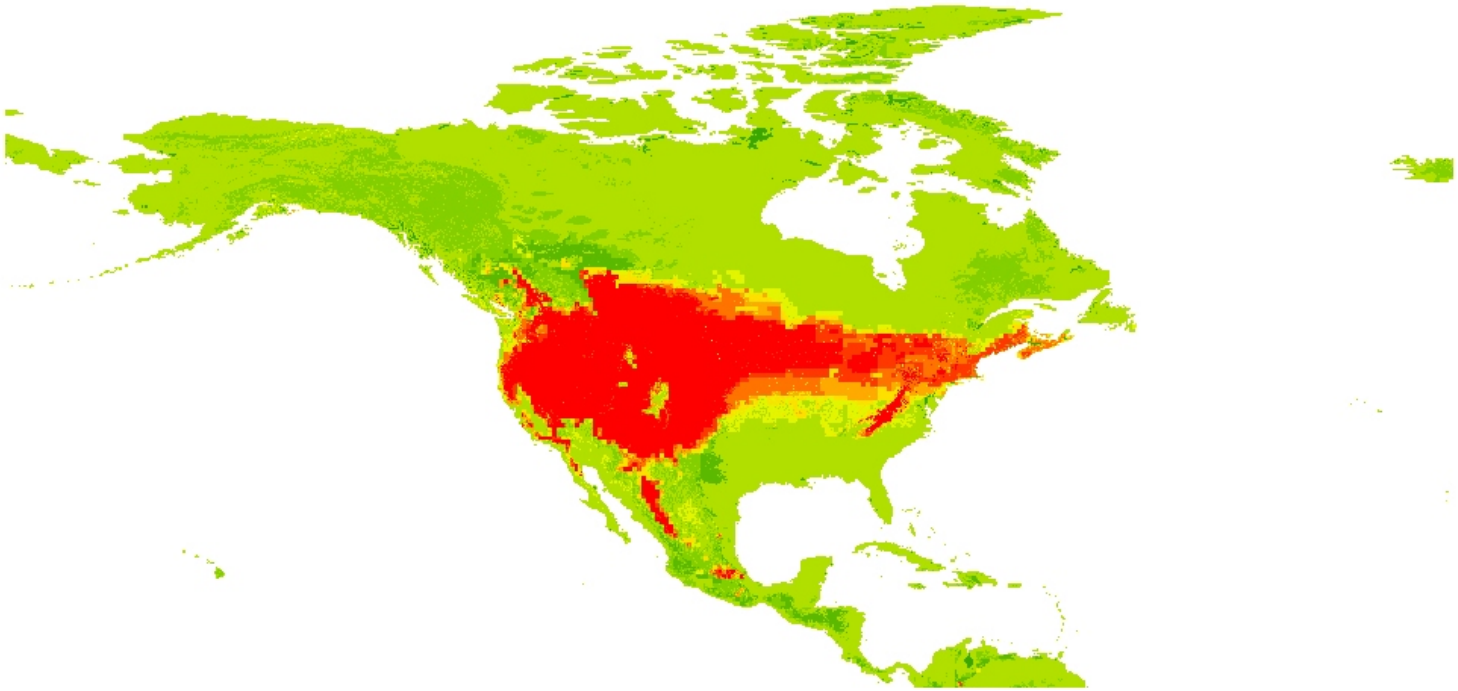
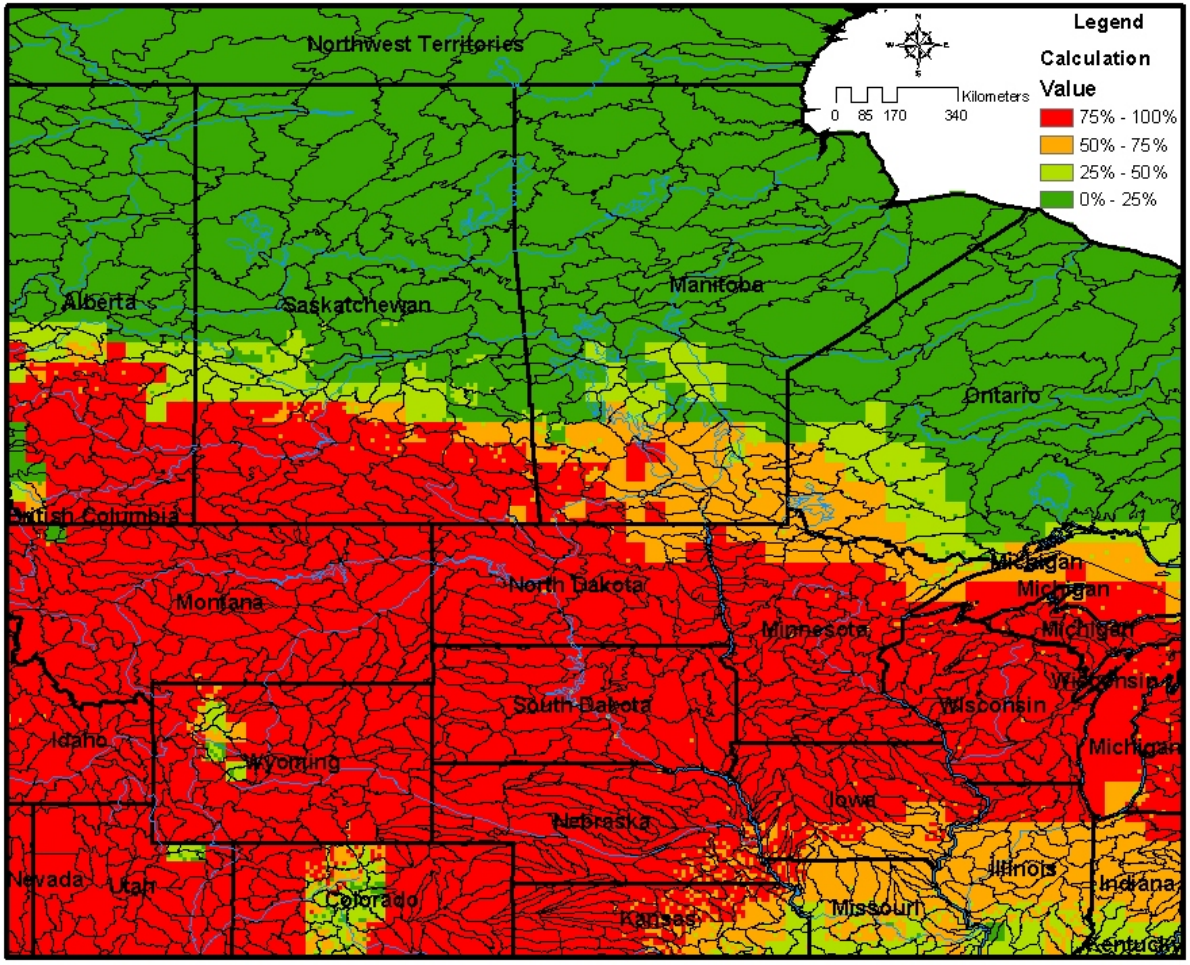


Figure 15. Zoom-scale projection of predicted distribution of New Zealand mudsnail in area of concern.



3.3.5 Aquatic vascular plants–*Tamarix* spp. While various state wide and county wide records are available for aquatic vascular plants, and wetland and riparian vascular plants (see Appendix 3A), only tamarisk presented georeferenced data sufficient to developing predicted species distribution. Here, tamarisk projections are generated based on a compilation of species presence data for *Tamarix chinensis*, *T. aphylla*, *T. parviflora*, *T. ramosissima*, and hybrids, which is represented by the dot map in Figure 16.

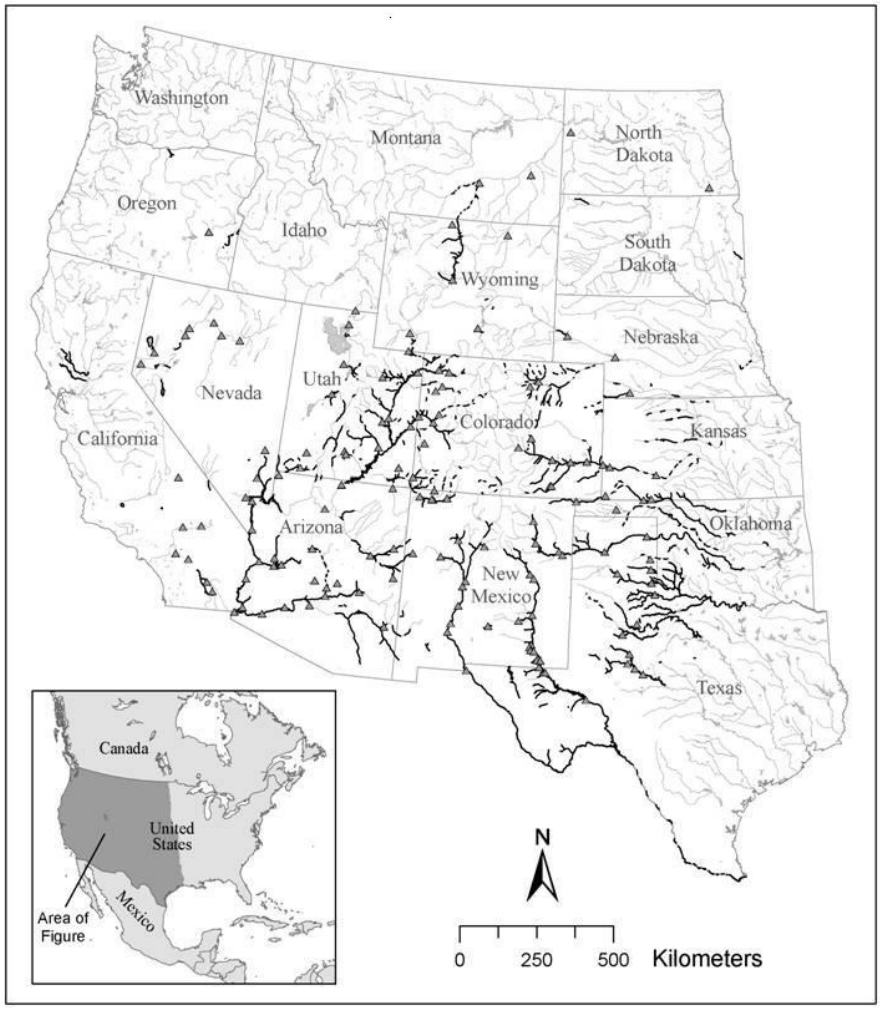


Figure 16. Dot map of tamarisks' (as various species within the genus) current distribution in North America.

Figure 17 and Figure 18 present predicted distributions for tamarisk species in North America and area of concern, respectively. As noted for other species amenable to spatial analysis with GARP, the current distribution of tamarisk in North America is consistent with the spatial sum of best subsets generated in the analysis. On the basis of these projected distributions for *Tamarix* spp., ongoing distribution expansions in the Upper Missouri River drainage, including recent entry into North Dakota along riparian habitats of tributaries to the Missouri River, should continue. Expansion of distribution will continue regardless of status of water diversions. The eastern and northern limits of expanded distribution, however, may be limited (e.g., due to physiological constraints associated with latitudinal advance) and riparian habitats in Red River basin are currently not included in these spatial sum best subsets. Projected best subsets currently present a relatively well-delineated limit to northern and eastern expansion, and future updates in species occurrence data may warrant additional spatial analysis (see uncertainty analysis in Section 4). Indeed, updated forecasts for *T. ramosissima, T. chinesis*, and their hybrids may be encouraged given observations of Pearce and Smith (2002, 2003) that suggest historic dispersal rates of 2.5 and 25 km/year may be realized in the northern expansion of species distribution (depending on extent of stratified disperal). Additionally, these authors noted that the northern limits of the species' native distributions in cold, dry deserts of northeastern Asia do not contraindicate invasion of the northern Great Plains of North America.

Ongoing compilation of georeferenced data, as available, continues for vascular plants as well as other biota of concern, although subsequent additions to this facet of analysis for inclusion to the revised report will necessarily be limited to species for which such data are available or can be assembled from existing museum records (e.g., hydrilla, Eurasian water milfoil).

Figure 17. Tamarisks' (as multiple species) predicted distribution projected to North America.

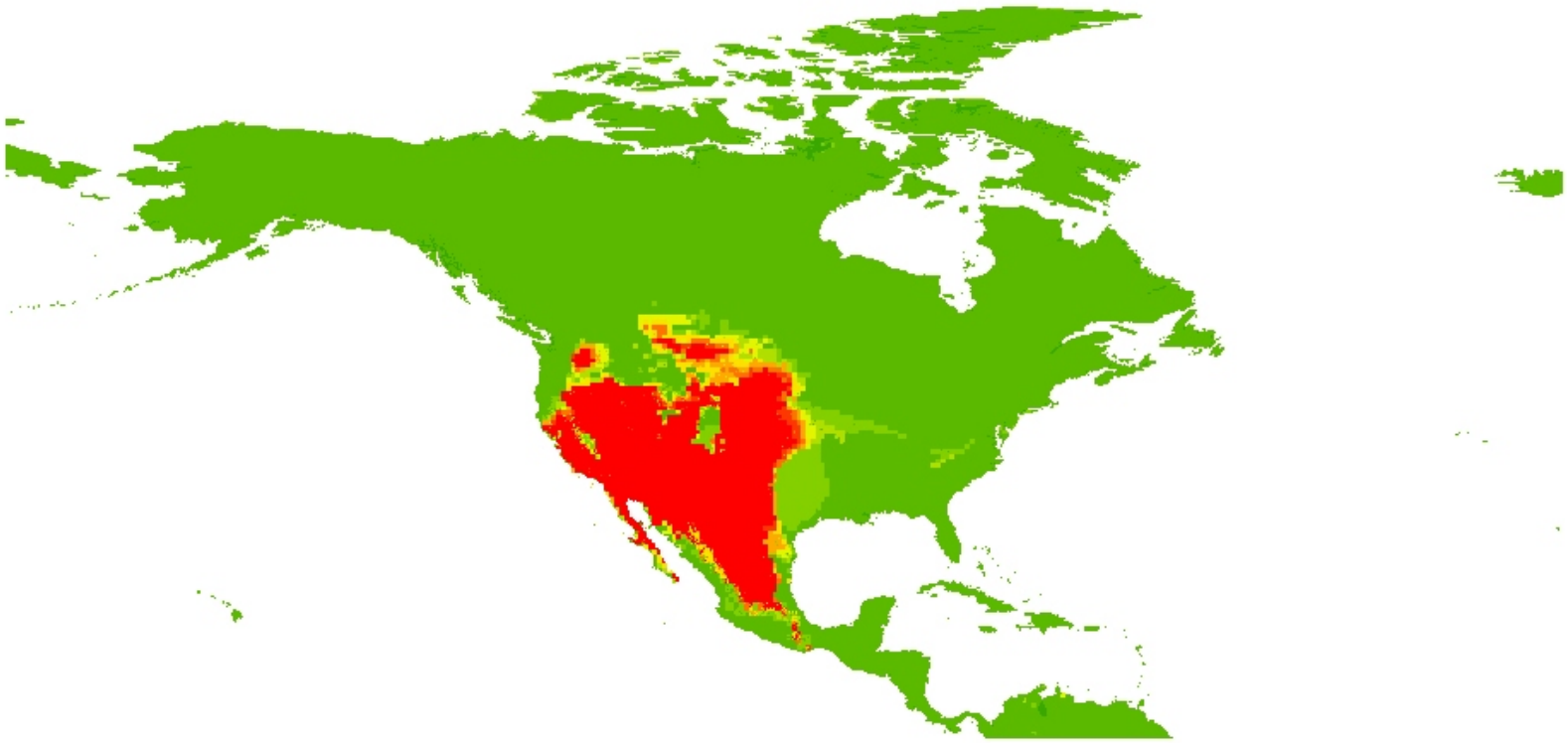
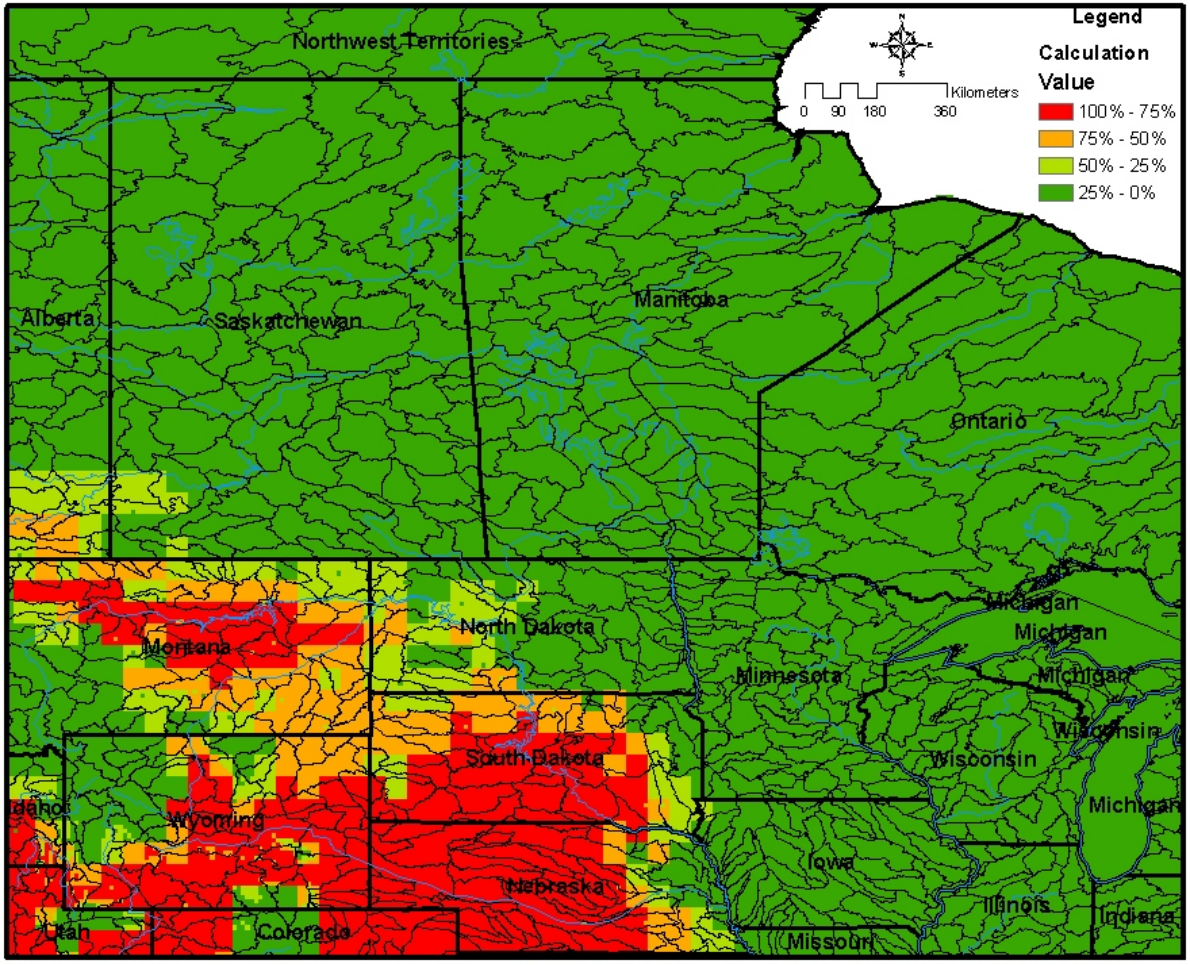


Figure 18. Zoom-scale projection of tamarisks' predicted distribution in area of concern.



3.3.6 Diseases of fish and waterborne disease. Georeferenced occurrence data for disease agents is relatively limited, although state wide and county wide records (especially for zoonoses and diseases of humans) are available for most of the biota of concern and have been included in Appendix 3B. For spatial analysis of disease agents included as biota of concern to stakeholders, the current investigation employed analytical approaches similar to those applied by other authors in developing predictive models of disease dispersal and spread in an illustrative analysis focused on whirling disease (see Peterson et al. 2002; Peterson et al. 2003).

While georeferenced data for the causative agent of whirling disease is limited or highly disperse and unavailable in compiled form, distribution data as "presence only" data for the disease host is readily available; hence, we viewed the potential introduction of *M. cerebralis* as the causative agent for whirling disease as a function of occurrence of its host, rainbow trout (*O. mykiss*). Figure 19 and Figure 20 illustrate the spatial sum of best subsets of predicted species distribution for rainbow trout as projected by GARP. Current distribution of rainbow trout is consistent with GARP's projection based on spatial sum of best subsets. The occurrence of whirling disease compiled on a state wide basis (see Appendix 3B) suggests that the potential for occurrence of the disease is clearly widespread in North America, with the limiting factors being vectors serving to transport diease agent from source areas to previously unoccupied habitats occupied by sensitive host species. Simply stated, if potential for expanded species distributions are realized through unaided or aided (e.g., active stocking programs) transport of rainbow trout, then the potential for whirling disease exists. And given the natural history of the disease (see Appendix 3B), the occurrence of whirling disease in these expanded rainbow trout distributions will be realized through time.

Although analytically speculative, based on current and presumptively potential species distributions realized by host species, similar outcomes for occurrence of diseases among other fishes may be realized for other disease agents such as ERM and IHNV. Similar outcomes might also be anticipated for terrestrial vertebrates, e.g., wildlife diseases, if hosts (primary and intermediary, if necessary) occur in the receiving system and pathways linking sources and receptors are realized. As noted in previous summaries focused on categorical and quantitative outcomes, these conclusions are not solely dependent on interbasin water transfers, but unrestricted diversions (e.g., water transfer via open conveyance) could potentially afford routes for emigration from Missouri River basin that were otherwise absent.

Figure 19. Predicted distribution of rainbow trout, the primary host for whirling disease, projected to North America.

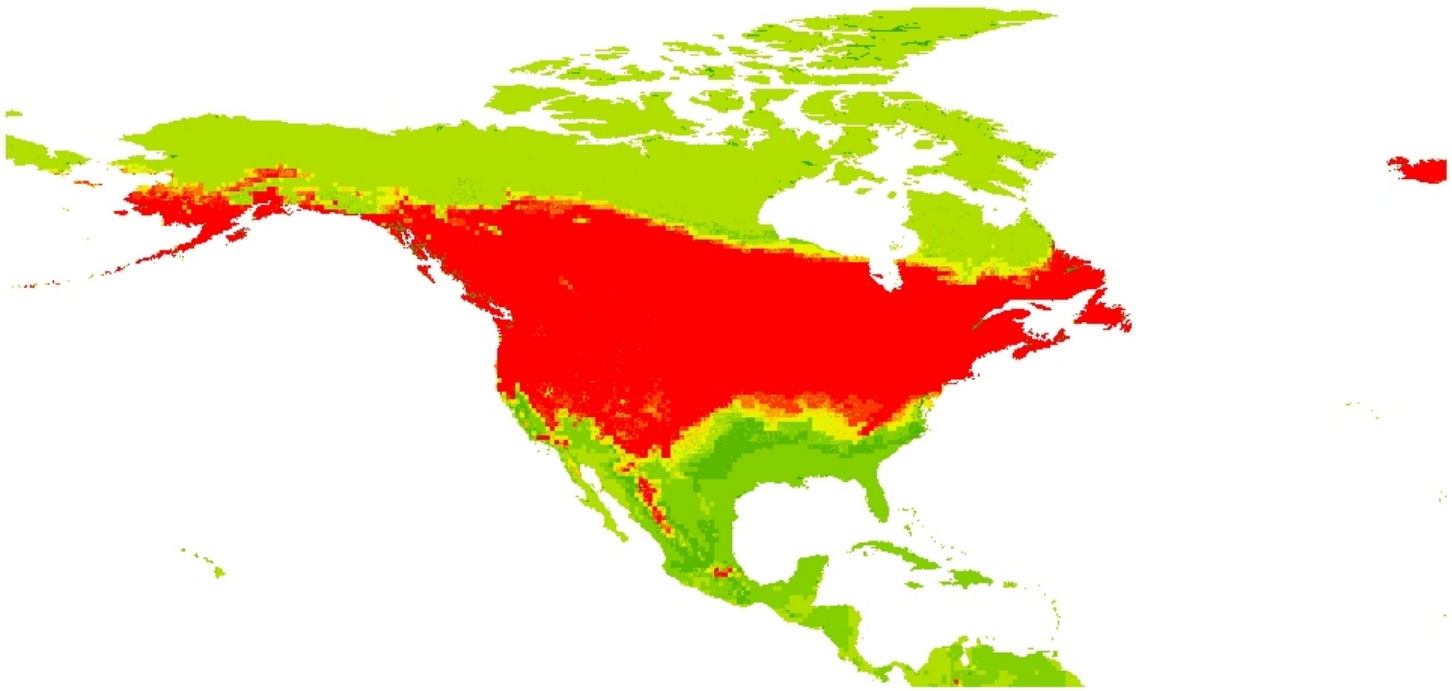
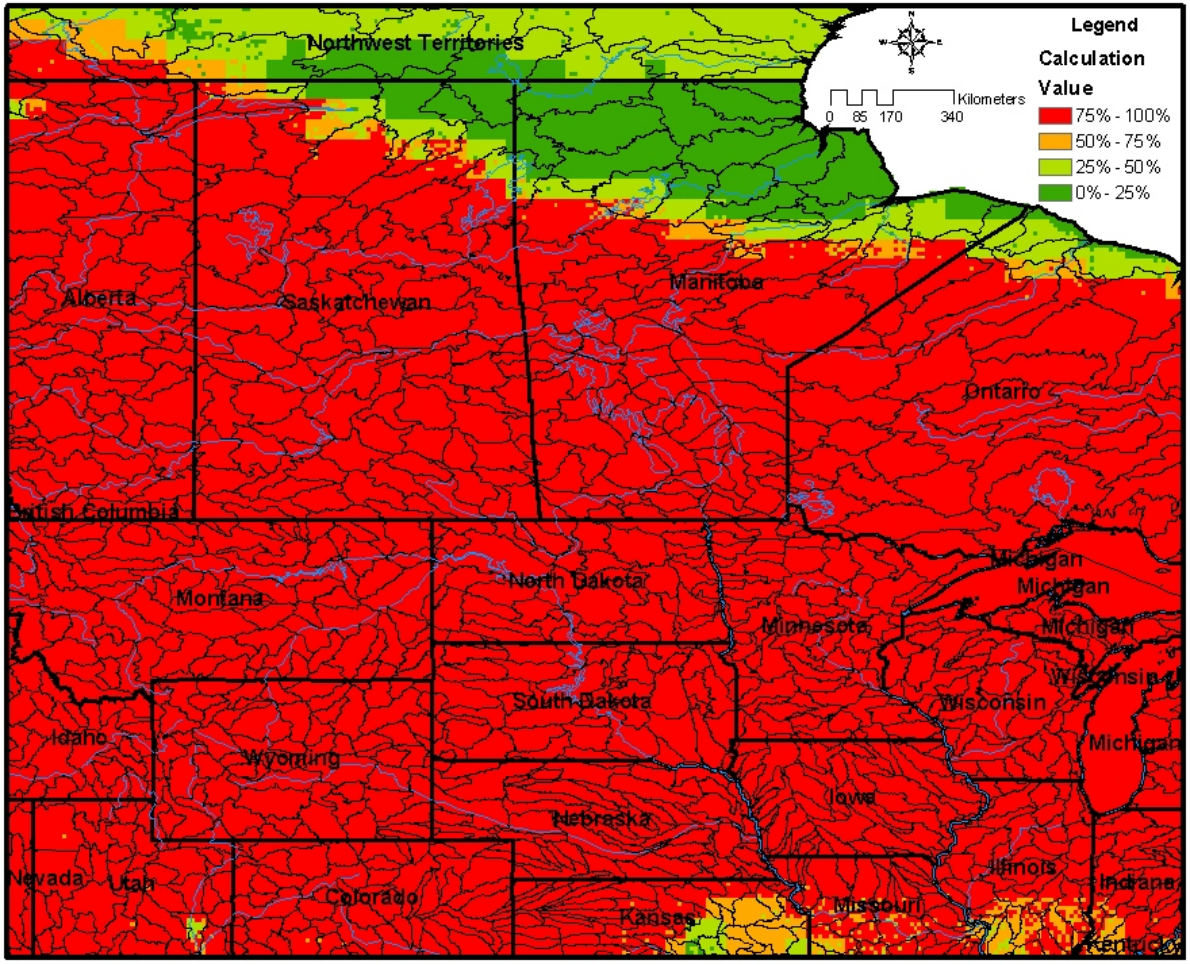


Figure 20. Zoom-scale projection of rainbow trout predicted distribution in area of concern.



3.4 Narrative Risk Analysis for Biota of Concern

Each of the groups of biota of concern identified in Table 10 will be considered in a narrative integration of outcomes derived from categorical analysis, simple probabilistic analysis captured in FPTs, spatiotemporal analysis for representative mollusks and riparian plants, and predictive species distributions generated for selected biota of concern. Regardless of biota of concern, from the perspective of invasion biology, the process of emigration reflects greater stochasticity than does the establishment of sustainable populations, which is highly dependent on life-history attributes related to, e.g., intrinsic rates of increase and other traits characteristic of the species.

3.4.1 Narrative analysis: Fishes.[2] Limited georeferenced data needed to evaluate predicted distributions for paddlefish and pallid sturgeon are available, and preliminary efforts to develop comparable numerical and map outputs of predicted distributions suggested that the existing records were not sufficient for analysis. This judgment largely reflected an initial review of preliminary outputs from GARP that clearly indicated that projected distributions based on available georeferenced occurrence data did not correspond to current museum records for distribution of sturgeon (i.e., either pallid or shortnose; see Section 4). The fishes, however, have been subject to much biogeographical study over the past 100 years (see historic accounts Jordan and Everman 1896-1900; Woolman 1896 and more recent accounts Eddy et al 1972; Scott and Crossman 1973; Eddy and Underhill 1974; Crossman and McAllister 1986; Underhill 1989; Loomis et al. 1999), with much of the regional focus on the ichthyofauna stemming in part from recent concerns associated with water diversions such as those currently under consideration (see Petreka 1978, 1992; Swain et al. 1980; North Dakota Game and Fish Department 1986, 1994; Ryckman 1981; Stewart et al. 1985; Petreka and Koel 1996; Koel 1997).

For example, Peterka and Koel (1996) and Koel (1997) completed a distributional survey of the fishes of the Red River then analyzed their survey finds relative to historic records in characterizing the ichthyofauna of the basin. Koel (1997) had observed that historic fish distribution lists for the Red River basin cited different species occurrence records, e.g., Crossman and McAllister (1986) had listed 75 fish species for the Red River basin in the United States, while Underhill (1989) had listed 80 species. Koel (1997) subsequently compiled historic records for fish distributions in the region, including field survey records of fish occurrence, and documented records for 77 native and 7 introduced fish species in the Red River basin during the recording period, 1892–1994. Diversity of fishes in the Red River basin was considered relatively high, particularly in contrast to other rivers in the basin. Observations similar to those of other workers publishing during the period were noted for fish species common to the Red River and

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[2]Updated and edited from material originally developed by John J. Peterka and Todd M. Koel, Zoology Department, North Dakota State University, Fargo, ND 58105 (October 1996); Todd Marvin Koel, Zoology Department, North Dakota State University, Fargo, ND (May 1997) for USGS/BRD/NPWRC, Jamestown, ND.

immediately adjacent basins. For example, Koel (1997) observed that 69 fish species were listed as occurring in the Upper Mississippi River (above St. Anthony Falls, Minneapolis), and 72% of those species (62 out of 69) also occurred in the Red River basin. Similar observations were noted for the Minnesota River where 72 of 88 species (84%) were shared with the Red River and for the Missouri River (in North Dakota) where 46 of 65 species (54%) were common to Red River and Missouri River waters (Ryckman 1981). Koel speculated that the ichthyofauna of the Red River basin appeared more closely related to that of the Minnesota River to the south and the upper Mississippi River to the east, a hypothesis reflecting a previously posited suggestion that current day fishes of the Hudsonian region reflect postglacial dispersal patterns of fishes (see Underhill 1989). Koel (1997) suggested that "the low faunal similarity between the Red and Missouri Rivers may indicate a lack of any significant postglacial dispersal route between the two basins, or it may simply be due to differences in habitat that are available to fishes."

Petreka and Koel (1996) and Koel (1997) continued a line of published documentation that reinforces observations related to survey sample designs (e.g., difficulty in characterizing presence-absence of "rare targets;" see Thompson and Seber 1996; Manly et al. 2002; Helsel 2005) and the dynamic character of biogeographic distributions of plants and animals throughout North America (see Scott et al. 2002). A focus on fishes clearly illustrates how a characterization of a faunal distribution through a sample collected during a "snippet of time" can lead to seemingly confounding observations, particularly when these snippets are compiled in a haphazard time-series analysis reliant on sample designs of different specifications. For example, a focus on interfaces between major drainage basins (e.g., HUC10, Missouri River and HUC09, Red River-Souris River-Rainy River) clearly cannot avoid considering source areas for "immigrants" from areas other than those of principal concern. Koel (1997) and others (see Crossman and McAllister 1986) clearly indicate the importance of geographic interfaces with other drainage basins, especially the Upper Mississippi (HUC07) and the Great Lakes (HUC06). For example, Table 11 and Table 12 list occurrences of grass carp (*Ctenopharyngodon idella*) and silver carp (*Hypophthalmichthys molitrix*), respectively, in the Red River and Missouri River basins, as well as basins immediately adjacent to these basins of concern. Not surprisingly, fish species lists for the Red River basin do not include either of these exotics, yet these species have emigrated or have been released, then subsequently collected from locations in Missouri River basin, Red River basin, and adjacent basins, apparently before sustainable populations were established. As with Asian carp, these fishes considered biota of concern in the current investigation have previously been collected from waters in the Red River basin, so opportunity for invasion has occurred in the past. Those documented occurrences, although transient, suggest that future emigrations from any of the adjacent HUCs or releases by human agency (e.g., intentional or accidental releases mediated by human intervention) may establish "beachheads" that subsequently serve as a pioneering collection of individuals that potentially lead to sustainable populations. Distinguishing sources of these pioneering individuals may be frustrated by inadequate characterization of baseline or given our current range of diagnostic tools may not be technically plausible (see Scott et al. 2002).

Interpretation of risks associated with fishes potentially transferred collaterally with interbasin water diversion. As suggested by the preceding narrative regarding the current status of fishes in the Missouri River and Red River basins and the observations of Scott et al. (2002), the only certainty is we may never realize a complete list of ichthyofauna for these or any other river basins in North America. And the status of the fishes of the Missouri River and Red River basins represents an effort to catalog species of a region that equals or exceeds those efforts for other biota identified for characterization in the current investigation. While the literature variously documents the effects of one species on another, e.g., the effects associated with introduced fishes in the Great Lakes, and general observations regarding the effects of invasive species on native fishes (see Fuller et al. 1999), we can only interpret risks associated with biota transfers that may occur collaterally with interbasin water diversions within the context of probability—largely, qualitative—shaped by integrating outcomes derived from analysis using tools such as those applied in the current investigation.

While Section 4 will focus on risk characterization and an analysis of uncertainties, from the perspective of our categorical analysis, interbasin water diversions mediating transfers of fishes such as those representatives included as biota of concern from the Missouri River to the Red River basin would be less likely to be a problem than transfers yielding other biota, e.g., propagules of invasive plants or microbiological agents already established in the Red River basin (see Table 8). Some of those species, e.g., pallid sturgeon, although identified as species of concern by other investigators 20 to 25 years ago (Swain et al. 1980), present little risk to receiving waters in the Red River basin in view of the species' current plight in maintaining populations in waters of the Missouri River.

While fishes consistently presented relatively low categorical scores relative to other biota of concern (Table 8), risks associated with fishes vary across species in line with each species' life history attributes favoring their being successful invaders. For example, of those fishes identified as biota of concern in the current investigation, Asian carp (e.g., bighead carp) appears the mostly likely fish species to present other than low risk to the Red River basin. Top ranking scores of biota of concern summarized in Table 8 are dominated by species already present in both the Missouri River and Red River basins, but the highest ranking "nonresident" that presents risk of invasion is bighead carp (and by extension, other Asian carp; see Appendix 3A). Projected species distributions generated by GARP suggest that bighead carp and other exotic carps originating from Asia may be successful at establishing sustainable populations in the Red River basin, if pathways are completed, linking Missouri River sources with receiving waters. These completed pathways, however, are not limited to those realized in the event of an interbasin water diversion (see Section 4).

Based on outcomes of the categorical analysis, but recognizing our inability to project potential species distributions using GARP, other fish species identified as biota of concern—especially, Utah chub, paddlefish, zander and by extension, those fishes presenting life history

attributes similar to these fishes—would appear to present relatively low risks for invasion of Red River basin via interbasin water diversions, given their current status and distribution (see Appendix 3A). In contrast, rainbow smelt and gizzard shad present marginally higher rank categorical scores (Table 8), suggesting their potential as species of concern to the Red River basin exceeds that of zander, Utah chub, paddlefish, and pallid sturgeon. Projections of potential species distributions suggest that gizzard shad may be less problematic than rainbow smelt, which is consistent with each species current status and distribution (see Appendix 3A).

Of biota of concern identified by Reclamation and Technical Team, the fishes appear to present the least risk of becoming problematic as collateral transfers realized consequent to an interbasin water diversion. Depending on implementation of the proposed water diversion (e.g., open conveyance *vs* closed conveyance of treated waters; see Section 4), risks associated with fishes would appear to become less an issue to resource managers when greater control is practiced in the implementation, especially in light of those biota of concern that would challenge a highly managed diversion with multiple-step control technologies in place (see Section 4).

Table 11. Grass carp (*Ctenopharyngodon idella*) records from HUCs immediate adjacent to Rainy River-Red River-Souris River basin (HUC09).

State	County	Locality	Year	HUC Number	Drainage Name	Status
IA	Delaware	Delaware County	1987	07000000	Upper Mississippi	collected
IA	Linn	Linn County	1987	07000000	Upper Mississippi	collected
IA	Washington	Washington County	1987	07000000	Upper Mississippi	collected
IA	Lee	Lee County	1987	07000000	Upper Mississippi	collected
IA	Van Buren	Van Buren County	1987	07000000	Upper Mississippi	collected
IA	Jefferson	Jefferson County	1987	07000000	Upper Mississippi	collected
IA	Davis	Davis County	1987	07000000	Upper Mississippi	collected
IA	Monroe	Monroe County	1987	07100009	Lower Des Moines	collected
IA	Koekuk	Koekuk County	1987	07080000	Upper Mississippi-Iowa	collected
IA	Mahaska	Mahaska County	1987	07000000	Upper Mississippi	collected
IA	Tama	Tama County	1987	07080200	Iowa	collected
IA	Lucas	Lucas County	1987	07000000	Upper Mississippi	collected
IA	Wayne	Wayne County	1987	10280000	Chariton-Grand	collected
IA	Jasper	Jasper County	1987	07080100	Upper Mississippi-Skun	collected
IA	Story	Story County	1987	07000000	Upper Mississippi	collected
IA	Black Hawk	Black Hawk County	1987	07080000	Upper Mississippi-Iowa	collected
IA	Hamilton	Hamilton County	1987	07000000	Upper Mississippi	collected
IA	Winnebego	Winnebego County	1987	07000000	Upper Mississippi	collected
IA	Worth	Worth County	1987	07080200	Iowa	collected
IA	Kossuth	Kossuth County	1987	07100000	Des Moines	collected

Table 11. Grass carp (*Ctenopharyngodon idella*) records from HUCs immediate adjacent to Rainy River-Red River-Souris River basin (HUC09).

State	County	Locality	Year	HUC Number	Drainage Name	Status
IA	Warren	Warren County	1987	07100008	Lake Red Rock	collected
IA	Decatur	Decatur County	1987	10280100	Grand	collected
IA	Clarke	Clarke County	1987	00000000	>1	collected
IA	Madison	Madison County	1987	07000000	Upper Mississippi	collected
IA	Union	Union County	1987	10000000	Missouri	collected
IA	Adair	Adair County	1987	10280102	Thompson	collected
IA	Cass	Cass County	1987	10240000	Missouri-Nishnabotna	collected
IA	Pottawattamie	Pottawattamie County	1987	10000000	Missouri	collected
IA	Mills	Mills County	1987	10240000	Missouri-Nishnabotna	collected
IA	Montgomery	Montgomery County	1987	10240000	Missouri-Nishnabotna	collected
IA	Page	Page County	1987	10240000	Missouri-Nishnabotna	collected
IA	Taylor	Taylor County	1987	10240000	Missouri-Nishnabotna	collected
IA	Guthrie	Guthrie Weld County	1987	07100007	South Raccoon	collected
IA	Audubon	Audubon County	1987	10240000	Missouri-Nishnabotna	collected
IA	Monona	Monona County	1987	10230000	Missouri-Little Sioux	collected
IA	Woodbury	Woodbury County	1987	10230000	Missouri-Little Sioux	collected
IA	Ida	Ida County	1987	10230000	Missouri-Little Sioux	collected
IA	Sac	Sac County	1987	00000000	>1	collected
IA	Buena Vista	Buena Vista County	1987	00000000	>1	collected
IA	Plymouth	Plymouth County	1987	10000000	Missouri	collected

Table 11. Grass carp (*Ctenopharyngodon idella*) records from HUCs immediate adjacent to Rainy River-Red River-Souris River basin (HUC09).

State	County	Locality	Year	HUC Number	Drainage Name	Status
IA	O'Brien	O'Brien County	1987	10230000	Missouri-Little Sioux	collected
IA	Osceola	Osceola County	1987	10000000	Missouri	collected
IA	Lyon	Lyon County	1987	10170200	Big Sioux	collected
IA		Mississippi River	1987	07000000	Upper Mississippi	collected
IA		Missouri River drainage in Iowa	2002	00070600		unknown
IL	Randolph	Mississippi River near Chester	1971	07140105	Upper Mississippi-Cape	collected
IL	Randolph	Mississippi River near Chester	1971	07140105	Upper Mississippi-Cape	collected
IL		Mississippi River	1971	07000000	Upper Mississippi	collected
IL	Randolph	Mississippi River near Chester	1971	07140105	Upper Mississippi-Cape	collected
IL		Mississippi River up to Pike County	1979	07000000	Upper Mississippi	collected
IL	Clinton	Kaskaskia River, Pelican Pouch, about 4 mi. SSW Carlyle	1991	07140202	Middle Kaskaskia	collected
IL	Jackson	Big Muddy River at Rattlesnake Ferry	1992	07140106	Big Muddy	collected
IL	Alexander	Horseshoe Lake spillway (west side ditch) (Cache R. dr) 1.0 mi. E of Miller City	1993	07140108	Cache	collected
IL	Alexander	Horseshoe Lake (Cache R. dr) west arm and near dam	1993	07140108	Cache	collected
IL	Calhoun	Mississippi River, Pool 25, Cockerill Hollow Access at Batchtown, RM 243.5	1993	07110004	The Sny	collected

Table 11. Grass carp (*Ctenopharyngodon idella*) records from HUCs immediate adjacent to Rainy River-Red River-Souris River basin (HUC09).

State	County	Locality	Year	HUC Number	Drainage Name	Status
IL	Alexander	Horseshoe Lake, Cache River drainage, at spillway, ditch, west side, flooded ditch	1993	07140108	Cache	established
IL		Illinois River, river mile 157.8	2000	07130003	Lower Illinois-Lake Chautauqua	collected
IL		Illinois River, river mile 157.8	2000	07130003	Lower Illinois-Lake Chautauqua	collected
IL		Illinois River, river mile 157.8	2000	07130003	Lower Illinois-Lake Chautauqua	collected
IL		Illinois River, river mile 157.8	2000	07130003	Lower Illinois-Lake Chautauqua	collected
IL		Illinois River, river mile 157.8	2001	07130003	Lower Illinois-Lake Chautauqua	collected
IL		Illinois River, river mile 157.8	2001	07130003	Lower Illinois-Lake Chautauqua	collected
IL		Illinois River, river mile 157.8	2001	07130003	Lower Illinois-Lake Chautauqua	collected
IL		Illinois River, river mile 157.8	2001	07130003	Lower Illinois-Lake Chautauqua	collected
IL		Illinois River, river mile 157.8	2001	07130003	Lower Illinois-Lake Chautauqua	collected
IL		Illinois River, river mile 157.8	2001	07130003	Lower Illinois-Lake Chautauqua	collected
MI	Newaygo	Little Muskegon River (?) [See Atlas]	1980	04060102	Muskegon	collected
MI		St. Clair-Detroit drainage	1980	04090001	St. Clair	collected
MI		southeastern Lake Michigan drainage	1980	04060200	Lake Michigan	collected
MN		Mississippi River, lower portion in MN	1971	00070400		unknown
MN	Winona	pond near the Mississippi River near Winona, pond overflows into	1977	07040003	Buffalo-Whitewater	extirpated

Table 11. Grass carp (*Ctenopharyngodon idella*) records from HUCs immediate adjacent to Rainy River-Red River-Souris River basin (HUC09).

State	County	Locality	Year	HUC Number	Drainage Name	Status
		Gilmore Creek, which in turn flows into Lake Winona				
MN		upper St. Croix River	1982	07030001	Upper St. Croix	collected
MN	Kanabeck/ Aitkin	Snake River	1982	07030004	Snake	collected
MN		lower Mississippi River drainage	1991	07040000	Upper Mississippi-Blac	collected
MO	Perry	Mississippi River near Chester	1971	07140105	Upper Mississippi-Cape	collected
MO	Cole	Missouri River near Jefferson City	1973	10300102	Lower Missouri-Moreau	collected
MO		Mississippi River	1974	00000000	>1	collected
MO		Missouri River	1974	10300000	Lower Missouri	collected
MO		St. Francis River	1974	08020200	St. Francis	collected
MO		Mississippi River whole length of border	1975	00000000	>1	collected
MO		Missouri River - whole distance through state	1975	10300000	Lower Missouri	collected
MO	Cole	Moreau River 2, 4, and 8 km from mouth	1987	10300102	Lower Missouri-Moreau	established
MO	Callaway	Auxvasse Creek, 2, 4, and 8 km from mouth	1987	10300102	Lower Missouri-Moreau	established
MO	Carroll	ditch off of river (tributary of Missouri River floodplain), Norbourne, MO	1989	10300101	Lower Missouri-Crooked	established
MO	Miller	Osage River at Osage Beach	1994	10290111	Lower Osage	collected

Table 11. Grass carp (*Ctenopharyngodon idella*) records from HUCs immediate adjacent to Rainy River-Red River-Souris River basin (HUC09).

State	County	Locality	Year	HUC Number	Drainage Name	Status
MO		Osage River	1998	10290100	Osage	established
MO		Mississippi River	1998	00000000	>1	established
MO		Mississippi River	1998	00000000	>1	established
MO		Missouri River	1998	10300200	Lower Missouri	established
MO		Missouri River	1998	10300100	Lower Missouri-Blackwa	established
ND	Barnes	Sheyenne River, Barnes County (probably Lake Ashtabula)	1980	09020200	Devils Lake-Sheyenne	collected
ND		non-specific	1994	00000000	>1	collected
ND	Stutsman	Spiritwood Lake, 20 miles N of Jamestown	1998	10160003	Upper James	stocked
NE		non-specific	1984	10000000	Missouri	collected
NE		Missouri River	1998	10240000	Missouri-Nishnabotna	collected
NE		Missouri River	1998	10230000	Missouri-Little Sioux	collected
NE		Platte River	1998	10200200	Lower Platte	collected
SD	Union	Missouri River, Lewis and Clark Lake	1980	10170101	Lewis and Clark Lake	collected
SD		non-specific	1994	00000000	>1	collected
WI		eastern Wisconsin	1975	04000000	Great Lakes	collected
WI		southern Wisconsin	1975	07000000	Upper Mississippi	collected
WI	La Crosse	La Crosse	1984	07040006	La Crosse-Pine	collected
WI	Waukesha	Oconomowoc Country Club near	1990	07090001	Upper Rock	extirpated

Table 11. Grass carp (*Ctenopharyngodon idella*) records from HUCs immediate adjacent to Rainy River-Red River-Souris River basin (HUC09).

State	County	Locality	Year	HUC Number	Drainage Name	Status
		Oconomowoc				
WI	Waukesha	Edgewood Country Club near Edgewood on Pewaukee Lake	1990	07120006	Upper Fox	extirpated
WI	?	Abbey Springs Country Club, WI	1990		?	extirpated
WI	Waukesha	Westmoor Country Club	1990	07120006	Upper Fox	extirpated
WI	Dane	Blue Mound Country Club	1990	07090004	Sugar	extirpated
WI	Milwaukee	Tuckaway Country Club	1990	04040003	Milwaukee	extirpated
WI	Washington	West Bend Country Club	1990	04040003	Milwaukee	extirpated
WI		non-specific	1992	00000000	>1	collected
WY		lakes and ponds east of the Continental Divide (Missouri drainage)	1994	10000000	Missouri	collected
WY		found in lower elevation lakes, resevoirs, and ponds east of the Continental Divide	1994	10000000	Missouri	collected

Table 12. Silver carp (*Hypophthalmichthys molitrix*) recorded in the HUCs immediately adjacent to Rainy River-Red River-Souris River basin (HUC09).

State	County	Locality	Year	HUC Number	Drainage Name	Status
IL		Illinois River, river mile 157.8	2000	7130003	Lower Illinois-Lake Chautauqua	collected
IL		Illinois River, river mile 157.8	2000	7130003	Lower Illinois-Lake Chautauqua	collected
IL		Illinois River, river mile 157.8	2000	7130003	Lower Illinois-Lake Chautauqua	collected
IL		Illinois River, river mile 157.8	2000	7130003	Lower Illinois-Lake Chautauqua	collected
IL		Illinois River, river mile 157.8	2001	7130003	Lower Illinois-Lake Chautauqua	collected
IL		Illinois River, river mile 157.8	2001	7130003	Lower Illinois-Lake Chautauqua	collected
IL	Monroe	Mississippi River, RM 160 at Merrimac	1990	7140101	Cahokia-Joachim	collected
MO	Scott	Mississippi River, 16 river miles south of Cape Girardeau	2001	7140105	Upper Mississippi-Cape Girardeau	established
IL	Jackson	Big Muddy River at Rattlesnake Ferry	1994	7140106	Big Muddy	collected
MO		Headwater Diversion Channel (Castor River, Cape Girardeau County)	1998	7140107	Whitewater	established
IL	Alexander	Horseshoe Lake (Cache R. dr)	1994	7140108	Cache	established
IL	Alexander	ditch at Horseshoe Lake, 0.25 mi W of spillway on Promised Land Road	1995	7140108	Cache	established
NE		nonspecific (probably Missouri River)	2000	10000000	Missouri	collected
SD	Yankton	James River, at the mouth [~4 mi E of Yankton, SD]	2003	10160011	Lower James	observed
SD		Missouri River below Gavins Point dam	2003	10170101	Lewis and Clark Lake	established
NE	Dodge	Elkhorn River near Dead Timber State Recreation Area [~3 mi NW of Scribner, NE]	2003	10200202	Lower Platte	collected
MO		Missouri River	1998	10300100	Lower Missouri-Blackwa	established
MO		Missouri River	1998	10300200	Lower Missouri	established

3.4.2 Narrative analysis: Aquatic invertebrates. While lists of invertebrate fauna are available for larger geographic settings (e.g., Pennak 1953, 1978; Smith 2001; Higgins and Thiel 1988; Thorp and Covich 2001), regional catalogs for aquatic invertebrates that are comparable to those available for fishes are relatively limited taxonomically, spatially, and historically (e.g., historical accounts such as Young 1924 and contemporary catalogs such as Cvancara 1983 available at http://www.npwrc.usgs.gov/resource/inverts/mollusks/mollusks.htm, and Kondratieff 2000 at http://www.npwrc.usgs.gov/resource/distr/insects/mfly/nd/toc.htm). Hence, in our current investigation the selection of zebra mussel, New Zealand mudsnail, and Asian clam clearly focused our analysis on exotics that have a history solely linked to past invasions from outside North America. As evident by the current status of these representative biota (see Appendix 3A), once established in North America, each species has followed a typical path of invasiveness, relying on diffusion and stratified diffusion processes, and their inclusion as biota of concern serves to illustrate the potential risks realized by linkages between surface waters within and between watersheds at various spatial scales.

Interpretation of risks associated with aquatic invertebrates potentially transferred collaterally with interbasin water diversion. As indicated by each species' rank score in the categorical analysis, these exotic mollusks each present a moderate risk for invasion of Red River basin, although as with the fishes, the emigration to the region need not reflect sole dependence on the realization of water diversions between the Missouri River and Red River basins. Based on their rank scores, zebra mussel and Asian clam appear to present similar invasion risks, with zebra mussel—in the absence of jump events serving to link insular occurrences of the species across a disjunct distribution—apparently nearing its northern and western distributional limit as projected by GARP (Figure 12 and Figure 13, but see Section 4, especially the analysis of uncertainty). And given the current status of the Asian clam in North America, there is little reason to minimize the interpretation of risks associated with that species dispersal and spread to surface waters of the Red River basin, provided pathways linking the basin with sources are completed (see Appendix 3A).

Although later in its arrival to North America than zebra mussel or Asian clam, New Zealand mudsnail may present greater risk of invasion to Red River basin than either of the earlier arriving mollusks, in part, because of the species' life history and capacity to reproduce parthenogenically (Winterbourn 1970a,b; Foltz et al. 1984; Hauser et al. 1992; Hughes 1996). New Zealand mudsnail has effectively spread throughout the western US via diffusion and stratified diffusion processes (see http://www.esg.montana.edu/aim/mollusca/nzms/), and has been

observed in waters of the Great Lakes during its relatively short time in North America (Zaranko et al. 1997; see Appendix 3A). There is little reason to doubt its future success at establishing beachheads in other locations throughout the continent, as indicated by its projected species distribution (Figure 14 and Figure 15). Again, future expansions of the species' distribution are not reliant on interbasin water diversions between Missouri River and Red River basins, although the implementation of that transfer of water may influence the time course of invasion as witnessed by the jump events that have promoted the species' spread in the western US.

Crustaceans such as spiny water flea and others (see Appendix 3A) are categorically considered low-to-moderate risks for invasion, in part because aquatic macroinvertebrates such as these are similar to the fishes in their reliance on human agency in their emigration to unoccupied areas. At present, spiny water flea does not occur in Red River basin, although its relatively widespread occurrence in the Great Lakes basin suggests that if vectors are available, then invasion potential would be heightened, since life-history attributes of spiny water flea (and other crustaceans included in Appendix 3A) provide the capacity to establish sustainable populations.

3.4.3 Narrative analysis: Aquatic vascular plants, and wetland and riparian vascular plants. The aquatic vascular plants, and wetland and riparian vascular plants included as biota of concern for the current investigation have a long invasion history throughout North America (see Appendix 3A). Again, the availability of regional floras sufficient to the calculation of potential distributions using GARP restricted this quantitative tool to spatial analysis for tamarisk, although hydrilla, Eurasian water milfoil, and water hyacinth each present well documented occurrence data at a state and county level (see Appendix 3A). As with the aquatic invertebrates, the current investigation relied on these exotic species and subsequently minimized problems associated with incomplete catalogs of North American flora (especially for georeferenced occurrence data) or the dynamic state of species distributions, especially under conditions influencing unaided expansions and contractions of species distributions (see Scott et al. 2002; Kareiva et al. 1993). Hence, our evaluation of invasion risks potentially associated with interbasin water diversions focused on species clearly not linked to North America as indigenous species, and serve as starting points to evaluate plant species characterized by life history attributes similar to representatives on the list of biota of concern (Section 1, Table 1).

Interpretation of risks associated with vascular plants potentially transferred collaterally with interbasin water diversion. Tamarisk, whether individual species of the genus (e.g., *Tamarix chinensis*, *T. aphylla*, *T. parviflora*, *T. ramosissima*) or hybrids, has a long history

of invasion throughout the western US, and has recently emigrated to the northern Great Plains, including riparian areas of North Dakota (see Appendix 3A). The categorical analysis summarized in Table 10 suggests tamarisk presents moderate risks, although its relatively recent emigration into North Dakota and the potential tolerance of northern latitudes and dry winters (see Pearce and 2002, 2003) may warrant additional analysis with respect to the species long-term sustainability. Spatial analysis derived from GARP suggests the current occurrence data support an expanded distribution including areas within the Upper Missouri River in North Dakota. Current projections do not predict expansion to the Red River basin (but see Appendix 4, especially uncertainty analysis).

Categorical outcomes suggest Eurasian (also referred to as "European") water milfoil and purple loosestrife rank as a high-risk species, primarily because populations are currently found in the Red River basin (see Appendix 3A). In the absence of effective control programs, dispersal beyond the species current distribution in the Red River basin is anticipated. As noted in Appendix 3A, the western and northern limits of distribution for hydrilla and water hyacinth may have been reached at latitudes of the northern Great Plains, which may preclude either of these species from establishing sustainable populations, since physiological constraints associated with latitudinal advance have been realized (e.g., reduced tolerance to low annual temperature). Seasonal outbreaks of either species, however, should not be ruled out in evaluating risks (see Section 4), especially given potential long-term system changes in riparian habitats and dynamic character of species distributions (Scott et al. 2002; Kareiva et al. 1993) and multiple pathways by which propagules may emigrate to the area of concern.

3.4.4 Narrative analysis: Diseases of fish and waterborne diseases. Appendix 3B provides summaries of the current status of each of the disease agents considered as biota of concern in this current investigation. To reinforce the observations in Section 1, not all these disease agents are potentially invasive species, since numerous species included as biota of concern occur in both Missouri River and Red River watersheds (see Section 1, Table 1). Serotypes of *Escherichia coli* and *Salmonella* spp. are cosmopolitan in their distribution throughout the northern Great Plains, and similarly, *Legionella pneumoniae* is tracked in Manitoba, North Dakota, and Minnesota as part of larger federal programs in Canada and US. *Cryptosporidium parvum* and *Giardia lamblia* occur in all areas of the Missouri River and Red River basins, as do the cyanobacteria included as biota of concern (*Anabaena flos-aquae*, *Microcystis aeruginosa*, and *Aphanizomenon flos-aquae*). For each of these representative biota of concern, detection of biota transfers would necessarily rely on comparisons of disease

occurrence as zoonoses or diseases of wildlife "before diversion" relative to "after diversion," outcomes that would characterize shifts in metapopulations of these disease agents associated with interbasin water transfers (see §3.5).

Interpretation of risks associated with fish diseases and waterborne diseases potentially transferred collaterally with interbasin water diversion. In contrast to these disease agents potentially expressing shifts in metapopulations between Missouri River and Red River basins, linkages between interbasin water transfers and the occurrence of *Myxosoma cerebralis*, *Polypodium hydriforme*, *Yersinia ruckeri*, and infectious hematopoeitic necrosis virus (IHNV) would more closely express an invasion reflected by the emergence of a disease not previously observed in the receiving basin. The current status of each of these disease agents is summarized in Appendix 3B, including records of locations of disease occurrence. Unlike the analysis of distribution completed for fishes using GARP, the evaluation of potential locations where disease agents could occur was completed using approaches similar to those applied by Peterson et al. (2002, 2003), wherein distribution of disease host was considered as a necessary and sufficient condition for evaluating potential distribution of disease agent.

To illustrate the analytical approach, georeferenced data were available to focus on rainbow trout as host of *M. cerebralis*, the causative agent of whirling disease. Given the potential distribution of rainbow trout (Figure 19 and Figure 20), *M. cerebralis* as the causative agent of whirling disease could potentially occur throughout the Upper Missouri and Red River basins. At present, whirling disease has been recorded in Montana and other states of the western US (see Appendix 3B) but has not been observed in waters of the Missouri River basin in North Dakota or the Red River basin. However, if rainbow trout were systematically introduced in sufficient numbers throughout the surface waters of the Missouri River watershed, e.g, in North Dakota or Manitoba, or the Red River basin of North Dakota, Minnesota, or Manitoba, and if these populations became established or were actively maintained through continued stockings, then presence of the tubificid intermediate host throughout the northern Great Plains would make the occurrence of whirling disease in the area nearly inevitable. The occurrence of whirling disease would likely be projected coincident with the host species once dispersal of the disease agent was realized (Figure 19 and Figure 20). Such a scenario is not dependent on any interbasin water diversions but is more dramatically affected by independently developed natural resource management plans focused on development of rainbow trout fisheries in the northern Great Plains.

Data were not sufficient to complete a similar host-disease agent linkage for other biota of concern, but outcomes of such analyses would likely yield similar results, if widespread occurrence of hosts (primary and intermediate, as necessary) were realized for disease agents considered as biota of concern in this or any future investigation of the spread of diseases of fish and wildlife, or zoonoses involving terrestrial vertebrates.

3.5 Shifts in metapopulations associated with biota transfers associated with water diversions

Reclamation and Technical Team acknowledged the potential for interbasin water diversions to influence existing local populations in Missouri River and Red River basins—hence, the inclusion of species that currently occupy both basins on the list of biota of concern. Species invasions are not the issue in this facet of the biota transfer issue, yet mechanistically, the process of dispersal via pathways directly related to proposed water diversions are similar, if not identical, to the initial events characteristic of an invasion that results in an expanded species distribution. Extensive works have been published (see Gilpin and Hanski 1991; Hanski and Gilpin 1997; Hanski 1999; Hanski and Gaggiotti 2004; Beissinger and McCullough 2002) which highlight an increasing focus on populations—microbial, plant, and animal—and the interrelationships among local populations that are mediated by dispersal events across various spatiotemporal scales (see Colbert et al. 2001; Bullock et al. 2002).

Conceptually, Hanski and Gilpin (1997) characterized metapopulations as populations that are spatially structured; that is, there are patches of habitat in which the species can successfully growth and reproduce. From any given species' perspective, much of the landscape serves as an uninhabitable matrix, and the metapopulation consists of an assemblage of local breeding populations linked by movements of individuals, e.g., through migration between local populations. Alteration of local population dynamics and genetics results from these interactions, and as a consequence of the spatiotemporal linkage of metapopulations, local populations have the capacity, e.g., to reestablish themselves following extinction of local populations. Such a characterization of metapopulation leads to the standard definition posited by Hanski and Gilpin (1991) wherein metapopulations are considered as a "system of local populations connected by dispersing individuals" and refines the original term coined by Levins (1969).

From a practical perspective, the technical issues involved in the analysis of altered metapopulatoin dynamics directly linked to interbasin water transfers consistently outpaced the data available for analysis. Appendix 3B identifies available data and resources capable of collecting data sufficient to the analysis, if future concern warrants the design of monitoring studies to track disease occurrence. For this initial foray into the evaluation of risks potentially realized consequent to interbasin water diversions, a range of tools from statistical time-series (see Anderson 1971; Hipel 1985; Chatfield 1995; Kedem and Fokianos 2002) and disease outbreak analysis (see Woodward 1999; Diekmann and Heesterbeek 2000; Kulldorff et al. 2004) were available, but a simple analysis of graphical and summary numeric data (see Appendix 3B) was applied to this preliminary evaluation. Provided data are sufficient to more rigorous analyses, such an analysis may be indicated in future iterates of the risk analysis process.

With the exception to data collected under the auspices of public health agencies, the current review of data collections available through public domain are not sufficient for a rigorous statistical analysis required to distinguish between sources of disease agents originating in the Missouri River basin and those originating from the Red River basin. Even those data collections from public health sources that were available for this effort limited the tools for the analysis. Hence, we opted for a relatively simple assemblage of available occurrence data (see Appendix 3B) and a brief narrative interpretation of risks from a technical perspective. In general, our inability to distinguish between sources of disease agents adversely affects our ability to evaluate baseline levels and adequately characterize initial conditions in an analysis wherein projections are required to characterize how past records of disease occurrence (e.g., existing populations and outbreaks associated with disease) relate to future events such as comparisons of disease occurrence “before diversion” *v.* “after diversion.” For example, state wide and province wide data available for microbiological, e.g., *Legionella pneumoniae* and apicomplexa disease agents, e.g., *Cryptospordium parvum* suggest that data are available within-agency to conduct the necessary baseline analysis to evaluate “before diversion” status, although data resolution, e.g., at a county level, does not easily fit into the current investigation’s watershed-based analysis. Nonetheless, design of monitoring studies to evaluate “after diversion” condition could be folded into the evaluation process.

Unfortunately, one limitation to such a straightforward analysis is the characterization of source, if disease outbreaks were observed “after diversion” were realized. Misassignment of cause is a highly likely outcome of such a simple analysis. The evaluation of cause-effect relationships—whether the focus is on the assessment of species invasions or shifts in

metapopulations—provides an example of how technical analysis fits into adaptive resource management (Walters 1986). Causes may be direct or indirect in their linkage to events related to biota transfers, and these linkages reflect conditions that influence the level of certainty associated with our conclusions of cause-effect relationship (see Section 4). Within an adaptive management context, characterization of cause may be captured by response and explanatory variables, and risk factors that influence the expression of response (or non-response, as it may be). Explanatory and response variables may be direct or indirect in their association with multifactorial systems being complicated by interactions among component factors that influence the expression of response (Figure 21).

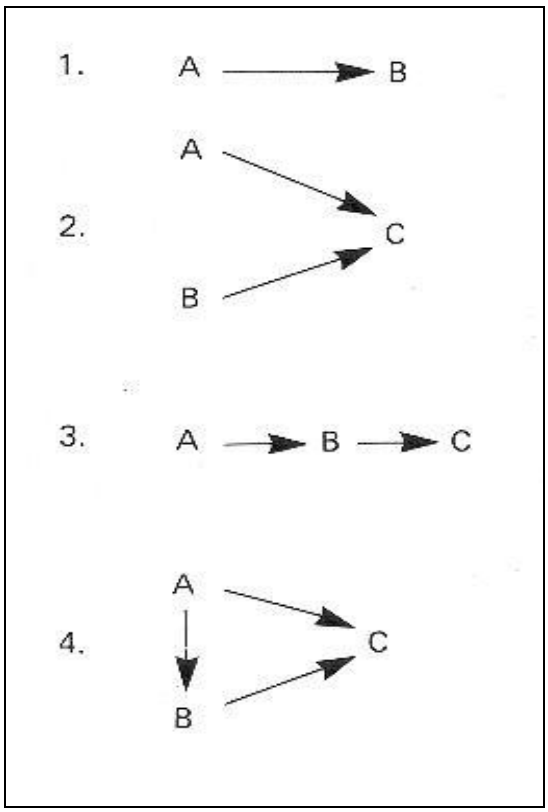

Figure 21. Simplified illustrations of direct and indirect causal relationships. In (1) A is the direct cause of B, while in (2) A and B are independent but both are direct causes of C. In (3) and (4), relatively simple multifactorial cases are illustrated. In (3) A and C are indirectly linked by B, which is the direct cause of C. A and B are direct causes of C in (4), although A may also occur as an indirect cause, if B serves as a contributing or intervening factor promoting C.

The degree of complication in multifactorial systems yields various categories of cause. For example, a frequent categorization of cause used in epidemiological studies characterizes factors as “necessary” or “sufficient.” These terms are most easily illustrated in simple systems, wherein a cause is sufficient, if it inevitably yields an effect. In multifactorial processes, such as disease, sufficient cause nearly always occurs as a set of interacting component causes, where one component is commonly described as the cause. A necessary cause must always be present to produce a specific effect (e.g., *M. cerebralis* must always be present for a diagnosis of whirling

disease). In contrast to whirling disease, many infectious and noninfectious diseases may be produced by different sufficient causes that may or may not have component causes in common. Uncomplicated infectious disease is frequently characterized by a disease agent that serves as a necessary cause, and in some instances, a factor may be necessary and sufficient, depending on the specific process being considered. In multifactorial processes such as those characteristic of environmental exposures, factors may be necessary, sufficient, neither, or both.

Component causes in a multifactorial system are generally characterized as predisposing factors, precipitating factors, reinforcing factors, and enabling factors. In characterizing failures in biological systems, predisposing factors are those that increase susceptibility (e.g., of a host to a disease agent). For example, the manifestation of disease in a host is frequently influenced by its immune status. A predisposing factor might be age of exposed individuals or the nature of a stream's substrate, since these factors may be critical to the development of whirling disease. Precipitating factors are those that are associated with the definitive onset of response but are not sufficient in the absence of a necessary cause (e.g., whirling disease may be precipitated by infection with *M. cerebralis* in sensitive species of trout). Reinforcing factors are those that aggravate the expression of response, which in the case of disease agents might be repeated exposures to the causative agent or a behavioral factor that exacerbates exposure. Enabling factors tend to be less clearly characterized than other categories of component factors, since enabling factors are those components of exposure that facilitate the expression of response (e.g., dry years may enable disease outbreaks to occur in wetland habitats that usually have a low incidence of disease, or reduced prey-base may enable disease outbreaks predicated on malnutrition of host).

Epidemiological cause-effect models approach ecological complexity when disease processes are considered within a field setting where multiple factors are a common feature of exposure. In such settings, simple linear models of cause-effect may be of limited use because multifactorial systems are characterized by component factors of varying intensity that interact at various levels in the system. These multifactorial systems are adaptive and highly dynamic, yielding a "web of causation" (e.g., Grenfell and Dobson 1995; Thrusfield 1995) similar in complexity to hierarchical ecosystems (e.g., Puccia and Levins 1985). Indeed, beyond simple cause-effect analysis focused on identification of a single disease-causing agent, exposures in the field must necessarily acknowledge the ever-present role of confounding factors that inevitably produce spurious associations among variables and potentially mask real cause-effect relationships.

As the brief overviews of biota of concern (Appendix 3A and Appendix 3B) suggest, source identification of species invasions is generally fraught with complications that impact the characterization of pathways and sources, especially at the local level or along a flow of events typical of the invasion process. While the country or region of origin for an invasive species may be easily resolved for an invasive species, the proximate cause linked to the species release to previously unoccupied areas may be difficult, if not impossible, to determine. To evaluate shifts in metapopulations consequent to an interbasin water diversion would likely be more intractable, given the data presently being collected as a routine measure of public health. The identification of cause would also be highly dependent on the design of the water distribution system serving the area where outbreaks were observed. These issues related to causal analysis and the identification of source are pervasive—whether the focus is on invasive species or shifts in metapopulations—and, as such, represent a source of uncertainty that may be deferred in deference to adaptive management plans that recognize where resources (e.g., as time and financial support for monitoring programs) are best allocated.

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4.0 Risk characterization and uncertainty analysis

Abstract. Synthesis and integration of results from risk analysis are the primary output for risk characterization. The analysis of risks supports management decisions regarding water resources in the northern Great Plains. When completed in parallel with an analysis of uncertainties associated with those risks, risk managers are better positioned to develop and implement resource management practices, e.g., technically evaluate alternatives as management options to reduce risks (see Wittenberg and Cock 2001; Downes et al. 2002). Characterizing risks associated with a specific management activity such as water diversions moves us toward weighing potential consequences of an event—here, a species invasion or shift in metapopulation dynamics of an organism—relative to a specific pathway and designing and implementing options to address those risks and associated consequences. The integration of ecological consequences potentially linked to future invasions or shifts in metapopluations was considered relative to the adverse effects that organisms might cause, and served as our "risk input" for subsequent economic analysis. Economic consequences were focused on biological and ecological effects, and in Section 5 these associated economic outcomes have been captured through an evaluation that focused on habitat equivalency analysis and collateral measures of economic effects. While categorical and quantitative estimates of risk were developed in Section 3 and are characterized with respect to their attendant uncertainties in this section, a narrative analysis of pathways and their potential risk derivatives has also been considered, with a particular focus on biota of concern lacking data sufficient to more quantitative estimates of risks.

Overall, risks of biota transfers varied across representative species of concern and followed a priority risk ranking as

Fishes << Aquatic invertebrates $\leq$ Aquatic and terrestrial-wetland plants < Waterborne disease agents $\leq$ Cyanobacteria

suggesting interbasin transfers of fishes would be least likely to occur; hence, risks would be very low. In contrast, transfers of waterborne disease agents and cyanobacteria (or their toxins) would be associated with greater risks, particularly if control systems were not incorporated into water diversion processes and infrastructure. Risks were greatest when interbasin water diversions were envisioned as being implemented via open conveyance and only slightly reduced if untreated waters were piped from exporting to importing basin. Greatest risk reduction was achieved when source waters were treated (e.g., using combined control technologies such as conventional water

treatment and pressure-driven membrane filtration) within the exporting basin, then transferred via closed conveyance (e.g., piped transfer) to importing basin.

4.1 Overview of Risk Characterization Process

The focus of the current investigation resolved on risks associated with pathways of invasion directly related to water transfers between Missouri River and Red River basins (e.g., as captured in Section 2, Figure 7), although characterizing biota transfers and potential invasions required characterization of competing pathways (e.g., as captured in Section 2, Annex Figure 1 through Annex Figure 5). In an effort to characterize risks within the context of the management approach fostered by the oversight of Reclamation and the Technical Team, the following section reflects an interpretative framework developed by National Invasive Species Council (NISC 2001). To minimize the potential for introduction of invasive species, NISC considered these principles as a foundation for characterizing risks:

- Pathway evaluation should be open and participatory, involving experts and stakeholders, since broad involvement conveys two benefits: more eyes examining the problem and greater credibility for the finished product.
- Management actions should be proactive and take advantage of opportunities available to natural resource professionals charged with managing risks associated with invasive species.
- Specific attention should be given to pathways that are not regulated yet afford significant opportunity for invasion to occur.
- Pathways should be evaluated periodically since risks associated with any particular pathway can change over time due to changes in magnitude (e.g., propagule pressure), changes in sending or receiving ecosystem, and other factors (e.g., other management practices inadvertently altering risks associated with water diversions).
- Given limited resources, costs of actions should be weighed against benefits to ensure cost-effective preventive measures are practiced in managing invasive species.

4.2 Overview of Interpretative Context for Evaluating Risks Associated with Biota Transfers Associated with Interbasin Water Diversions

As NISC (2001; see also http://www.invasivespecies.gov/) guidance recommends, the current investigation reflected a collaborative effort with Reclamation and the Technical Team in developing conceptual models as an outcome of problem formulation, particularly as those conceptual models related to identifying and prioritizing of pathways critical to the invasion process. For project-specific priority pathways such as those directly associated with water diversions, the analysis also focused on other pathways (i.e., intentional or unintentional) associated with introductions or observations of "first occurrence" in the Red River watershed, e.g., unintentional introductions of disease agents and other organisms that might accompany living plants and animals introduced intentionally (e.g., introduction of whirling disease as collateral event associated with intentional stocking programs for rainbow trout) as confounding sources influencing our characterization of risks. Because of incomplete catalogs of species indigenous to each basin of concern, the current investigation identified exotic species or species whose current and historic range clearly indicated a geographic separation of distribution from Missouri River and Red River watershed (HUC10 and HUC09, respectively). Hence, biota of concern represented introductions that initially were frequently linked to sources outside the US with subsequent movement of species between ecosystems within the North America. For those biota of concern present in both Missouri River (HUC10) and Red River (HUC09), an preliminary discussion of metapopulation analysis has been incorporated as part of the risk characterization, although insufficient population data required the analysis being qualitative in character.

Provided input from Reclamation and Technical Team during problem forumlation, a primary goal of the current investigation was identifying risk reduction tools that might minimize unintentional introductions of biota to Red River basin because of interbasin water diversion. Elimination of all risks of species invasion or altered metapopulation dynamics associated with interbasin water transfers may be a management goal, but attaining zero risks is technically "not going to happen" and is highly unlikely within the context of pathways and competing risks (e.g., water diversion pathway *v.* all other pathways). On the other hand, if "very close to zero" is acceptable risk, then such a guiding management objective could be achieved within the context of developing and implementing technical practices focused on prevention, and eradication and control. Regardless of management options of choice (e.g., within-basin water supply *v.* water attained through an interbasin water diversion), biological invasions may be inevitable given the number of trials recorded through time and across the spatial extent of HUC09 and HUC10; hence, control measures and eradication tools should be developed as part of mitigation plans that should be derivatives of the management process crafted in anticipation of invasive species issues. These issues go beyond the scope of this technical support effort, and indeed, beyond the scope of

Reclamation's and Technical Team's sole responsibilities. As such, the tools applied in the current investigation may be generalized beyond our limited scope and extended to other species of concern that present attributes similar to those of the biota of concern identified by participants in the current investigation.

4.3 Multiple Pathways and Their Role as Competing Risks

Although our focus resolved on the characterization of risks directly associated with interbasin water, in order to adequately interpret those risks, baseline or "before-project" characterizations necessarily had to be completed to place risks in context. All scenarios considered in risk analysis, regardless of their being project related or not, shared common shortcomings in comparing risks associated with various pathways serving to potentially link basins of primary concern, e.g., sparse empirical data related to observed frequencies of transfers and inadequately characterized failure rates for species establishment. The invasion biology literature is replete with "rules of thumb" based on field observations and "best professional judgments," (see Section 4.4), but there are very few fully characterized quantitative data needed to develop an empirically based probabilistic analysis of invasion events. However, the available data and existing literature is far from being woefully absent, given the historic and ongoing activities focused on topics of invasion biology reflected by concerns related to loss of biodiversity (see Stein et al. 2000).

The current investigation focused on pathways' characterization and risk rankings relative to biota transfer project and relied on a comparative analysis of both given the multiple pathways apparent (see Section 1, Figure 5 and Section 2, Annex Figure 1 through Annex Figure 5) and multiple entities identified as biota of concern. However, regardless the species of interest, the initial steps of biological invasion are highly dependent on pathways of introduction. NISC (2001) expended much effort to characterize pathways of invasion and developed a ranking of pathways into high, medium and low categories (see http://www.invasivespecies.gov/vectors/main.shtml). The current investigation's view of project and nonproject pathways (Section 2, Annex Figure 1 through Annex Figure 5) was similar to that NISC (2001) developed in its consideration of pathways and their relationship to the invasion process. In the current investigation, as well as in NISC's effort, pathways were assigned to categories as identified similar to those identified in Section 2 (see Annex Figure 1through Annex Figure 5). A quick review of those figures in Section 2 clearly indicates that from a system's analysis perspective, pathway features of the

invasion process, although spatially distinct (e.g., HUC10 *v.* other source areas), shared many common attributes, e.g., similar pathways are potentially serving as links between sources regardless their occurring in the Missouri River basin or not. NISC (2001) had recognized three generic pathway categories which are consistent with the categorical assignments that guided the current investigation:

- Transportation-related pathways including various pathways related to the transportation of people, goods, and the transport vehicles themselves (e.g., private and public sector, commercial, industrial, and military vehicles). Specific facets of the transportation category included modes of transportation and shipping materials.

- "Living industry" pathways including various pathways associated with living plants and animals or their by-products, e.g., food-to-market pathways, pathways related to transport of plants and animals, including commercial trade or exchange of plant and animals (such as plant and aquarium trade).

- Miscellaneous pathways were those considered outside the other categories and included various pathways related to other aquatic and terrestrial pathways, ecosystem disturbance, other nonliving animal and plant-related pathways, and natural (no human agency involved) dispersal of previously established populations of invasive species.

Implementing pathways' analysis for the current investigation focused our effort beyond the more global context of NISC, but attributes of pathways common to project and nonproject routes are identical to those identified by NISC (see http://www.invasivespecies.gov/vectors/main.shtml). For example, "Anthropogenic Pathways" (Section 2, Annex Figure 4; NISC terminology referred to pathways associated with "Human Agency") are a common feature to nonproject pathways that are potentially linked to biota transfers potentially yielding species invasions or shifts in metapopulations. Transportation-related pathways include various modes by which initial "beachheads of invasion" could be achieved. While any of those identified in the current investigation or by NISC could provide opportunity, aquatic pathways would be the most likely to prove instrumental in linking the Red River basin with Missouri River or other adjacent basins. For example, past analyses of aquatic routes likely associated with invasion processes (e.g., Carlton 1993; D'Itri 1997) clearly indicate that multiple vehicles of biota transfer are participating in large numbers of "trials" through time, e.g., ship and barge traffic on surface waters, recreational boats, and other craft on surface waters or in transit between bodies of water,

among other candidate modes of transit. The list is long, and from a competing risk perspective, the sum of these multiple aquatic pathways qualitatively decreases the probability of controlled interbasin water transfers from contributing significantly to the overall risk of invasion. Intensively controlled interbasin water transfer will likely not increase risk of species invasions and could actually reduce basinwide risks of species invasions, especially if control systems are incorporated into diversion system's design (e.g., multiple water treatment technologies employed in engineering design). With managed controls incorporated into water diversion systems, other water sources within HUC09 currently being exploited could be "replaced" with water derived from sources having designed controls in place to prevent or at least minimize biota transfers from waters of the Missouri River. If control systems constructed as part of the delivery system involved in interbasin water transfer complied with Safe Drinking Water Act (SDWA) as amended in 1996, including filtration to meet guidance for control of *Cryptosporidium* spp. as stipulated in Interim Enhanced Surface Water Treatment Rule (IESWTR) and Stage 1 Disinfectants and Disinfection Byproducts Rule, significant reduction in risks associated with interbasin water transfers could be realized. Water-user needs and water-supplier costs, however, may limit such implementation.

For the aquatic species represented on the current investigation's list of biota of concern, surface water-related modes of transportation initially contributed to establishing beachheads for invasion. Ballast water and its associated suspended sediments and other devices such as live wells were the likely pathways that linked distant sources (e.g., source areas for zebra mussel, *Dreissena polymorpha*; spiny water flea, *Bythotrephes cederstroemi*, were in Europe) to establishing beachheads and initial spread of the organism. In addition to promoting the advance of invasive species by serving as pathway for establishing initial beachheads, the current investigation also recognizes the ongoing role that aquatic pathways play in dispersal from points where beachheads have been successfully established. The dispersal of zebra mussel illustrates the role that anthropogenic-linked mechanisms of aquatic transport have played in enhancing the simple reaction-diffusion process of species dispersion, e.g., pathways linked to transport via boat hulls and surface fouling as it occurs on barges have contributed to stratified diffusion processes linked to first records of zebra mussels in the Missouri River basin (see Appendix 3A).

The "variations on theme" for aquatic pathways suggest that the number of candidate mechanisms and the number of trials completed in any given time interval, while not infinite, represent a sufficiently large number that breaches to system integrity should be anticipated. These breaches are inevitable, and overall risks of species transfers approach unity, even with a very low

number of successful transfers, given the very large number of trials occurring in time. For example, zebra mussel and other aquatic nuisance species whose invasions were originally linked to ballast water discharges illustrate the ability of "hitchhikers" and "stowaways" to establish beachheads that subsequently develop into sustainable populations of invasive organisms. Similarly, environmental matrices such as dredge spoils or sediments as source materials in depositional habitats have provided opportunity for a range of invasive plants and animals to become established in expanded distributions, frequently some distance from original home ranges (see NRC 2002a).

From an ecological perspective, the interrelationships between aquatic habitats and transportation systems configured through terrestrial habitats open numerous component pathways for invasive species or corridors to enhance shifts in metapopulations (see http://www.100thmeridian.org/). For example, road systems of various types have been developed (e.g., improved structures such as state and federal highways and bridges, unimproved structures such as secondary and tertiary roads, private roads) and provide for vehicular traffic potentially capable of transporting a wide range of biota, including hitchhiking or accidently stowed aquatic nuisance species (e.g., zebra mussel; see Buchan and Padilla 1999). Similarly, given development goals associated with implementation plans (e.g., increased tourism and travel-related business), collateral effects serving as indirect mechanisms promoting species transfers will potentially influence invasion potentials for biota of concern, as well as other "surprise" invaders (e.g., unanticipated locally, but well characterized from historic events or "new" invasive speces such as disease agents that previously have not been observed). For example, travelers and their associated gear (e.g., vehicles, baggage) potentially serve as biotic and abiotic vectors for disease. Similarly, public, commercial, and industrial transportation of animals (e.g., as companion animals or animals in-trade) and plants (e.g., unintended transport of invasive aquatic plants; see Maki and Galatowitsch (2004), or plant diseases with horticultural exchanges as recently witnessed by transmission of agent of sudden oak death, see http://kellylab.berkeley.edu/SODmonitoring/default.htm) present diffuse sources of risk of invasion.

Other living industry pathways identified by NISC would also serve to confound evaluations of linkages between interbasin water diversions and species invasions suspectedly associated with biota transfers. For example, given the past history of invasive events in North America, anthropogenic pathways related to food acquisition remain diffuse alternative routes whereby invasions occur, e.g., market-ready live, fresh, and frozen foods (animal or plant),

including stowaways and hitchhikers[1]. Parasites and pathogens associated with these food sources have been and will continue to be prominent sources of "founder populations" and other live animal (e.g., domestic livestock, game birds and potentially their associated disease organisms imported and transported throughout the US) and plant (e.g., fruits, vegetables, nuts, roots, seeds, edible flowers) foods. Regardless of the interbasin water diversions, alternate pathways linking sources with receiving systems will often be characterized by less control than some alternatives proposed for interbasin water diversions, and depending on the allocation of risks across competing pathways, overall risk of species invasions or shifts in metapopulations associated with water resources may be reduced, if diversion are implemented with sufficient control systems as part of the design.

Pathways that directly require biota as vectors may be highly diffuse, and may become more prominent when human agents are integral to pathway (see Taylor and Irwin 2004 and Erickson 2005 for interactions between invasions and economic activities of human enterprise as those related to exotic plants and aquatic nuisance species, respectively). For example, nonfood animal pathways are currently recognized as critical components in the invasion process, e.g., aquaculture from supplier to buyer (e.g., spanning distance from facilities where organisms are raised, transporting organisms from facilities to wholesale distributors, and to retail outlets). NISC also considered subordinate pathways nested as lower-level components in the invasion process (and referred to as "subpathways"), e.g., intentionally released (authorized or unauthorized) or escaped biota derived from aquaculture trade, hitchhikers that occurred on or in cultured organism (e.g., parasites and pathogens), and biota that occurred in water, food, growing medium, nesting or bedding. From a systems analysis perspective, the invasion process linked to the bait industry (recreational or commercial) would be similar to that for the aquaculture industry in both food and nonfood modes. Here, releases would involve in-trade bait organisms either intentionally (authorized or unauthorized) or unintentionally released (e.g., escaped or accidental), and hitchhikers associated with bait organisms (e.g., parasites and pathogens) or in water, food, growing medium, nesting or bedding, or organisms subject to transport.

Other human-agent dependent-pathways also contribute to misinterpretation of causal linkages between appearance of invasive species (e.g., observation of founder population) and source. For example, importation of nonfood, nonpet animals is widespread (e.g., introductions of

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[1] The term "hitchhiker" includes propagules of plants, animals, invertebrates, parasites, diseases, and pathogens, as suggested by NISC (2001).

game animals and introductions associated with entertainment such as zoos and public aquaria). Again, subpathways focused on nonfood, nonpet organisms subject to interstate or international trade may be intentionally released (authorized or unauthorized) or escaped, dispersed as hitchhikers (including disease agents such as parasites and pathogens) or in food or bedding material or transport media (e.g., water for aquarium trade). Similar mechanisms expedite plant invasions in both terrestrial and aquatic habitats, including importation of plants and sites or deliberate introductions of plants (e.g., botanical gardens, nurseries, landscaping facilities, research facilities, public and private plantings, and aquaria and water gardens; see Maki and Galatowitsch 2004). Other than whole plants, various plant propagules likely serve to establish beachheads, including seeds, belowground vegetative structures such as bulbs, culms, roots, and tubers, and aboveground structures such as cuttings and stems capable of adventitious rooting. Propagules of aquatic plants display a similarly wide range of reproductive structures capable of mediating founding events (see, e.g., Cronk and Fennessy 2001), and aquatic and terrestrial plants in-trade are subject to intentional release (authorized or unauthorized) or escape. Hitchhikers occur aplenty in all life forms (e.g., parasites and pathogens occurring on or in transport media such as potting soils and vermiculite, and for aquatic plants, in growing media and associated biofilms or packing material).

NISC recognized the role that interconnected waterways, including interbasin water transfers, potentially play in linking disjunct biota by creating pathways that promote species invasions (see http://www.invasivespecies.gov/vectors/main.shtml#pathways; Section 2, Annex Figure 5). History presents numerous examples that continue to be regional areas of concern when preventing or controlling species invasions becomes resource management issues, e.g., interconnected waterways (e.g., Chicago Ship and Sanitary Canal and links between Upper Mississippi and Great Lakes basins) and interbasin transfers (e.g., California Aqueduct and All American Canal in the southwestern US; see NRC 1992). These interconnected waterways may be considered derivatives of a larger set of ecosystem disturbances that reflect “short-term disturbances” that facilitate introduction (e.g., habitat creation, restoration, enhancement; forestry) and “long-term disturbances” that facilitate introduction (e.g., rights of way for utilities and transportation corridors such as roads and rail lines, land development including agriculture and logging practices, surface water management including dam construction and stream channelization).

From a technical perspective, one difficult problem to address has been, and will continue to be, distinguishing between dispersal directly or indirectly linked to “human agency” and

dispersal that occurs by a "natural process." While many dispersal events and the subsequent establishment of invasive species are strongly linked to human activities (e.g., Ruiz and Carlton 2003), distinguishing between these processes and the dispersal, establishment of sustainable populations, and continued spread of invasive species as a process not reliant on human intervention may present intractable, or costly, questions seeking answers. These costs may be even greater, if technical analysis of shifts in metapopulations is necessary for implementation of a water resource management plan. Examples of dispersal and species invasion occurring independently of human agency are numerous, including migratory events, movements of propagules and spread of previously established populations via water and wind currents (including movements of particulate materials such as dusts), unusual weather events (e.g., hurricanes), and spread as hitchhikers on migratory mammals and birds. Dispersal without the intervention of human agency has a long history (see MacDonald 2003; Bullock et al. 2002; Colbert et al. 2001). Such natural processes occur in the absence of human agency, and prior to human occurrence, were the drivers behind dispersal, establishment, and expansion of any species distributions before invasive species acquired their current sociopolitical and socioeconomic status.

With literally millions of species known worldwide, many more not described, and only a handful of those fully characterized with respect to their life history (UNEP-WCMC 2000), stakeholder concerns for "as yet to be identified," or unknown, invasive biota are understandable. Yet guiding environmental decisions and crafting policy based solely on epistemic uncertainty may not find wide acceptance, given perceived and actual societal needs for water resources. Recognizing this recurring resource management issue related to "managing in the face of uncertainty" (see, e.g., Walters 1986), NISC developed the National Invasive Species Management Plan with contingencies in place to address such issues (NISC 2001). For example, NISC's Pathways Task Team developed a process to "implement a system for evaluating invasive species pathways" (see Campbell and Kriesch 2003) focused on alternatives for addressing risks of invasive species as yet identified or poorly characterized under the auspices of the Management Plan. Preferred pathways (or less frequently observed "pathways of opportunity") and life history attributes characteristic of invasive species are highly linked, and in the absence of knowing which as yet unidentified species will become problematic, life history attributes may guide pathways analysis to prevent, or at least minimize, dispersal of any species into areas previously outside their current distribution.

Having determined that the data may not exist to rank species or pathways linking their current distributions with potential distributions, NISC developed a categorical approach evaluating any given species' potential to become invasive, owing to its life-history attributes and preferred (or opportunistic) pathways for dispersal. Pathway and life-history attributes were considered by NISC when it developed an approach to working with as "yet to be identified" invasive species, then folded into a categorical analysis similar to that completed during the current biota transfer study completed for Reclamation and stakeholders.

NISC guidance reflected the integration of pathways and species life-history attributes that were amenable to categorical analysis such as that effort completed in the current technical support activity. For any species, an integrated evaluation of pathways and species life history focused on (1) magnitude, (2) survivability during and subsequent to transport, (3) prospects for detection during transport, (4) serving as links to habitats compatible with species life-history attributes, (5) serving as links to habitats conducive to establishment of sustainable populations and continued expansion of species distribution, (6) relationships between source areas and receiving areas as those relate to historic and current distributions, as well as potential for continued expansion of species distribution, and (7) impacts of species, if invasion is successful. Once scoring was completed, NISC guidance suggests summing the scores to yield a total numerical score then dividing the total score by the number of questions answered (excluding "uncertain" answers from the total count). Their "average score" was then given an ordinal assignment between 1 and 5 (for NISC, these categories were "High;" "High-Medium;" "Medium;" "Medium-Low;" and "Low"), following a process similar to that detailed in Section 2, implemented in Section 3 and reported here in Section 4.

In an extension of their categorical analysis, NISC developed an "uncertainty factor" based on the number of "uncertain" responses scored in their integrated pathways life-history scoring system summarized in the preceding paragraph. NISC also characterized a "regulation modifier" that reflected the level of regulatory control over a specific pathway. The categorical analysis completed as part of this evaluation of risks did not include uncertainty factors or regulation modifiers in the scoring system yet considered these components in the following narrative analysis completed in conjunction with the categorical and spatial analyses. The analytical approach used in the current technical support effort is consistent with that developed by NISC and extended its categorical analysis by incorporating the predicted species distribution and the simple probability simulation study into the overall risk evaluation process.

4.4 Risks Associated with Potential Interbasin Biota Transfers Directly Associated with Water Diversions

As suggested by NISC and summarized in Section 3, competing pathways that are directly accountable for securing species invasions are numerous, yet our focus in this risk characterization lies with interbasin water transfers. That is, our initial quantitative estimates of risks associated with intrabasin biota transfers are concerned only with events directly linked to proposed water diversions between the Missouri River and Red River basin. These risks are considered relative to (1) baseline, which refers to the dynamic state of historic and future species invasions realized in the absence of water diversion and (2) competing risks, which refers to interrelated risks that are associated with direct linkages expressed via alternate routes (i.e., direct pathways other than interbasin water diversions). In Section 3, risk analysis generated results derivative to:

- categorical evaluations focused on ranking of biota of concern with respect to their becoming an invasive species (i.e., previously unrecorded, but discovered as a sustainable population in the Red River basin) or species experiencing apparent shifts in metapopulations (e.g., as disease outbreaks or distribution expansions for biota currently in Red River basin),
- predicted distributions for selected biota of concern that served as illustrations for the spatiotemporal processes operating for any potentially invasive species or species experiencing a shift in metapopulation dynamic, and
- quantitative estimates of risk derived from a simulation study based on a simple probability model that considered the flow of events that would yield interbasin biota transfers linked to water diversions from the Missouri River to the Red River basin.

In this risk characterization, these results are integrated and presented as summary "strength and weight of argument[2]" or "strength and weight of evidence" tables (Table 1 through Table 3) and supporting graphic summaries (Figure 1) that are the primary outputs of the section.

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[2]The term "argument" is used herein as "a reason given in proof. . .as an independent variable upon whose value that of a function depends."

Consistent with NISC (2001), scenarios identified in Section 3 (i.e., open-water, piped untreated-water transfers, piped treated-water transfers) were included as initial conditions wherein subsequent estimations of risk were characterized with a particular focus on project-related and competing pathways. Given the prospective role of resource management in water diversion proposals, summary lines of argument reflect assignment to one of five ranks (Table 1 through Table 3; Figure 1) resulting from an integration of quantitative estimates of scenario-dependent risks summarized in Section 3 (and supporting appendices) as (1) categorical risks and (2) instantaneous estimates of risk from simulation output. Overall risk categories in the summary lines of argument tables were characterized by ordinal assignments of risk as "very low," "low," "moderate," "high," and "very high" which were based on percentile values (see Appendix 4) reflected in Table 9 that accompanied Figure 1 in Section 3.

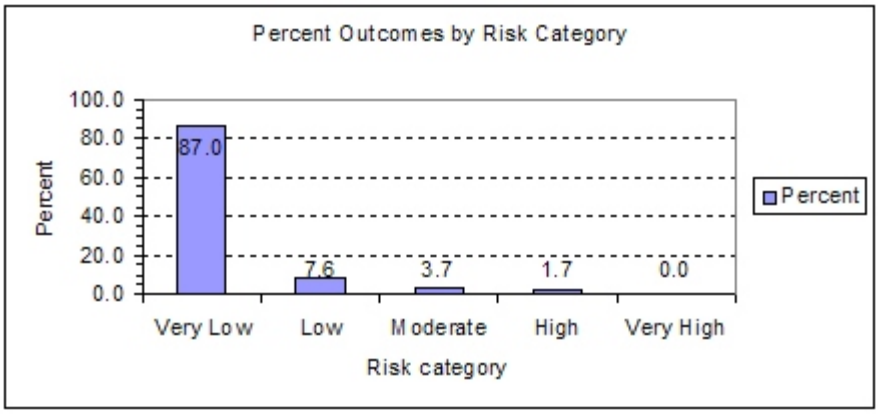

Figure 1. Categorical assignments of risk ranging from "Very low" to "Very high" derived from iterative analysis summarized in Section 3.

Outcomes of the simulation study are consistent with an existing "rule of thumb" that was originally posited on empirical data (see Williamson 1989; Williamson 1996; Williamson and Fritter 1996) and referred to as the "tens rule" or "ten-ten rule." The "rule" was originally envisioned by members of the Scientific Committee on Problems of the Environment (SCOPE; see Drake et al. 1989) which focused on the ecology of biological invasions. As evidenced by biological invasions that have occurred in the past, SCOPE noted invasions tended to be initiated by stochastic events, which made the initiation of any particular invasion poorly predicted. Accordingly, SCOPE launched an approach wherein the study of invasions became statistical, characterizing the probability of outcomes for classes of invasions. One outcome of SCOPE's effort was a basic rule, the tens rule introduced in 1989 to estimate how frequently invasive species establish and how frequently they become "pests." While jargon has changed since the tens rule's conception, it suggests that 10% of feral or introduced species become established, and

10% of those established become pests or invasive species (per definitions of Executive Order 13112). Originally derived from an analysis focused on invasive plants, the rule is very rough. Definitions of species, e.g., is the species invasive, and is it considered a pest, influence deviation from the tens rule, since human perception rather than ecological effects shape not only the endpoint but also the interpretation of available data. Nonetheless, studies on various biota have shown that the tens rule applies to a variety of groups (Williamson 1996). There are also cases in which the tens rule, or component steps among the flow of events yielding a tens-rule output, clearly do not hold, so observation of contrary outcomes suggests the tens rule needs to be interpreted with caution (see Hulme 2003). Hence, our current understanding of the tens rule may largely be phenomenological rather than mechanistic, as suggested by recent efforts to evaluate the invasion process and predictive tools such as those applied in our current analysis of risks (see Jeschke and Strayer 2005).

Outcomes of the simulation study, however, appear consistent with the tens rule, given 87% and approximately 8% of outcomes are characterized as very low to low risk, respectively. Yet, the remainder of outcomes (approximately 5–10%) clearly indicate the potential for invasions to occur. While the current investigation found data sufficient to categorize each of the biota of concern with respect to their overall risk of invasion directly associated with interbasin water transfers, we were unable to quantitatively compare competing risk scenarios related to transfers via alternative pathways. The inability to complete a strictly quantitative comparison between "project risks" and "not-project risks" (e.g., statistical comparison between alternatives) stemmed from two interrelated primary factors.

One, quantitative empirical data were insufficient (e.g., small sample size) to adequately characterize frequencies associated with nodes within a given nonproject scenario's flow of events. Such data insufficiency generally translated into an inability to use observed frequencies to characterize probabilities associated with transfers between steps in the invasion process regardless of efforts to collapse multiple-step processes into simpler systems (i.e., reduce granularity of risk scenarios). Two, developing a general process scenario focused on risk associated with project activities (e.g., open conveyance *v.* closed conveyance of treated water) was comparatively simple relative to alternative pathways (human agency or not), and empirical data supporting this general scenario, although sparse, were available for an interpretation of risks associated with "project" activities such as failures (e.g., breaks in distribution pipeline and limits of filtration technologies proposed as alternatives in control systems designed to implement water diversions). While simulation data served the purpose for these comparisons of relative risk (see

Section 4.10.2), insufficient quantitative data were available from the existing literature and public-domain sources to warrant statistical comparisons.

Numerical outcomes of risk scenarios summarized in Table 1 through Table 3 (see also Appendix 13) reflect biota transfer processes potentially yielding an invasion or shift in metapopulations. While overall risks are summarized within the context of broad groups of related scenarios in those tables (i.e., open conveyance, piped and untreated, piped and treated), depending upon the uncertainties associated with any given scenario within a particular broad group (such as "risk associated with specific biota of concern acting within an open conveyance" or "risk associated with specific biota of concern acting within a piped and treated conveyance"), risk management will necessarily be pursued given that some scenarios may represent "suspect situations." Suspect situations are those where a pathway may be variably active within the context of competing risks, but sufficient information confers less confidence in its assignment to a particular risk category. This concept of "suspect situation" is consistent with NISC guidance (NISC 2001; see supporting guidance at http://www.invasivespecies.gov/) and reflects the influence of uncertainty in assessing and managing risks.

Given the integration of outputs from the categorical analysis, the simulation study, and the spatial analysis focused on predicted distributions of selected biota of concern, we can identify a prioritized list of biota classes and the risks they display, if interbasin water diversions are realized. In general, risks displayed by biota of concern follow the general course

Fishes << Aquatic invertebrates $\leq$ Aquatic and terrestrial-wetland plants < Waterborne disease agents $\leq$ Cyanobacteria.

The generalized characterization of lowest risks being presented by fishes reflects, in part, the selection of representative biota of concern, especially given life history attributes characteristic of those species identified as biota of concern by Reclamation and Technical Team. Of those fishes identified as biota of concern, the composite group—Asian carp (including bighead carp, black carp, and silver carp)—would better be characterized as presenting risks as great as those presented by aquatic invertebrates included in the list of biota of concern. For example, when considering life-history attributes of bighead carp and zebra mussel, risks of invasion have more similarities than differences (see Appendix 3A). Both these exotics present less risk than New Zealand mudsnail, primarily because the latter is parthenogenic and could successfully invade previously unoccupied habitat with fewer limitations related to reproductive attributes. Similar

Table 1. Biota of concern identified for analysis focused on biota transfers from Upper Missouri River basin to Red River basin (open-water transfer, e.g., via lined canals)

Risk ranking	**Very Low**	**Low**	**Moderate**	**High**	**Very High**
Risk estimate less than	**1.00e–09**	**1.00e–06**	**1.00e–03**	**1.00e–02**	**1.00e+00**
Microorganisms and Disease Agents:					
Protozoa and Metazoa					
Myxosoma cerebralis (Myxobolus cerebralis)	x	x?[1]	?[2]		
Polypodium hydriforme		x			
Cryptosporidium parvum *			x		
Giardia lamblia*			x		
Bacteria and viruses					
Enteric redmouth			x		
Infectious hemtopoietic necrosis virus (IHNV)			x		
Escherichia coli (various serotypes)*			x		
Salmonella spp. (including Salmonella species and serotypes associated with water-borne infectious diseases)*			x		
Legionella spp.(e.g., Legionella pneumoniae)			x		

Table 1. Biota of concern identified for analysis focused on biota transfers from Upper Missouri River basin to Red River basin (open-water transfer, e.g., via lined canals)

Risk ranking	**Very Low**	**Low**	**Moderate**	**High**	**Very High**
Risk estimate less than	**1.00e–09**	**1.00e–06**	**1.00e–03**	**1.00e–02**	**1.00e+00**
Aquatic plants and cyanobacteria:					
Cyanobacteria					
Anabaena flos-aquae*				x	
Microcystis aeruginosa*				x	
Aphanizomenon flos-aquae*				x	
Vascular plants					
Hydrilla (Hydrilla verticillata)			x		
Eurasian water-milfoil (Myriophyllum spicatum)			x	x?	
Water hyacinth (Eichhornia crassipes)			x		
Purple loosestrife (Lythrum salicaria)			x	x?	
Salt cedar (Tamarix spp.)			x	x?	
Aquatic invertebrates:					
Mollusks					
Dreissena polymorpha (zebra mussel)				x	
Corbicula fluminea (Asian clam)				x	
Potamopyrgus antipodarum (New Zealand mudsnail)				x	

Table 1. Biota of concern identified for analysis focused on biota transfers from Upper Missouri River basin to Red River basin (open-water transfer, e.g., via lined canals)

Risk ranking	**Very Low**	**Low**	**Moderate**	**High**	**Very High**
Risk estimate less than	**1.00e–09**	**1.00e–06**	**1.00e–03**	**1.00e–02**	**1.00e+00**
Crustaceans					
Bythotrephes cederstroemi (spiny water flea)				x	
Aquatic vertebrates					
Fishes					
Gizzard shad (Dorosoma cepedianum)		x	?	?	
Rainbow smelt (Osmerus mordax)		x	?	?	
Bighead carp (Aristichthys nobilis)		x	?	?	
Paddlefish (Polyodon spathula)	x	x?			
Palid sturgeon (Scaphirhynchus albus)	x	x?			
Utah chub (Gila atraria)		x			
Zander (Sander [Stizostedion] lucioperca)	x	?			

Table 1. Biota of concern identified for analysis focused on biota transfers from Upper Missouri River basin to Red River basin (open-water transfer, e.g., via lined canals)

Risk ranking	**Very Low**	**Low**	**Moderate**	**High**	**Very High**
Risk estimate less than	**1.00e–09**	**1.00e–06**	**1.00e–03**	**1.00e–02**	**1.00e+00**
Invasive biota associated with sludge disposal and indirect pathways associated with interbasin water transfers	?	?	?	?	?
Potential plant and disease organisms (plant, wildlife, and human)	?	?	?	?	?
Potential genetically manipulated organisms	?	?	?	?	?

Asterisk (*) indicates the organisms are not invasives, but may be transported via interbasin water transfer and have adverses impact on fish and wildlife or human health or adverse ecological effects.

[1]Assignment to risk category influenced by uncertainties greater than other biota rankings; hence, categorical risks represented by range bounded by low risk rank indicated by “x” and higher risk ranks indicated by “x?” and “?”.

[2]Speculative risk ranking based largely on non-quantitative narrative analysis as indicated by “?”.

Table 2. Biota of concern identified for analysis focused on biota transfers from Upper Missouri River basin to Red River basin (e.g., piped-water transfer).

Risk ranking	**Very Low**	**Low**	**Moderate**	**High**	**Very High**
Risk estimate less than	**1.00e–09**	**1.00e–06**	**1.00e–03**	**1.00e–02**	**1.00e+00**
Microorganisms and Disease Agents:					
Protozoa and Metazoa					
Myxosoma cerebralis (Myxobolus cerebralis)	x	x?	?		
Polypodium hydriforme		x			
Cryptosporidium parvum *			x		
Giardia lamblia*			x		
Bacteria and viruses					
Enteric redmouth			x		
Infectious hemtopoietic necrosis virus (IHNV)			x		
Escherichia coli (various serotypes)*			x		
Salmonella spp. (including Salmonella species and serotypes associated with water-borne infectious diseases)*			x		
Legionella spp.(e.g., Legionella pneumoniae)			x		

Table 2. Biota of concern identified for analysis focused on biota transfers from Upper Missouri River basin to Red River basin (e.g., piped-water transfer).

Risk ranking	**Very Low**	**Low**	**Moderate**	**High**	**Very High**
Risk estimate less than	**1.00e–09**	**1.00e–06**	**1.00e–03**	**1.00e–02**	**1.00e+00**
Aquatic plants and cyanobacteria:					
Cyanobacteria					
Anabaena flos-aquae*				x	
Microcystis aeruginosa*				x	
Aphanizomenon flos-aquae*				x	
Vascular plants					
Hydrilla (Hydrilla verticillata)			x		
Eurasian water-milfoil (Myriophyllum spicatum)			x	x?	
Water hyacinth (Eichhornia crassipes)			x		
Purple loosestrife (Lythrum salicaria)			x	x?	
Salt cedar (Tamarix spp.)			x	x?	
Aquatic invertebrates:					
Mollusks					
Dreissena polymorpha (zebra mussel)			x		
Corbicula fluminea (Asian clam)			x		
Potamopyrgus antipodarum (New Zealand mudsnail)			x		

Table 2. Biota of concern identified for analysis focused on biota transfers from Upper Missouri River basin to Red River basin (e.g., piped-water transfer).

Risk ranking	**Very Low**	**Low**	**Moderate**	**High**	**Very High**
Risk estimate less than	**1.00e–09**	**1.00e–06**	**1.00e–03**	**1.00e–02**	**1.00e+00**
Crustaceans					
Bythotrephes cederstroemi (spiny water flea)			x		
Aquatic vertebrates					
Fishes					
Gizzard shad (Dorosoma cepedianum)	x	?	?		
Rainbow smelt (Osmerus mordax)	x	?	?		
Bighead carp (Aristichthys nobilis)	x	?	?		
Paddlefish (Polyodon spathula)	x	?	?		
Palid sturgeon (Scaphirhynchus albus)	x	?	?		
Utah chub (Gila atraria)	x	?	?		
Zander (Stizostedion lucioperca)	x	?	?		

Table 2. Biota of concern identified for analysis focused on biota transfers from Upper Missouri River basin to Red River basin (e.g., piped-water transfer).

Risk ranking	**Very Low**	**Low**	**Moderate**	**High**	**Very High**
Risk estimate less than	**1.00e–09**	**1.00e–06**	**1.00e–03**	**1.00e–02**	**1.00e+00**
Invasive biota associated with sludge disposal and indirect pathways associated withinterbasin water transfers	?	?	?	?	?
Potential plant and disease organisms (plant, wildlife, and human)	?	?	?	?	?
Potential genetically manipulated organisms	?	?	?	?	?

Asterisk (*) indicates the organisms are not invasives, but may be transported via interbasin water transfer and have adverses impact on fish and wildlife or human health or adverse ecological effects.

[1]Assignment to risk category influenced by uncertainties greater than other biota rankings; hence, categorical risks represented by range bounded by low risk rank indicated by “x” and higher risk ranks indicated by “x?” and “?”.

[2]Speculative risk ranking based largely on non-quantitative narrative analysis as indicated by “?”.

Table 3. Biota of concern identified for analysis focused on biota transfers from Upper Missouri River basin to Red River basin (e.g., piped and treated water transfer).

Risk ranking	**Very Low**	**Low**	**Moderate**	**High**	**Very High**
Risk estimate less than	**1.00e–09**	**1.00e–06**	**1.00e–03**	**1.00e–02**	**1.00e+00**
Microorganisms and Disease Agents:					
Protozoa and Metazoa	x				
Myxosoma cerebralis (Myxobolus cerebralis)	x				
Polypodium hydriforme	x				
Cryptosporidium parvum *	x				
Giardia lamblia*	x				
Bacteria and viruses					
Enteric redmouth	x				
Infectious hemtopoietic necrosis virus (IHNV)	x				
Escherichia coli (various serotypes)*	x				
Salmonella spp. (including Salmonella species and serotypes associated with water-borne infectious diseases)*	x				
Legionella spp.(e.g., Legionella pneumoniae)	x				

Table 3. Biota of concern identified for analysis focused on biota transfers from Upper Missouri River basin to Red River basin (e.g., piped and treated water transfer).

Risk ranking	**Very Low**	**Low**	**Moderate**	**High**	**Very High**
Risk estimate less than	**1.00e–09**	**1.00e–06**	**1.00e–03**	**1.00e–02**	**1.00e+00**
Aquatic plants and cyanobacteria:					
Cyanobacteria					
Anabaena flos-aquae*	x?				
Microcystis aeruginosa*	x?				
Aphanizomenon flos-aquae*	x?				
Vascular plants					
Hydrilla (Hydrilla verticillata)	x				
Eurasian water-milfoil (Myriophyllum spicatum)	x				
Water hyacinth (Eichhornia crassipes)	x				
Purple loosestrife (Lythrum salicaria)	x				
Salt cedar (Tamarix spp.)	x				
Aquatic invertebrates:					
Mollusks					
Dreissena polymorpha (zebra mussel)	x				
Corbicula fluminea (Asiatic clam)	x				
Potamopyrgus antipodarum (New Zealand mudsnail)	x				

Table 3. Biota of concern identified for analysis focused on biota transfers from Upper Missouri River basin to Red River basin (e.g., piped and treated water transfer).

Risk ranking	**Very Low**	**Low**	**Moderate**	**High**	**Very High**
Risk estimate less than	**1.00e–09**	**1.00e–06**	**1.00e–03**	**1.00e–02**	**1.00e+00**
Crustaceans					
Bythotrephes cederstroemi (spiny water flea)	x				
Aquatic vertebrates					
Fishes					
Gizzard shad (Dorosoma cepedianum)	x				
Rainbow smelt (Osmerus mordax)	x				
Bighead carp (Aristichthys nobilis)	x				
Paddlefish (Polyodon spathula)	x				
Palid sturgeon (Scaphirhynchus albus)	x				
Utah chub (Gila atraria)	x				
Zander (Sander [Stizostedion] lucioperca)	x				

Table 3. Biota of concern identified for analysis focused on biota transfers from Upper Missouri River basin to Red River basin (e.g., piped and treated water transfer).

Risk ranking	**Very Low**	**Low**	**Moderate**	**High**	**Very High**
Risk estimate less than	**1.00e–09**	**1.00e–06**	**1.00e–03**	**1.00e–02**	**1.00e+00**
Invasive biota associated with sludge disposal and indirect pathways associated with interbasin water transfers	?	?	?	?	?
Potential plant and disease organisms (plant, wildlife, and human)	?	?	?	?	?
Potential genetically manipulated organisms	?	?	?	?	?

Asterisk (*) indicates the organisms are not invasives, but may be transported via interbasin water transfer and have adverses impact on fish and wildlife or human health or adverse ecological effects.

[1]Assignment to risk category influenced by uncertainties greater than other biota rankings; hence, categorical risks represented by range bounded by low risk rank indicated by “x” and higher risk ranks indicated by “x?” and “?”.

[2]Speculative risk ranking based largely on non-quantitative narrative analysis as indicated by “?”.

contrasts in life history could be expanded across these general taxon-based groupings, if greater resolution were necessary to develop or refine management policies.

This general pattern of risks likely to be expressed consequent to an interbasin water transfer would be consistent across the three general scenarios developed for this iteration, although the differences in risks between open conveyance and untreated, piped-water transfers *v.* piped-water transfers of Missouri River water treated within HUC10 would likely be marked. The greatest "margin of safety" and maximum risk reduction would be realized with interbasin water transfers implemented via piped transfers of source waters treated within the Missouri River basin (see also Section 4.10).

4.5 Risk Characterization for Fishes and Aquatic Invertebrates

Risks related to fishes or aquatic invertebrates included as biota of concern are summarized in Section 4.5.1. The paleoecological setting for the late Pleistocene and early Holocene which is necessary for characterizing transfer risks related to fishes and other biota of concern is provided as background in Appendix 18.

4.5.1. Risk characterization for fishes. Of those biota of concern identified by Reclamation and stakeholders on the Technical Team, the fishes and aquatic invertebrates provided a relatively data-rich source of existing information, including georeferenced locations for records of occurrence (e.g., FishBase, http://www.fishbase.org/ and similar data sources). Owing to the long-standing academic interest, historic and ongoing efforts by resource management agencies, and past interbasin water diversion studies, the current analysis benefitted from a diffuse collection of life history and distribution accounts (see Appendix 3A, Appendix 6, and Appendix 7) upon which the analysis of risk could be implemented quantitatively through a categorical and spatial analysis, which is summarized here as part of the narrative analysis of risks associated with potential transfers of fishes collateral to an interbasin water diversion between Missouri River (exporting source area) and Red River (importing receiving area). Placing our current snapshot of species distributions in ecological context requires a background in the dynamic character of biogeography (see Appendix 18).

As a consequent source of uncertainty, the focus of our current analysis must acknowledge that we do not presently, nor will be have in the near future, unanimous consent on the origins of "native fishes" of the northern Great Plains. Current snapshots of species distributions must be viewed within that context of uncertainty, which reinforces the strengths of our biota of concern including exotic fishes such as "Asian carp" that clearly have origins outside North America (Table 4).

Table 4. Fishes identified as biota of concern by Reclamation and Technical Team in collaboration with CERC.
Gizzard shad (*Dorosoma cepedianum*) Rainbow smelt (*Osmerus mordax*) Bighead carp (*Aristichthys nobilis*) Paddlefish (*Polydon spathula*) Palid sturgeon (*Scaphirhynchus albus*) Utah chub (*Gila atraria*) Zander (*Sander [Stizostedion] lucioperca*)

Risks of biota transfers and the potential for species invasions associated with fishes included as biota of concern range from "moderate" to "very low," depending on which species and scenario is considered. Of the fishes included as biota of concern, two species—paddlefish and pallid sturgeon—would likely present risks of practically zero, particularly in view of their current status in the Missouri River system. While neither species has records of occurrence in surface waters of the Red River, an open-water transfer as originally conceived in the 1970s may have yielded sufficient numbers of individuals (probably as early life-stage individuals) for a founding group to establish an invasion beachhead and subsequently develop a sustainable population. If a simple "fish screen" were used to secure the pathway created by an open-water transfer between Missouri River and Red River basins as intended in the 1970s, fishes would potentially present moderate to high risk. However, while the fishes included on the list of biota of concern in the current investigation are nearly identical to those fishes considered in historic reports focused on interbasin biota transfers 20 to 30 years ago, if current visions of water distribution control systems are implemented, e.g., control technologies identified to implement proposed transfers, risks of biota transfer associated with these fishes are low to very low. And given the changes in status of some fishes included as biota of concern, their current conservation plight unfortunately reduces biota transfer risks to practically zero. For example, pallid sturgeon

and paddlefish have been adversely affected by habitat loss and other factors contributing to population declines, and their characterization as biota of concern for future evaluations of interbasin biota transfer may not be warranted, given each species' current status[3]. Regardless of our current focus on interbasin water transfers, other fishes considered biota of concern in the current investigation are likely to become more problematic in the near future, e.g., bighead carp (and other "Asian carp" in Appendix 3A). Gizzard shad and rainbow smelt will continue to be of concern as far as their entering previously unoccupied areas in the area of concern whether interbasin water diversions are realized or not.

4.5.2 Characterization of risks associated with aquatic invertebrates. The paleoecological context briefly summarized in Appendix 18 applies equally to the influences that landscape changes played on the historic and current distribution of aquatic invertebrates. In contrast to the fishes, the available literature for native species or species of North American origins that occurred or currently occur in surface waters of Missouri River basin and Red River basin is characterized by relatively coarse-grained distribution records (e.g., familial-level compilations such as Pennak (1953, 1978), Smith (2001), Thorp and Covich (2001) or spatially restricted collections of particular taxonomic groups such as aquatic mollusks (see Cvancara 1983), mayflies (Kondratieff 2000), or the growing list of works focused on issues of biological diversity (see Wilson 1988 for background). However, those biota of concern selected by Reclamation and Technical Team (Table 5) afforded a relatively rich source of georeferenced occurrence data and life history characterization for the mollusks, and a categorical, spatial, and narrative analysis of risks was completed. For the representative crustacean, *Bythotrephes cederstroemi*, the analysis relied primarily on qualitative evaluations of risks, given the well-developed life-history characterizations and currently available occurrence data (Appendix 3A).

Aquatic invertebrates. Overall, these aquatic invertebrates serve as representatives of other species having similar life-history attributes. Risks associated with these biota ranged from high to moderate to very low, depending on the generalized risk scenario being considered (open-water, piped transfers of untreated source water, and treated water piped to Red River basin, respectively). The aquatic invertebrates most problematic in the near future are zebra mussel and

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[3]Pallid sturgeon (*Scaphirynchus albus*) was listed as an endangered species on September 6, 1990 (55 FR 36641) pursuant to the Endangered Species Act of 1973 (16USC 1531 et seq.) as amended; no critical habitat is designated for the species. Paddlefish (*Polydon spathula*) was listed as extirpated from Canada in1987; the species is variously listed by states within the US as threatened or species of special concern (see species account in Appendix 3A).

New Zealand mudsnail. The current distribution of the spiny water flea suggests limited opportunities to disperse from the Missouri River basin, although pathways other than interbasin water transfers may link source areas in the Great Lakes basin with suitable habitats in HUC09.

Table 5. Aquatic invertebrates identified as biota of concern by Reclamation and Technical Team members in collaboration with CERC
Mollusks
Dreissena polymorpha (zebra mussel)
Corbicula fluminea (Asian clam)
Potamopyrgus antipodarum (New Zealand mudsnail)
Crustaceans
Bythotrephes cederstroemi (spiny water flea)

From the spatial analysis presented in Section 3, both zebra mussel and New Zealand mudsnail are potentially invasive species that are likely to find suitable habitats in the northern Great Plains, including areas of North Dakota and Minnesota in the US and Manitoba and Ontario in Canada, if transit to these areas is achieved. Indeed, provincial records in the Great Lakes basin of Ontario are replete with species records for zebra mussel, and as a confounding source, invasions of Red River basin from these areas of Ontario may occur via diffuse pathways mediated by human agency (e.g., trans-basin movements of poorly decontaminated recreational watercraft; see Buchan and Padilla 1999). The time course of zebra mussel spread throughout North America is well documented, and its dispersal and subsequent establishment in the Missouri River basin continues (see also Section 3 and Appendix 3A).

Although its introduction followed that of zebra mussel by 10 to12 years, New Zealand mudsnail has been expanding its distribution within North America at a rate relatively similar to that of zebra mussel (see Section 3). As such, the forecast for these two species of mollusks is similar with respect to their risks of being transferred consequent to an interbasin water diversion. In open conveyance and in piped transfers of untreated waters, risks are categorically considered as high and moderate, respectively. If interbasin water transfers were implemented via piped transfers of waters in full compliance of SDWA as amended in 1996, those risks would lessen to very low, and competing risks would likely dominate any invasion process realized in the near

future. Regardless of the completion or interruption of water diversions, both zebra mussel and New Zealand mudsnail are forecasted as likely to be observed in the northern Great Plains, initially as outcomes of the stratified diffusion processes that contribute to the spread to suitable habitats in both Missouri River and Red River basins. GARP best subset projections for zebra mussel distribution suggests the 100th meridian may limit the species' distribution in the Great Plains, which has been independently forecasted by Drake and Bossenbroek (2004; but see Section 4.8.3). Through a combination of simple diffusive dispersal and stratified diffusion, as witnessed by the initial spread of zebra mussel in the Great Lakes basin and the initial events of New Zealand mudsnail's distribution expansion in the western US, these mollusks species may be successfully established as sustainable populations in the areas of concern in the next 5 to 25 years, depending on the role that stratified dispersal plays in the spread of the species.

4.6 Risk Characterization for Aquatic, Wetland, and Riparian Plants

Vascular plants have gained an increasingly large share of invasive species concerns (see http://aquat1.ifas.ufl.edu/welcome.html), and many recent efforts in developing tools to predict which species become invasive and where these species may become a problem have been published as guidance for resource management agencies facing the interrelated issues of invasive species and continuing loss in biodiversity (see Westbrooks 1998). Those plants identified by Reclamation and Technical Team (Table 6) focused on aquatic vascular plants (both submerged and emergent vegetation), and on wetland and riparian plants potentially spreading into the areas of concern. For Eurasian water-milfoil (*Myriophyllum spicatum*) and purple loosestrife (*Lythrum salicaria*), concern was focused on their expanding distribution beyond that already established in the Red River basin of North Dakota (see Appendix 3A for current distribution in North Dakota and Minnesota).

Aquatic vascular plants, riparian and wetland plants. Risks associated with plants potentially linked directly to interbasin water transfers present similar ranges of forecasted risks as other biota of concern. For aquatic vascular plants such as hydrilla and water hyacinth, risks are considered moderate for open-conveyance water transfers and transfers mediated by piped transfers of untreated waters, while Eurasian water milfoil would likely be characterized as high risk for furthering its expansion from locations already established in the Red River basin under both these risk scenarios. For interbasin water diversions accomplished via piped transfers of

waters treated in the Missouri River basin, risks would be very low for interbasin transfer of these aquatic vascular plants or species characterized by similar life-history attributes. In this latter case, piped-water treated in the Missouri River basin would not contribute propagules of Eurasian water-milfoil to contribute to the spread of the population currently established in the Red River basin.

Table 6. Aquatic vascular plants, and wetland and riparian plants identified as biota of concern by Reclamation and Technical Team in collaboration with CERC.
Hydrilla (*Hydrilla verticillata*) Eurasian water-milfoil (*Myriophyllum spicatum*) Water hyacinth (*Eichhornia crassipes*) Purple loosestrife (*Lythrum salicaria*) Salt cedar (*Tamarix* spp.; at least eight species have been listed as introduced into the US and Canada)

For those riparian and wetland plants included on the list of biota of concern—salt cedar and purple loosestrife, respectively—risks associated with interbasin water diversions would range from high to moderate to very low, depending on the risk scenario being considered. As with Eurasian water milfoil, purple loosestrife currently occurs in wetlands of the Red River basin, and additional propagule pressure stemming from an interbasin water transfer would be the primary issue for considering risks. For open conveyance and piped transfers of untreated waters, risks associated with purple loosestrife and salt cedar collaterally transferred during interbasin water diversions would range between moderate to high, although those risk categories reflect different technical sides of initial conditions characteristic of each species. For purple loosestrife, risks would primarily be reflected in increased numbers of individual propagules potentially contributing to increased expansions to the species current range in the Red River basin, while risks associated with salt cedar would reflect expansion of species distribution to previously unoccupied territory (see Appendix 3A).

Although calculating differences in risks between open conveyance and piped, but untreated waters requires greater specification in any proposed interbasin water diversion system, risks for interbasin biota transfers associated with open conveyance designs would be greater than piped interbasin transfers of untreated water designs, if those latter designs did not release

contained water to the environment, e.g., use Sheyenne River as part of the delivery system. In open conveyance systems, or in piped-systems moving untreated water across basin boundaries, interbasin transfers of salt cedar propagules would be characterized by high risks. Given the relatively recent arrival of salt cedar to the Missouri River basin (see Appendix 3A), the existing estimates of dispersal rate (see Section 3), and in the absence of interbasin water diversions, salt cedar will likely continue to spread via stratified diffusion throughout riparian areas of the Missouri River system in North Dakota, and within 25–30 years salt cedar will likely be observed in riparian habitats of the Souris River, Assiniboine River, and Red River (see Pearce and Smith 2002, 2003). In contrast to these less-engineered systems characterized by moderate to high risks, an interbasin water diversion accomplished using a control system involving multiple steps, e.g., pretreatment, treatment such as chloramination, and ultrafiltration, would yield very low risks of salt cedar or purple loosestrife propagules breaching the Missouri River-Red River boundary.

4.7 Risk Characterization for Fish diseases and Waterborne Diseases of Terrestrial Vertebrates

Biota of concern ranged widely from aquatic vertebrates, specifically fishes, to the agents linked to diseases of fishes that would potentially emerge as health concerns for the fisheries of the Red River basin, if an interbasin water diversion were realized (Table 7). To complement our analysis of risks associated with causative agents of fish disease, an analysis focused on causative agents of waterborne diseases generally associated with terrestrial wildlife and humans was completed in parallel using the same suite of analytical tools.

4.7.1 Fish diseases. While the spectrum of fish diseases far outreaches those species identified as biota of concern in this report (see Noga 1996; Hoffman 1999; Wolf 1988; Roberts and Shepherd 1997; Hoole et al. 2001), *Myxosoma cerebralis*, *Polypodium hydriforme*, *Yersina ruckeri*, and IHNV illustrate the process available to address any number of species that are currently recognized as causative agents of fish disease (in culture or in the wild), while supporting generalized interpretations of risks associated with disease-causing agents that potentially are transferred collaterally in water diversions.

Bacteria, cnidaria, and viruses of fishes. *Myxosoma cerebralis*, as the causative agent of whirling disease in salmonids, is currently a serious disease problem in many states of the western US, including neighboring Montana immediately west of North Dakota. In Montana and

throughout the range of the disease in the western US, whirling disease has caused declines in wild trout populations in previously highly productive trout streams such as the Madison River in Montana where nearly 90% of the rainbow trout population has been eradicated by whirling disease. Since its initial record of occurrence in Pennsylvania in 1956, *M. cerebralis* has been isolated and confirmed in disease outbreaks that have occurred in 21 states. This nearly 50-year time course suggests the life-history attributes of the disease agent ease the dissemination of the disease, provided primary (sensitive strains of salmonids) and intermediate hosts (*Tubifex tubifex*) occur in the prospective region of distribution expansion. For example, *M. cerebralis* presents highly resistant spores that can survive in the environment for 30 years before, if not immediately ingested by their intermediate host.

Table 7. Representative biota of concern linked to fish disease and disease of terrestrial vertebrates (including humans) and identified by Reclamation and Technical Team members in collaboration with CERC.

Diseases of Fish	**Microorganisms and Disease Agents of Terrestrial Vertebrates***
Protozoa, Hydrozoa, and Myxozoa *Myxosoma cerebralis* (*Myxobolus cerebralis*) *Polypodium hydriforme* **Bacteria and viruses** *Yersinia ruckeri* (Enteric redmouth) Infectious hemtopoietic necrosis virus (IHNV)	**Protozoa and Myxozoa** *Cryptosporidium parvum* * *Giardia lamblia** **Bacteria and viruses** *Escherichia coli* (various serotypes)* *Legionella* spp.* *Salmonella* spp. (including *S. typhi*, *S. typhmurium*, other serotypes associated with other water-borne infectious diseases)* **Cyanobacteria** *Anabaena flos-aquae** *Microcystis aeruginosa** *Aphanizomenon flos-aquae**
* indicates current distribution in both Missouri River and Red River basins.	

In characterizing risks potentially associated with *M. cerebralis* or any disease agent enlisted as biota of concern in this investigation, host distributions (primary and intermediate) are

equally critical to the evaluation. Risks of whirling disease must capture two necessary and sufficient conditions before being realized. The intermediate host, *T. tubifex*, is a commonly occurring aquatic oligochete and would likely not limit the spread of whirling disease if *M. cerebralis* traveled to Red River basin by means of any pathway. But the occurrence of primary host, a sensitive strain of salmonid such rainbow trout (*O. mykiss* Walbaum) in the areas of concern would strongly influence the extent to which risks of whirling disease was realized. In Minnesota, for example, rainbow trout were introduced and routinely stocked in Minnesota, starting in the late 1800s (Eddy and Underhill 1974). Eddy et al. (1972) characterized rainbow trout as "an important sport fish in the cool headwaters of the Clearwater River and streams tributary to Red Lake." Subsequent to their introduction, rainbow trout have been recorded throughout the Red River basin from the headwaters of the Tongue River and at various locations on the Turtle, Sheyenne, Red Lake, and Clearwater Rivers (Figure 9). Historically, the species has also been stocked in reaches of the Pelican and Buffalo Rivers (see Peterka and Koel 1996).

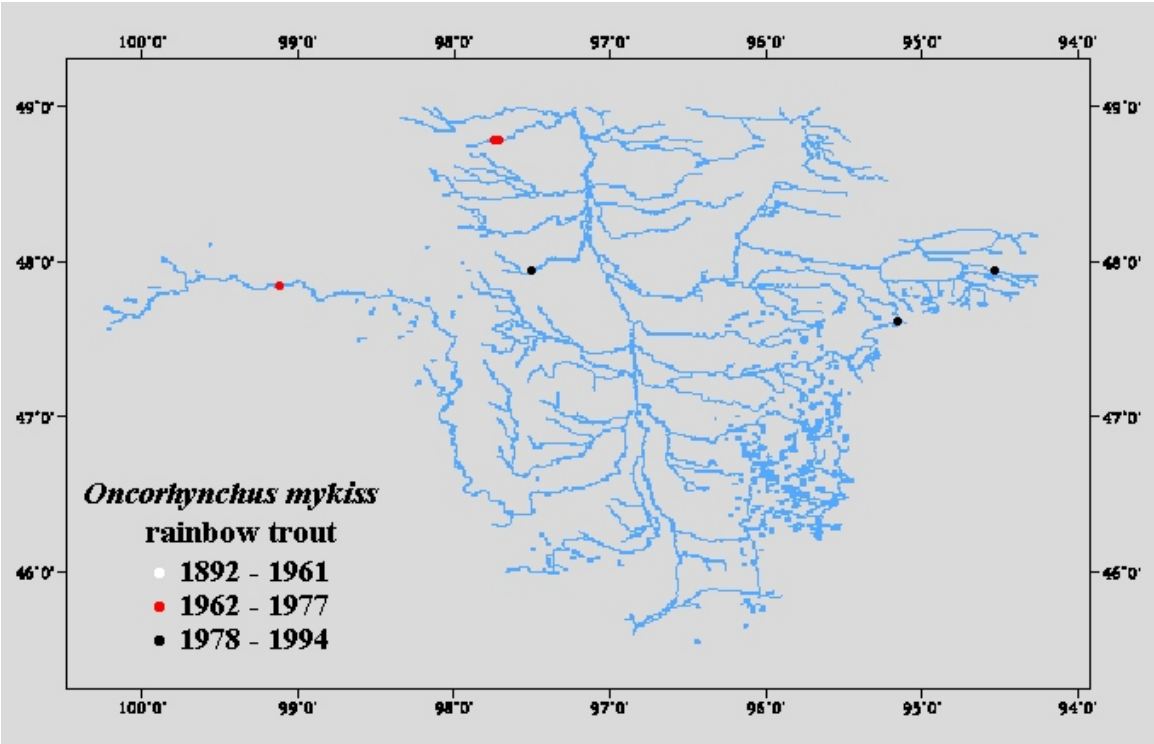


Figure 9. Distribution of the rainbow trout in streams of the Red River of the North basin (from Peterka and Koel 1996).

As summarized in Table 1 through Table 3, the risks associated with interbasin transfers of the causative agent of whirling disease vary across scenarios, although the uncertainty associated

with each scenario's outcome suggests that treated water transferred via pipeline would likely reduce risks greatest with lowest uncertainty (see Section 4.10). The relatively low-risk forecasts for an emergence of whirling disease in the Red River basin subsequent to water diversions accomplished via open conveyance and piped, untreated water scenarios stems from the apparently sparse rainbow trout fishery in the importing region. Unlike those areas of the western US (e.g., Montana and Colorado) where outbreaks have been well characterized and adverse impacts of the disease (including economic impacts associated with declining wild populations of rainbow trout), the receiving system has a relatively underdeveloped trout fishery. Given the relatively sparse prospective host population in the Red River basin, risks could be realized if resistant stages of *M. cerbralis* completed a successful transit from Missouri River waters to receiving waters of the Red River basin, but the possibility of an event is highly scenario dependent (e.g., if water is diverted via open conveyance, yet receives treatment for full compliance to SDWA, risks would remain low, but exposures to infective agent by receptive host, while water is in transit, preclude certainty in forecasts of low disease occurrence)—hence, the uncertainty reflected in Table 1 and Table 2. In contrast to water transferred via open conveyance or untreated water diverted via pipeline, water fully treated in facilities in the Missouri River basin to satisfy SDWA then passed through an ultrafiltration system prior to transfer would present negligible risks for transmission of causative agent of whirling disease (see Section 4.10). Risk estimates for conditions as specified would markedly reduce uncertainties associated with transmission of *M. cerebralis* and other disease agents potentially associated with interbasin water transfers that stem from Missouri River water sources. While "treatment" under the generalized scenarios considered in this analysis was not specified beyond full treatment to SDWA specificiations, given the intent to bound risks in this initial characterization, the control system yielding lowest risks would be one including multiple technologies with conventional pretreatment, chemical treatment, and ultrafiltration (see Section 4.10). A focus exclusively on pathways directly linked to interbasin water diversions, however, likely diverts attention from competing risks that reflect concerns of the technical community when competing risks are considered, e.g., role of birds as disease vectors in transfer of infective agent of whirling disease (see Appendix 9).

Polypodium hydriforme. Although the existing information and available data for this causative agent of fish disease were relatively limited compared to other biota of concern (see Appendix 3B), risks associated with *P. hydriforme* potentially transferred collaterally with waters from the Missouri River would be relatively low to very low, depending on the scenario being considered. Given the existing disease occurrence and a relatively undeveloped monitoring

program for the disease (yielding small sample sizes for evaluation), it is unlikely that an outbreak of disease linked to *P. hydriforme* potentially stemming from Missouri River waters could be identified without high uncertainty. Other potential disease agents of concern (e.g., *Icelanochohaptor microcotyle*, *Corallataenia minutia*, *Actheres ambloplitis*, *Ergasilus cyprinaceus*; see Dick et al. 2001) are characterized by uncertainties that exceed those of *P. hydriforme*, and any estimates of risks beyond those forecasts for the parasitic hydrozoan of acipenserid fishes would be largely unsupported by empirical data.

Yersinia ruckeri, the causative agent of enteric redmouth, and infectious hemtopoietic necrosis virus (IHNV) would present similar risks relative to their being collaterally transferred as part of an interbasin water diversion between the Missouri River and Red River basin. For these biota of concern, risks would vary from moderate under an open-water conveyance scenario to very low, if water were treated in the Missouri River basin then transferred via pipeline to controlled releases at points in the Red River basin. Although relatively limited in its characterization, Missouri River Sturgeon Iridovirus, or MRSIV and other fish viruses (see Appendix 3B; see also MacConnell et al. 2001) would also present a similar range of risks, although risks across disease agents such as these would inherently vary as a function of host (alternate hosts, as indicated by specific entity) and intermediate host. Even if specified, a particular disease agent is likely to present relatively limited data for a comprehensive analysis of risks focused on a quantitative or probabilistic evaluation, and a qualitative approach may be employed out of necessity.

4.7.2 Waterborne diseases of terrestrial vertebrates (including humans). A range of waterborne diseases frequently expressed by terrestrial and wetland vertebrates, including humans, was considered as part of the evaluation of risks associated with interbasin water transfers. In contrast to most of the freshwater fishes and aquatic invertebrates, however, each disease agent in this section would not be considered as a potential invasive species, since each currently occurs in Missouri River basin and in Red River basin. These organisms, however, do serve as representative waterborne disease agents that potentially represent disease agents of terrestrial vertebrates that are potentially subject to outbreaks linked to shifts in metapopulations of these agents in the receiving area.

Although the list of biota of concern generated through the collaborative efforts of Reclamation, Technical Team, and CERC did not include waterborne viruses such as adenovirus, calicivirus, coxsackievirus, and echovirus associated with diseases of terrestrial vertebrates

(Appendix 3B; see also Embrey et al. 2002), the waterborne disease agents considered in connection with fish diseases suggest a range of risks that is captured by these agents targeted on terrestrial hosts.

Bacteria, protozoans, and microsporidia of terrestrial vertebrates. *Cryptosporidium parvum* is a parasitic microsporidian parasite that presently challenges water treatment systems (Appendix 3B; see also Embrey et al. 2002), and has received much attention within the context of risk evaluations focused on human health and diseases in other terrestrial vertebrates. Given the basic scenarios considered in this work, the risks of *C. parvum* being transferred from Missouri River basin to Red River basin in sufficient numbers to document increased disease occurrence in Red River basin ranges from moderate in open-conveyance and piped, untreated systems to very low in water diversions implemented using control technologies within the Missouri River basin that ensure piped waters exceeding compliance specifications under SDWA as amended in 1996 and subsequently meeting Interim Enhanced Surface Water Treatment Rule (IESWTR) and Stage 1 Disinfectants and Disinfection Byproducts Rule.

Giardia lamblia is a parasitic protozoan that remains a public health concern in untreated waters intentionally or coincidentally consumed (e.g., backcountry drinking water sources or ingestion when swimming, respectively) or in treated waters likely to have become contaminated with contaminated materials prior to ingestion. As with other microbiological biota considered in this analysis, risks associated with *G. lamblia* collaterally transferred in interbasin water diversions range from moderate in open-water and untreated, piped-water conveyance scenarios to very low when water of the Missouri River is piped to distribution systems in the Red River basin following passage through a serially arranged control system comprised of pretreatment, treatment (e.g., chloramination) and ultrafiltration (e.g., see Schippers et al. 2004).

Commonly encountered waterborne bacteria that have a long history of cause-effect relationships with disease in terrestrial vertebrates were identified as biota of concern by Reclamation and Technical Team, as summarized in Section 1. *Escherichia coli* has numerous serotypes that currently occur in both Missouri River and Red River basins, e.g., in North Dakota, Minnesota, and Manitoba, yet it could potentially be transferred in water diversions from the Missouri River to the Red River basin (see Appendix 3B). It is highly unlikely, however, that outbreaks of any of various diseases associated with serotypes of *E. coli* could be unequivocally linked to interbasin water transfers completed via open-water conveyance or piped, but untreated conveyance. Risks associated with interbasin water transfers have been conservatively rated as

being moderate, but given the multiple intervening inputs into such an open-water conveyance, linking Missouri River water with shifts in metapopulations expressed as increase disease outbreaks is highly unlikely unless sufficient "fingerprinting" of source waters and waters available to end-users were routinely completed (see Grayman et al. 2001). Although an untreated, but piped-water conveyance would likely yield less risk than an open-water conveyance, the level of risk reduction may be relatively small unless greater specification to the distribution system were characterized. Regardless of whether interbasin transfers occurred via open-water conveyance or untreated, piped-water conveyance, a monitoring program yielding data sufficient for serotype fingerprinting may be prohibitive as a routine monitoring tool, depending on water user and stakeholder specification.

In contrast to moderate risks being associated with open-water or untreated, piped-water conveyance, if interbasin water diversions were implemented via a control system characterized as previously noted for reducing risks associated with microsporidians and viruses, risks associated with *E. coli* serotypes would be very low. While constructing a control system characterized by serially arranged pretreatment, treatment, and ultrafiltration treatments will likely minimize risks, the feasibility of such as system (e.g., engineering cost analysis) was not included in the analysis of risk reduction tools potentially amenable to the water diversions (see Section 4.10).

Risk analysis for *Salmonella* spp. tracks a course similar to that of serotypes of *E. coli*. *Salmonella* spp. (including *S. typhi*, *S. typhmurium*, and other serotypes associated with other waterborne infectious diseases) were considered, not because Reclamation and stakeholders anticipated an outbreak of typhoid fever, but rather, these species of enterics present a long history in infectious disease and a rich technical literature with respect their role as sources of waterborne diseases. Appendix 3B briefly characterizes the life history and epidemiological characteristics of *Salmonella* spp., a group that is the object of many risk assessments in the existing literature (see Haas et al. 1999 and citations therein). For our current application to the analysis of risks potentially associated with interbasin water diversions from the Missouri River to the Red River basin, these disease agents, as were the serotypes of *E. coli*, are currently cosmopolitan in their distribution; hence, any risks associated with these disease agents would require an analysis of shifts in metapopulations, most likely manifested as disease outbreaks in the importing basin. As with the serotypes of *E. coli*, it is highly unlikely that outbreaks of any of various diseases associated with *Salmonella* spp. could be unequivocally linked to interbasin water transfers, especially those completed via open-water conveyance or piped, but untreated conveyance. Moderate risks could potentially be realized with interbasin water transfers

completed with these less-engineered systems, yet their character, e.g., multiple intervening inputs into an open-water conveyance, ensures that causal linkages between source waters and disease outbreaks in the importing basin would easily defy attribution. Untreated, a piped-water conveyance would likely yield less risk than an open-water conveyance, but the technical requirements for distinguishing sources of a disease agent such as *Salmonella* spp. may be a practically intractable problem from an epidemiological perspective unless a monitoring program yielding data sufficient to the effort were in place (see Emde et al. 2001; Grayman et al. 2001).

While the less-engineered systems were conservatively considered to present moderate risks, if interbasin water diversions were implemented via a control system characterized as previously noted for reducing risks associated with microsporidians and viruses, risks of waterborne disease outbreaks associated with *Salmonella* spp. originating from waters from the Missouri River would be very low. As noted for other microbial species enlisted as biota of concern, water diversions mediated by a control system characterized by serially arranged pretreatment, treatment, and ultrafiltration treatments will likely minimize risks, although the capital costs of such an alternative may not be acceptable to stakeholders and decision makers. A complete engineering cost analysis was beyond the scope of this risk analysis, although the background materials presented in Section 4.10 suggest such an effort may be warranted, provided risk reduction is sufficient to allay concerns focused on interbasin biota transfers.

Legionella spp., as most commonly exemplified by *L. pneumoniae*, are ubiquitous and occur in a wide range of freshwater environments (see Fliermans et al. 1981; Hurst et al. 2002). Because of the public health origins of much of the early literature for *L. pneumoniae* (see Hurst et al. 2002), the ecological interactions that lead to the species being included as a member of the current investigation's list of biota of concern are commonly overlooked, which is frequently a shared "case attribute" for instances where low probability events are concerned and investigations are subsequently pursued. As summarized in Appendix 3B, a wide range of *Legionellaceae*, including *L. pneumoniae*, are potentially subject to interbasin transfers collateral with water diversions between the Missouri River and Red River basin. And while not exclusively an attribute unique to *L. pneumoniae*, the role that biofilms play in mediating transfers and influencing risks becomes a more prominent technical issue in the current analysis (see Appendix 3B). Biofilms and intracellular parasitism are key factors that bring additional uncertainties to any evaluation of risks characteristic of these relatively recently described microbes (see Storey et al. 2004).

Risks of interbasin transfers of the Legionellaceae, including *L. pneumoniae*, are moderate under either the open-conveyance or piped, but untreated water scenarios that serve this initial risk characterization. This risk estimate for both open-water and piped, but untreated-water transfers stems largely from a comparative analysis of the integrated outcomes from the categorical analysis in Section 3 and a review of the current record of disease occurrences for *L. pneumoniae* (Appendix 3B). Although not widespread in occurrence in the areas of concern, Legionellaceae as represented by *L. pneumoniae* are present in both Missouri River and Red River basins, as are other biota of concern in the grouping of disease-causing organisms. In contrast, the causative agent of whirling disease, *M. cerebralis*, was characterized as very low risk, given its current distribution in the western reaches of the Missouri River drainage and the relatively low populations of rainbow trout in North Dakota, Minnesota, or Manitoba. *P. hydriforme* was characterized as being associated with low risk, given its documented occurrence in fishes of Canada near the areas of concern, and suggesting that the comparative risks of these three disease-causing species might follow from their life-history attributes as disease agents (see Section 4.8, Uncertainty analysis).

Under the conservative scenario wherein source waters are treated in the Missouri River basin prior to piped transfers to distribution nodes in the Red River basin, risks associated with *L. pneumoniae* and other members of the family are very low. In such a scenario for interbasin water diversion, control systems whose designs include mutiple technologies (e.g., conventional pretreatments followed by combinations of chemical treatments and pressure-driven filtration devices) reduce risks to levels not unlike those for other disease agents included as biota of concern. Under this conservative scenario, this very low risk reflects, in part, our relatively limited technical ability to distinguish between sources of the disease agents (e.g., in the absence of a monitoring program as detailed by Emde et al. 2001).

Cyanobacteria. Cyanobacteria present a significant challenge to water systems throughout North America (see, e.g., Knappe et al. 2004) and the rest of the world (Chorus and Bartram 1999), and the list of biota of concern generated by Reclamation and Technical Team in collaboration with CERC included *Anabaena flos-aquae*, *Microcystis aeruginosa*, and *Aphanizomenon flos-aquae*. Each of these species has a long history of causing water quality problems for fish and wildlife (see Wobeser 1997), domestic livestock (see Svrcek and Smith 2004; see also http://www.ext.nodak.edu/extpubs/ansci/animpest/v1136w.htm accessed December 4, 2004), and public health (Chorus and Bartram 1999). The current analysis of risks clearly indicates that, if conditions amenable to cyanbacterial growth exist within the water

distribution system, a margin of safety will be achieved with control systems that incorporate sufficient water treatment technology (e.g., slow sand filtration, ultrafiltration with sufficiently low rejection value) to reduce risks associated with cyanobacteria and their associated toxins.

Risks associated with interbasin transfers of cyanobacteria are high if scenarios involving untreated water are considered and if the design of the transfer system provides conditions sufficient to support cyanobacterial growth. Wherever conditions of temperature, light, and nutrient status are conducive to algal or cyanobacterial growth, surface waters may experience proliferation of these aquatic organisms, frequently as an algal or cyanobacterial "bloom" when the event is dominated by a single (or a few) species. The type of the water transfer system significantly affects the risks associated with cyanobacteria, since problems associated with these biota of concern are likely to increase when ponds and lakes (including water supply reservoirs) are included in the design, especially in areas experiencing eutrophication, e.g., increased population growth with inadequate waste water treatment, and in regions with agricultural practices contributing to nutrient loads to surface waters, e.g., through overfertilization and erosion (see Appendix 3B; see also Chorus and Bartram 1999).

Risks to terrestrial vertebrates and to aquatic life are most frequently associated with cyanobacterial toxins in freshwater blooms, and these toxins, e.g., cyclic peptide toxins of the microcystin family, pose a major challenge for the production of safe drinking water from surface waters containing cyanobacteria with these toxins (see Appendix 3B). In a relatively uncontrolled water storage system, risks will vary seasonally, since cyanobacteria often dominate the summer phytoplankton and tend to bloom if nutrient conditions exists (e.g., phosphorus is the limiting nutrient controlling the occurrence of cyanobacterial blooms of cyanobacteria, and the lack of nitrate or ammonia favors the dominance of these species, since cyanobacteria tend to be nitrogen fixers). If cyanobacteria are present or even dominant at any particular time of the water year, practical problems associated with high cyanobacterial biomass and the potential health threats from their toxins increase. High cyanobacterial biomass may also contribute to aesthetic problems, impair recreational use (due to surface scums and unpleasant odors), and effect the taste of treated drinking water.

Direct cyanobacterial poisoning of animals can occur by two routes: through consumption of cyanobacterial cells from the water or indirectly through consumption of other animals that have themselves fed on cyanobacteria and accumulated cyanotoxins. Cyanotoxins bioaccumulate in common aquatic vertebrates and invertebrates, including fish, mussels and zooplankton.

Consequently, there is considerable potential for toxic effects to be transferred through aquatic food chains (see Appendix 3B).

Risks associated with cyanobacteria, however, can be significantly decreased through various control system designs; hence, risks are forecasted as very low under the conservative scenario involving multiple technologies to implement interbasin water diversions. For example, slow sand filters and their associated biofilms may contribute significantly to degradation of dissolved organic substances such as cyanotoxins (see Newcombe 2002; Knappe et al. 2004), although for removal of cyanobacteria, water quality (e.g., turbidity) and the biomass of cyanbacteria removed by the slow sand filter likely lead to rapid blocking and decrease the practicability of slow sand filtration (see Chorus and Bartram 1999). Filtration itself may not achieve removal of extracellular toxin, but biological adsorption may lead to decreased cyanotoxin concentrations in multistage treatment systems. For example, bulk cell removal by coagulation and clarification before slow sand filtration may be an effective approach for obtaining the benefits while avoiding rapid fouling (see LeChevallier and Kwok-Keung Au 2004). Both slow sand filtration and rapid sand filtration have been considered as control measures in water treatment systems, e.g., for treatment of wastewater from fish culture facilities (see Bomo et al. 2004; Bomo et al. 2003; Logsdon et al. 2002; Arndt and Wagner 2004), and pressure-driven technologies are considered highly effective preventive measures to address concerns related to control of *M. cerebralis* propagules (personal communication G. Rupp; see Appendix 10).

Membrane processes, e.g., ultrafiltration (UF), may be effective in the removal of cyanobacteria and intracellular toxins, if membrane rejection properties or adsorption ability for microcystins are sufficient. Generally speaking, molecular cut-off values for most UF membranes would likely not yield removal of soluble toxin, although nanofiltration membranes would be characterized by rejection values yielding reduced risks relative to UF processes. Hence, risks associated with cyanobacteria illustrate the role that subsequent engineering analysis plays in potentially influencing risks potentially associated with interbasin water diversions.

4.8 Uncertainty analysis

Two general types of uncertainty—aleatory uncertainty (also referred to as, random uncertainty or stochastic uncertainty) and epistemic uncertainty—affect the characterization of risks, especially within the context of their roles in influencing risk management. Aleatory

uncertainty deals with the randomness (or predictability) of an event, while epistemic uncertainty reflects our "state-of-knowledge." Hence, epistemic uncertainty is also referred to as subjective uncertainty or parameter uncertainty. Within the context of our current investigation, aleatory uncertainty would be illustrated by a forecast of failure of a control technology such as ultrafiltration, e.g., where the occurrence of failure occurs at a random time, but we cannot predicted exactly when that failure will occur, even if a large quantity of failure data is available. In contrast, epistemic uncertainty includes parameter-specific uncertainty and model-specific uncertainty. As such, aleatory uncertainty relates to our inability to fully characterize a model of a system that represents higher levels of development than those detailed by basic events in a process. In any process, these basic events in turn contain lower-level events, e.g., such as the failure rate or probability of a failure under specified conditions.

The concept of uncertainty when applied in a scientific context contains a complexity that is often inadequately appreciated across all members of a stakeholder group, including experts within the technical community. Presently, when faced with analysis of complex adaptive systems, e.g., ecological systems, the evaluation of model, parameter, and aleatory uncertainty is often based on expert opinion (see Helton 1994; Hoffman and Hammonds 1994). Some types of uncertainty are more easily quantified than others, although a complete quantitative treatment of all types of uncertainty is oftentimes not achievable, as evidenced for many biota of concern in the current investigation.

Uncertainty arising through error, bias, and imprecise measurement, and uncertainty arising through inherent variation in natural parameters can be addressed through sampling in the field or in data-mining efforts, wherein data quality and quantity are specified to ensure these sources of uncertainty are characterized. Uncertainty that arises through lack of knowledge or scientific ignorance reflects uncertainty related to state-of-knowledge (or rather lack of knowledge), which has also be termed irreducible uncertainty. Each of these types of uncertainty undoubtedly exists in every analysis or prediction that forms part of risk characterization. The current characterization of risks associated with biota transfers collateral to interbasin water diversions is not unique from this perspective.

4.8.1 Uncertainty and characterization of risks of biota transfer. For biota transfers potentially realized from interbasin water diversions, a range of aleatory and epistemic uncertainties prevailed for (1) biological and ecological (biotic and abiotic) factors contributing to uncertainty and (2) engineering and hydrologic factors contributing to uncertainty. These

uncertainties, however, were no greater than those encountered in other complex biological systems analyses intended to support resource management (see Alex Grzybowski & Associates 2001; Hulse et al. 2002). Reducible uncertainties associated with species life history attributes were relatively limited, given the list of biota of concern enlisted by Reclamation and Technical Team, although the relatively diffuse character of the existing literature and the number of species included as biota of concern required our reliance on synthesis reports, limited reviews of primary literature, and existing compilations of available data (e.g., through open-source literature available via public domain such as USGS research centers and cooperative national and international organizations such as ICUN, ISSG, and online sources such as FishBase; see Froese and Pauly 2000). These public domain sources maintain quality assurance practices similar to those specified by US EPA in regard to spatial data or associated metadata (e.g., US EPA 2003) that ensured data sufficient to the analysis, with supplemental data and peer-reviewed literature providing sources to update these open-source compilations to reflect our current state-of-knowledge.

Reducible uncertainties captured in this analysis reflect data gaps in our current knowledge, e.g., of the species-specific processes involved in biological invasion and establishing sustainable populations. Our analysis ranged from one vested in sufficient empirical data to characterize risks with relatively limited aleatory uncertainty (e.g., zebra mussel, New Zealand mudsnail, *E. coli*, *Salmonella* spp., and tamarisk). Existing literature and data for these species varied with respect to the statistical support available for a spatial analysis of predicted distributions and a precise characterization of "time-to-invasion" most species necessarily reflected "best estimates" based on comparative analysis of recent history. For example, prediction of species distributions for zebra mussel, New Zealand mudsnail, and tamarisk were developed with high confidence, given the data support available from open sources, while a comparable data compilation for *Polypodium hydriforme* was lacking or very sparsely populated. Some mappings were limited, not because of data absence but rather because data forms were not sufficient to a point-process analysis as completed via GARP, as was the case, e.g., with *Corbicula fluminea* and other biota of concern such as *Lythrum salicaria* and other aquatic vascular plants whose data through public domain focused on county- or statewide observation records. As the summary of current distribution of biota of concern in Appendix 3A and Appendix 3B suggest, data resolution may be insufficient for fully developing maps of predicted distribution in this current investigation, but from a resource management perspective, these relatively coarse-grain data may be sufficient to the task of managing risks potentially associated interbasin biota transfers. The uncertainties in spatial resolution may largely be reducible, although prohibitively

time-consuming in their completion given stakeholder's anticipation, and the level of effort to data-mine the necessary point data to generate predicted distribution maps may not benefit the management decision-making process.

Some uncertainties apparent in the current analysis stem from an inability to acquire data that may exist but are not currently available from open-source organizations (e.g., point occurrence data for diseases in northern Great Plains). Such data gaps, while theoretically reducible in character, are practically intractable given the focus and time constraints of the current investigation as detailed in Section 1. These sources of reducible uncertainty largely reflect a mix of shortcomings in open-source data compilations (e.g., incompleteness owing to voluntary data submissions, representativeness potentially inadequate stemming from haphazard collection method yielding potential geographic bias) and the ongoing efforts on many fronts to better resolve our "state-of-knowledge" or epistemic uncertainties (e.g., species distributions are dynamic, and "snapshots" through time reflect cumulative sampling efforts, changes in survey design and sampling methods). For example, fish distributions in the northern Great Plains have been, and continue to be, a rich source for research into biogeography and systematics, with records available from the mid-1800s (e.g., Jordan 1877) to present day (e.g., Lee et al. 1980; Peterka and Koel 1996; Koel 1997; Mandrak and Crossman 1992). Latter-day research efforts reflect, in part, focused efforts by researchers to address biota transfer issues, e.g., develop catalogs of existing ichthyofauna of the northern Great Plains and characterize distributional records in view of relatively recent geological events (e.g., late Pleistocene glaciations). Early efforts to characterize the freshwater fauna of the northern Great Plains (e.g., Young 1924) also demonstrate the historic context supporting the current investigation, and the continuing efforts to revise and update faunistic and floristic catalogs for the area continue (e.g., Smeins 1967; Facey no date, Kaloupek 1972; Larson and Barker 1983; Reed 1986 on aquatic and wetland vascular plants) to characterize the dynamic baseline for evaluating the biogeographic setting of the area.

The early as well as current efforts to characterize the biodiversity of the northern Great Plains illustrate the intractable problems that this and any subsequent biogeographic analysis focused on biota transfer issues will encounter. These intractable problems stem directly from the sources of uncertainty that influence the current characterization of risks and that ultimately are critical inputs into risk management decisions associated with interbasin water diversions. For example, a comprehensive catalog of indigenous flora and fauna, including microorganisms, of the northern Great Plains and in particular the Missouri River and Red River basins, will always be subject to epistemic uncertainty, in part because of limitations on sampling and survey efforts

targeted on such a task. While the literature will practically record *all* species indigenous to the area, the absence of many species, especially those at the extremes of their range (e.g., emigrants from adjacent Great Lakes and Mississippi basins) need not infer occurrence in a particular region of potential habitats, especially for organisms occurring in low numbers of widely separated individuals. Absence in a catalog of species distributions is better interpreted as "not found," which would be more appropriate for characterizing species rare in occurrence. These uncertainties characteristic of the current investigation are not unique to our focus on biota transfers potentially occurring collateral to interbasin water diversions and inevitably link intractable problems and long-standing data gaps to our analysis and subsequent characterization of risks.

4.8.2 Illustrations of uncertainty in analysis of risks related biota transfer.

Uncertainty, then, exists as two general forms, both of which impact the current analysis. While the current analysis will never resolve uncertainties associated with our current "state-of-ignorance," we can illustrate aleatory uncertainties primarily influencing (1) categorical estimates of risk and (2) quantitative estimates of risk as outputs of simple probability simulations and forecasts of potential species distributions, including when data were sufficient, spatiotemporal outcomes of the invasion process.

A shared source of aleatory uncertainty reflected in the derivation of categorical risk estimates or quantitative risk estimates is our potential for "missing" pertinent data or existing information during the course of data mining. Between the relatively diffuse character of the open-source literature and the dynamic manner in which data are acquired and information subsequently available in the public domain, we may have missed critical elements of life-history data, e.g., dispersal rate for *Polypodium hydriforme* or other biota of concern necessary to the analysis. Subsequently, our state-of-ignorance is a reflection of incompleteness rather than ignorance. As indicated in Section 3, our literature search yielded outcomes that varied across biota of concern, with some species (e.g., zebra mussel, New Zealand mudsnail, zoonotic disease agents) having relatively easily acquired existing data and literature to other species that were relatively data limited (e.g., *P. hydriforme*). Only a limited few biota of concern had georeferenced occurrence data sufficient to developing predicted distributions using GARP, and those georeferenced data compilations captured a range of aleatory uncertainties (see Section 4.8.3).

Another shared characteristic of aleatory uncertainties associated with categorical and quantitative analyses reflected differences in data quantity across biota of concern. For the most part, the range in available literature from open sources reflected the state of characterization of species life history, e.g., life histories for zebra mussel, New Zealand mudsnail, tamarisk, purple loosestrife, and others were relatively well developed, while more recently described invasive species were less well developed (see Appendix 3A and Appendix 3B). This disparity in existing literature necessarily implies that uncertainties associated with each species of concern varied; that is, uncertainty varies from one species to another. For example, zebra mussel presented less uncertainty with respect to geospatial occurrence data than did species characterized by a relatively poorly developed point data, e.g., most of the fishes. The relatively poorly developed point data for the fishes illustrate how life-history data in the form of narrative summaries is very well developed, yet point data critical to the analysis of "where the species occurs or has occurred" and "where it might occur" are sparsely developed. And that point data available may be incomplete and potentially serving to bias-predicted distributions. In the current investigation, collapsing numerous species sharing common life-history attributes and similar native distributions, e.g., Asian carp, provided data sufficient to a spatial projection of potential distribution, yet species-specific predictions are wanting, if individual species projections are desired.

For the categorical evaluation of risks, the estimation process largely was focused on technical analysis of the existing literature (see Appendix 3A and Appendix 3B) with scoring completed to derive those risk rankings characteristic of each biota of concern (see Section 3, Table 1 through Table 8). The current analysis applied a common categorical data tool to the evaluation of mined data, yet alternative methods of scoring are amenable to the risk assessment process, particularly one with a wide range of stakeholder perspectives. While alternative methods are numerous, especially in the sample survey literature (see Groves et al. 2004), one may illustrate alternatives that account for reducing epistemic uncertainty reflected by having numerous stakeholders participate in an "expert panel" scoring process wherein Delphi methods are employed (see, e.g., Adler and Ziglio 1995). The Delphi method is a systematic interactive forecasting tool based on independent inputs of selected members of a stakeholder expert panel. As such, Delphi method recognizes the value of expert opinion, experience and intuition and allows using the limited information available in these forms, when full scientific knowledge is lacking.

The track record of the Delphi method is mixed (see, Adler and Ziglio 1995, Groves et al 2004); hence, its strengths are offset by weaknesses inherent to the tool. There have been many cases when the method produced poor results; that is, as a predictor of future events, the Delphi method was incorrect more times than not, although poor performance may reflect poor application of the method and not to the weaknesses of the method itself. Also, application in areas such as science and technology may yield forecasts associated with a degree of uncertainty, so great that exact and always correct predictions are impossible. A high degree of error is to be expected even with assembly of the "best" of expert panels (see Biemer et al. 2004). Another weakness of the Delphi method is that future developments are not always predicted correctly by developing an iterative consensus of experts, and "unconventional thinking" of "nonexpert outsiders" may be as likely to yield a good forecast of future events. Depending on Reclamation and Technical Team interactions, the Delphi method has been a widely accepted forecasting tool and has been used successfully for forecasting technical outcomes when data and information are sparse.

Each categorical analytical tools will present strengths and weaknesses, particularly with respect to addressing various forms of aleatory uncertainty. For example, the current implementation could be revisited by an increased number of survey participants, and facets of aleatory uncertainty might be reduced, e.g., variance. Yet epistemic uncertainty would likely remain unchanged. Given an assemblage of objective panelists, departures from the current rankings would be likely be insignificant, e.g., low-ranking species such as pallid sturgeon or paddlefish would remain low-ranking, and high-ranking exotics such as zebra mussel and New Zealand mudsnail would remain higher in ranking. Variability about individual rank score may be apparent, particularly in view of similar scores across many species in the middle ranks. From a risk-management perspective, these species in mid-ranks might be subject to focused studies completed in future work.

In contrast to the subjective uncertainty reflected in the categorical analysis and ranking of biota of concern, the aleatory uncertainty in the quantitative estimation process related to the analytical models used in the evaluation. The representativeness and completeness of data used in those models also influence uncertainty. For example, evaluating the probability of invasive events, simulations were completed using the simple probability model specified in Section 2 (see also Annex Figure 1 through Annex Figure 5). Therein, a simple linear chain of events was envisioned that linked biota in source areas of HUC10, the Missouri River basin, with importing areas in HUC09, the Red River basin. From a model perspective, numerical methods such as that

applied to the analysis of risks associated with biota transfer are simple simulation models that reflect approaches commonly referred to as Monte Carlo methods, where a statistical simulation employs sequences of random numbers to perform the simulation of a specific model. In Monte Carlo simulation, the process is simulated directly, and there is no need to fully develop the differential equations that describe the behavior of the system. The only requirement is that the physical (or mathematical) system be described by probability density functions (pdfs), which assume the behavior of the system itself. Once the pdfs are known or assumed, the Monte Carlo simulation can proceed by random sampling from the pdfs, yielding many simulations (multiple "trials"). Given our primary focus on following the flow of events depicted in Annex Figure 1 through Annex Figure 5, the current analysis simply considered all outputs from the simulation, and considered the range of probabilities described for events such as "probability of control system failure." Monte Carlo methods may be extended to calculate an average, in our case, probability, over the number of observations or trials completed in the simulation. In such an application, the variance associated with this average can be characterized, an estimate of the number of Monte Carlo trials required to achieve a given error could be characterized. Greater detail in the Monte Carlo application for the current investigation could be included in future iterations of the analysis.

Monte Carlo simulation has limitations. For example, in our simple stochastic model of the chain of events resulting in a successful species invasion (or shift in metapopulation), the simulation lumps epistemic uncertainty with variability as that metric reflects aleatory uncertainty. We have simply looked at outputs from the simple flow of events as phenomena that reflect a system "failure" or "success." The flow of events that guided the simple stochastic process of species invasion captured a "snapshot" of risks, and no cumulative risk was calculated. Assumptions of linearity, e.g., risk invariant through time, could be made to yield an integrated Monte Carlo output, or a simple arithmetic calculation could be completed to arrive at some characterization of cumulative risks, yet such an assumption potentially reflects greater uncertainty in bias estimators of risks. For example, if we consider "typical" failure distributions (e.g., "bathtub curves," see Appendix 4), risks vary as a function of time, and once a control system is designed, cumulative risk forecasts could be derived as part of the risk reduction evaluation. Even this example, however, retains uncertainties associated with the chain of events that vary with time, such as seasonal variation in transfer rates between component events of the invasion process (e.g., both anthropogenic and nonanthropogenic pathways display seasonal patterns that are currently assumed to be time invariant).

We have also performed the simulation assuming that the constituent events are independent, and we have assumed correlations among input events are absent. Both assumptions can bias output from a Monte Carlo. In part these assumptions reflect our uncertainty in the invasion process. While much of the uncertainty may be reducible, we inevitably encounter irreducible uncertainty that renders simple, unbounded estimates of risk to guarded interpretation. Perhaps the one characteristic of Monte Carlo simulations that may be most critical from a risk management perspective lies in the output distribution's "tails" (see Appendix 4). The tails of Monte Carlo risk distributions are very sensitive to the shape of the input distributions. The extent to which iteration is employed to reduce uncertainty is largely driven in applied settings by the risk management goals of the resource manager.

There are several mathematical, statistical and computational algorithms for generating predicted species distributions (see Scott et al. 2002). Genetic Algorithm for Rule-set Prediction, or GARP, was used in the current investigation, but other models are available, e.g., GAM, GLM and BIOCLIM. There are also new knowledge areas that could be used to generate such algorithms like cellular automata, fuzzy logic, neural nets, and cognitive agents, but given their relatively underexploited use in biological and ecological predictive modeling, these were not considered in the analysis of risks associated with biota transfers. Despite their differences, all algorithms for species distribution modeling share some attributes, and their computational infrastructure must

- read georeferenced environmental maps stored in different formats (e.g., Arc/Info Grid) ,
- deal with different coordinate systems and projections to combine the different maps and the species occurrence points, and
- resample the environmental characteristic maps and the species occurrence points generate the species distribution map based on the resulting model.

GARP finds wide application in biodiversity and invasive species research and conservation biology, and as a tool, GARP presents strengths and weaknesses characterized in the literature (see Scott et al. 2002).

To predict patterns of species distribution, GARP relies on georeferenced data derived from museum records and databases compiled and maintained by various open-source cataloging organizations (e.g., USGS, USDA, FishBase). The utility of GARP output reflects inherent limitations of such compiled data: (1) records may not reflect species and habitats being sampled

equally; (2) data acquired from these open-sources were used for both model development and testing, and consequently may overlook poor fit of some models; and (3) available data may not provide the desired spatial resolution or capture temporal changes in species distribution.

With GARP output, as with any other distribution predictions, interpretation of potential changes in a particular species distribution through time may be confounded by unrelated events influencing biogeographical patterns, e.g., climate change. At relatively large spatial scales (e.g., 10 to 100 km^2 or greater), climate change has been seen as a crucial element in the distribution patterns of many organisms. However, genetic adaptation is unlikely to match the rate of climate change (e.g., Huntley et al. 1995, Etterson and Shaw 2001 on vegetation), and consequently, climate change may have already had an impact on many natural systems (IPCC 2001), or is predicted to cause major changes to biodiversity and species distributions (see, e.g., Peterson et al. 2002).

To predict distribution changes of any particular given species, e.g., under climate change or species invasions, GARP assumes that species' distributions are directly dependent on local climate. For GARP this assumption involves linking a species current distribution with combinations of current climate data, then plotting shifts, e.g., distribution expansions, by linking habitat attributes in currently unoccupied landscapes to potential species dispersing to those habitats in a simple "invasion scenario." Methods of linking habitat and "candidate invaders" are broadly based on two methods, generalized linear models and BIOCLIM approaches (see Nix 1986; see also http://cres.anu.edu.au/outputs/anuclim/doc/bioclim.html last accessed December 4, 2004).

Generalized linear models, or GLM, rely on largely complete datasets incorporating absence data, while BIOCLIM-type approaches use less complete datasets which focus on species presence data. Combinations of the two approaches are employed by GARP, which uses a combination of BIOCLIM rules, logistic regression and machine-learning methods. (Peterson et al. 2002). BIOCLIM-type approaches are based on ecological niche wherein a species' "climate envelope" is characterized by the overlay of a number of ranges of climate variables. These ranges describe, e.g., the minimum and maximum values of a climate variable found at the location where a species occurrence is recorded. In this way, all areas exhibiting a combination of climatic conditions within the range of conditions associated with a species' distribution are identified. Then, GARP delineates climatically suitable areas for the species, their climate envelope, for projecting potential distribution. As climate variables are added to the model, the description of

suitable climate becomes increasingly specific to the species distribution, resulting in a climate envelope more spatially representative of that species distribution. Given the niche-defining variables that yield the climate envelope, the overlay technique of BIOCLIM may yield overprediction of suitable areas unless GARP is implemented with adequate discrimination, e.g., using "best-subset" routines (see Section 3).

Minimizing overpredictions, while maximizing climate envelopes that capture species occurrences can be achieved via the genetic algorithm (GA) of GARP. GAs are adaptive heuristic search algorithms were initially developed by Holland (1975) and based on the concept of natural selection. GARP defines climate envelopes using GA to develop decision rules capable of controlling overprediction, yielding optimized climate envelopes for a species (see Stockwell and Peters 1999). In addition to providing a method to find the near optimal climate envelope, the heuristic optimization approach of GAs has certain advantages over more traditional statistical approaches to creating a predictive model of species presence/absence. For example, logistic regression may be affected by overdispersion caused by model misspecification, which may result from the spatial autocorrelation common to climatic variables. Biologically and ecologically, the genetic algorithm of GARP also considers ranges in values of climate variables that may be suitable for the occurrence of a species rather than using statistical approaches which rely on assumptions of single, optimal variable values associated with areas where species occur.

Most species' distribution models use either presence-only data, including records from herbaria or museums and observation data, or presence-absence data from systematic surveys. Plant and animal specimens held in museums and herbaria serve as a data resource, providing records of current distribution and historic information. Most of these data are point based, although some models also include area-based or grid-based data. All species' collection data are samples of geographic space and inevitably incorporate some degree of spatial bias (Williams et al. 2002). Sampled areas are subsets within a species distribution and there are few, if any records of where a species may have been looked for, but not found; that is, absence data are not as frequently recorded as presence data (Margules and Austin 1994). These data, however, have drawbacks when used for modeling species distributions. For example, records may carry little geographic information other than a general description of the location where they were collected (Chapman and Milne 1998), and much of the historic data are poorly georeferenced (e.g., lack latitude and longitude) or may have been added at a later date by individuals other than the original collector. As such, these data supply only presence data at a point in time (Peterson et al. 1998), and usually collected opportunistically rather than statistically resulting in large biases, e.g.,

collections that are highly correlated with road networks (Williams et al. 2002; Peterson et al. 2002). GARP relies on presence-only data and may reflect differences in scale for those climate variables applied to the modeling process for characterizing climate envelopes, or as it is commonly referred to, ecological niche modeling. Presence data may also be subject to errors of accuracy, e.g., errors in locations of presence records and in species identification associated with point-data. Completeness of presence-only data is also a potential concern, as illustrated by the current investigations mapping attempts for some fish species (see Section 3).

Aleatory uncertainty associated with the predictive value of GARP models requires continued study, especially comparisons with distribution patterns from independent data sets. For example, recent publication of predicted distributions for zebra mussel are nearly identical to those GARP outputs developed in this current investigations (e.g., Drake and Bossenbroek 2004); hence, confidence in mappings for zebra mussel are very high and lend support for outputs developed for other biota of concern (but see Section 4.8.4). When employed at appropriate temporal and geographic scales, GARP models show promise for conservation biology applications such as invasive species evaluations and provide initial estimates for processes responsible for observed and predicted patterns of species distributions (Peterson et al. 2002).

4.8.3 Spatial and temporal uncertainties: Examples from current investigation.

Both aleatory and epistemic uncertainty may confound interpretations of risks characterized following spatial and temporal analysis, and the following examples illustrate alternative outcomes that agree, and in some cases disagree, with results originally identified in Section 3 for, e.g, predicted distributions for selected biota of concern. These differences in GARP output reflect a spatial and temporal sensitivity analysis completed in order to evaluate the robustness of projections of species distributions. As noted earlier in this section, species distributions are a dynamic function of current climate and habitat condition regarding discussion of paleoecological context (see Appendix 18), which remains a concern of global and regional efforts focused on climate change and its role in altering species distributions. In part, these regional analyses of climate change and their impacts on species distributions support our current emphasis on exotic species as biota of concern, since species considered for assessment and monitoring should provide sufficient background (e.g., occurrence data) to minimize confounding effects potentially associated with changes in distribution attributed to responses to climate change. A limited focus on species occurring only in North America would likely have yielded greater opportunity for confounded interpretation of risks than apparent for species included on the list of biota of concern compiled by CERC in collaboration with Reclamation and Technical Team. Scenarios

involving interactions between biota transfers and climate change were not included as part of this investigation.

To illustrate the spatial and temporal factors potentially influencing the aleatory uncertainty of the current investigation, a sensitivity analysis was completed using New Zealand mudsnail, zebra mussel, and tamarisk. Outputs from GARP and simple spatial correlation analysis (see Appendix 14) suggest that uncertainty will vary across species included as biota of concern, and that risk management decisions should be developed with this variability being considered.

Spatial-censored data and their effect on predicted distribution for New Zealand mudsnail. As part of a spatial sensitivity analysis, species distributions were projected from georeferenced point data that were spatially restricted relative to the complete set of presence-only data applied to the analysis summarized in Section 3. For this illustration (Figure 10 and Figure 11), point data evaluated by GARP were only those from the Missouri River basin; that is, data were spatially censored to those points mostly likely to serve as source areas for dispersal in the western reaches of HUC10. Besides reducing the number of point data available to GARP for projecting future distributions in North America, this spatial truncation of point data yielded a less diverse set of point data specifying conditions for the species' climate envelope or niche, and distributions predicted for each set of point data were poorly correlated (see Table 8, r = 0.297).

Time-censored data and their effect on predicted distribution for zebra mussel. As suggested by observations of species distributions changing through geologic time, time-censored point data may also impact predictions of species' distributions, in part, because time-censored data may similarly reflect spatial-censored data. In this investigation, we illustrate the case of time-censored point data and their role in potentially influencing our predicted distribution for zebra mussel (Figure 12 and Figure 13). Here, a predicted distribution was developed with GARP using only those point data collected between zebra mussel's first record in 1988 through 1993, which limited the species' presence data to the upper Mississippi River. No incursions were observed in the Missouri River drainage until 1999; hence, time-censoring limited the spatial extent of data considered by GARP in this sensitivity analysis. In contrast to the space-constrained sensitivity analysis for New Zealand mudsnail, the time-censored species distribution predicted for zebra mussel is well correlated with that projection developed from a complete data set (i.e., point data compiled through 2003; r = 0.905, see Table 8).

These comparisons across time suggest the range of habitats initially captured in the time-censored data were very similar to those characterized by the larger data set compiled from 1988 through 2003. However, the "sum-of-best-subsets" distribution projected from data compiled from 1988 through 2003 reflects the potential for greater spatial coverage for zebra mussel distributions, given the increased latitudinal and longitudinal spread reflected in the data compiled through 2003. This potential for increased spatial coverage for zebra mussel distribution is suggested by the incursion of potential distributions beyond the 100th meridian in the coverage projected by GARP when data compiled through 2003 are included as part of the derivation (see Figure 11, e.g., 50–75% of best-subset distributions included areas outside those suggested by the time-censored outputs derived from data compiled between 1988 through 1993). Within a risk characterization, these differences between outputs given censored and not-censored data inputs reflect aleatory uncertainty as spatial variance that should be considered as part of risk-management activities developed as outgrowths of this investigation.

Table 8. Summary correlation table for comparisons of spatial- (New Zealand mudsnail) and time-censored (Zebra mussel) predicted distributions derived from GARP.

	Correlation Coefficient (r)[1]		
Species and data support[2]	NZMSHUC10	T-CZM	ZM
NZMS	0.297	na	3
ZM	na	0.905	1.03

[1]see Appendix 14 for detail.

[2]NZMS = New Zealand mudsnail; NZMSHUC10 = New Zealand mudsnail HUC10 only; ZM = zebra mussel; T-CZM = time censored zebra mussel (data compiled 1988-2003) ; na=comparison not applicable

[3]Correlation analysis completed for identical (ZM v. ZM) and contrasting (ZM v. NZMS) cases serving as quality control checks on calculation.

Simple logistic regression and its effect on predicted distribution for zebra mussel. Given the strengths of GAs, the full implementation of GARP incorporates logistic regression as one of the tools available to the analysis of potential species distributions, and as such, logistic regression was considered as one of the routines used in the analysis. As noted earlier, strict reliance on a statistical tool such as logistic regression may yield outcomes that ignore the optimization capabilities of GA (see also Haupt and Haupt 1998, 2004; Spall 2003). Again, the current work with zebra mussel illustrates the relative insensitivity of logistic regression as the only tool brought to the table in the analysis of potential distributions for any species. Figure 14

and Figure 15 display the predicted distribution of zebra mussel as output derived solely from logistic regression, and as apparent from this illustration, the projected species distributions for zebra mussel are highly sensitive to model uncertainties. Hence, interpretation of risks must acknowledge this type of aleatory uncertainty, and risk management decision should be developed with contingencies in place sufficient to address concerns potentially associated with outcomes projected by a simple statistical analysis of point data that displayed greater discrimination under GARP (see Section 3). A similar output for a "logistic regression only" analysis for New Zealand mudsnail and tamarisk presented similar results in a sensitivity analysis focused on model uncertainty, including observations of predicted distributions including highly unlike locations, e.g., invasions of habitat above the Arctic Circle.

Updated occurrence data and their effects on predicted distributions of tamarisk. While illustrations for zebra mussel and New Zealand mudsnail summarized results of sensitivity analysis focused on time-censored and spatial-censored data frequently encountered in predictions of a species being invasive or not invasive, the following illustration using tamarisk data consider aleatory uncertainty associated with input data compiled by various organizations through time. This analysis shares attributes of the time-censored and spatial-censored outcomes portrayed in Figure 10 through Figure 15 but extends those observations through a different perspective, one focused on potential confounding issues related to "data warehouse" management (see, e.g., Chen 2001; Dasu and Johnson 2003; Kantardzic 2003).

Point data for tamarisk is generally a compilation of *Tamarix* species records made available through http://www.fort.usgs.gov/resources/spotlight/EcoForecasting/EF_projects.asp (last accessed December 4, 2004) and other open-source libraries. During the current investigation's 2-year data collection effort, open-source data warehouses were queried regarding availability of georeferenced point-data for tamarisk, and during the 2-year period data data were received from multiple sources, generally having a focus on regional concerns shared by many organizations in, e.g., the southwest US. Early in the data search and retrieval, small data sets (less than 25 point data) were available, and by compiling multiple sources point data collected by mid-June, 2004 were greater than 100. Subsequently, open-source data became available having greater than 5000 point data, which suggested an exploratory "Bayesian approach" (see, e.g., Congdon 2003) to updating a distribution through time in order to address the dynamic character of data acquisition.

Figure 10. New Zealand mudsnail based on presence data from HUC10 only.

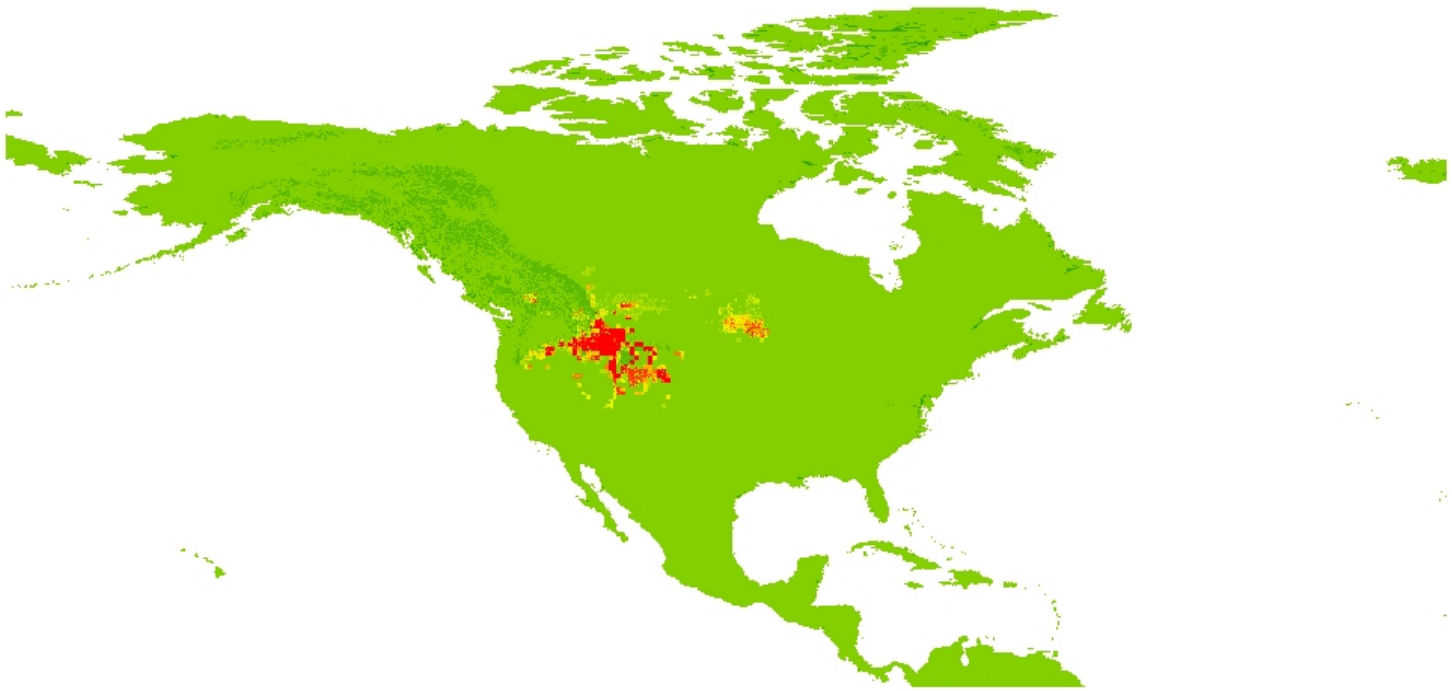


Figure 11. New Zealand mudsnail based on presence data from HUC10 only.

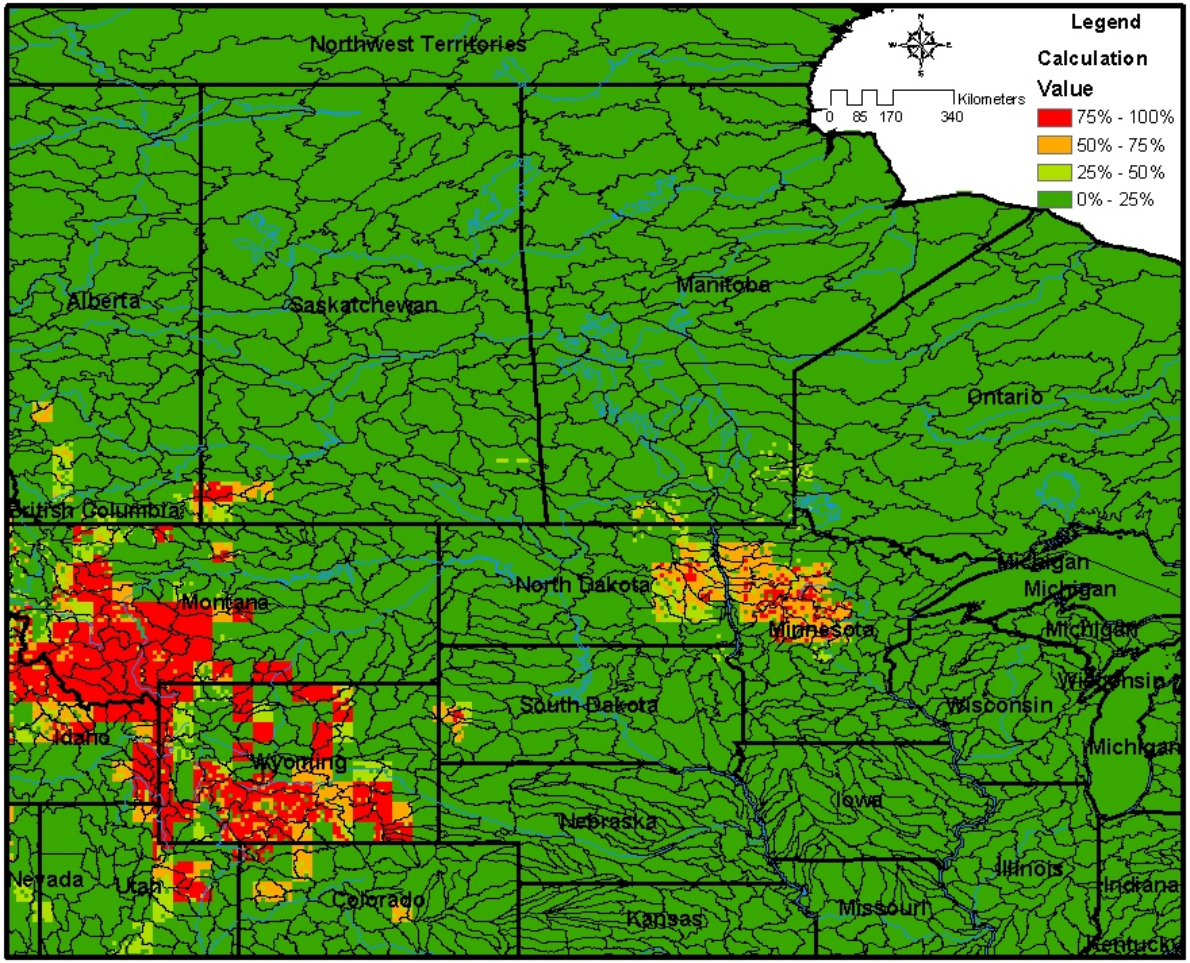


Figure 12. Zebra mussel predicted distribution based on 1988–1993 presence data.

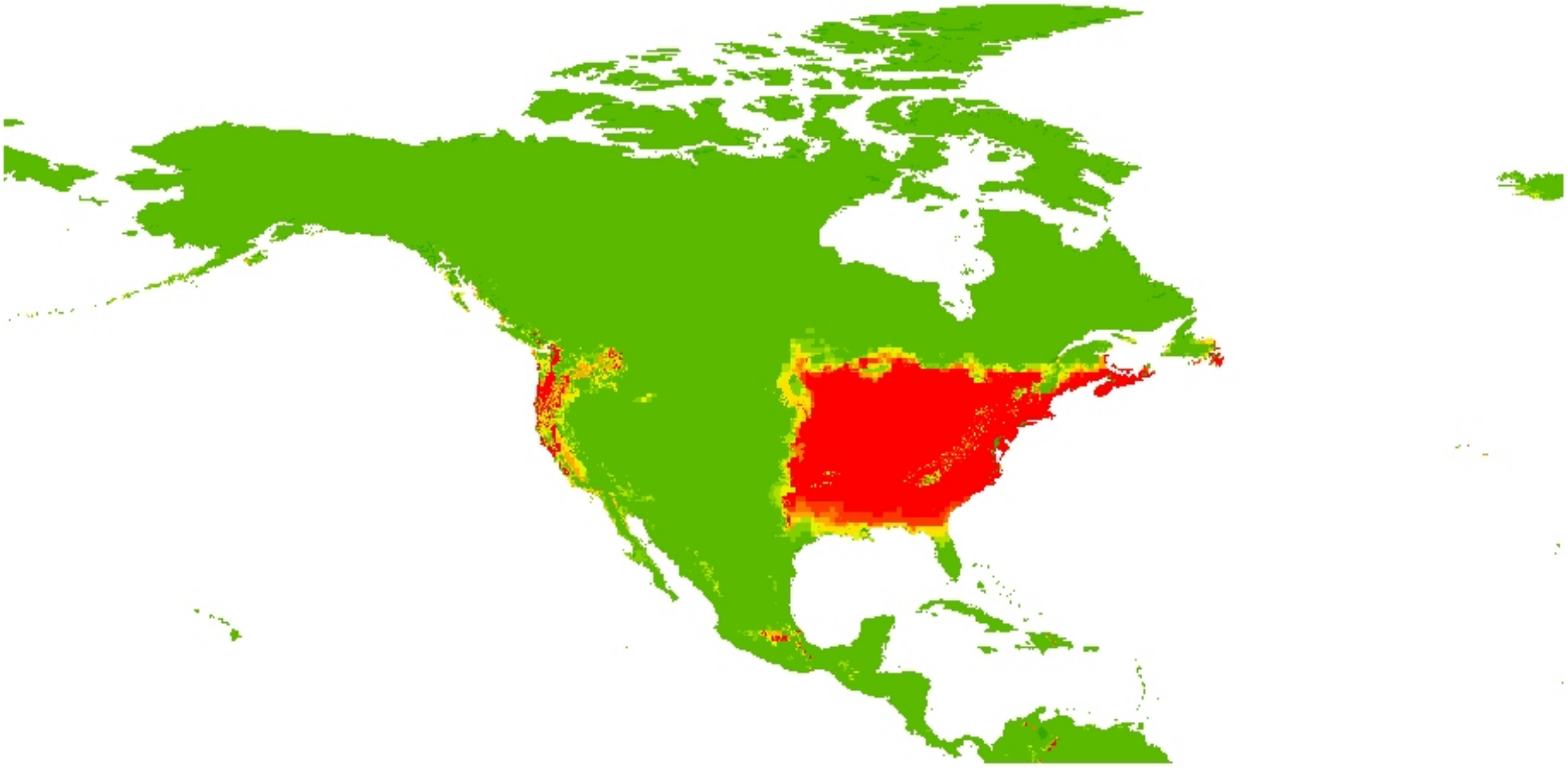


Figure 13. Zebra mussel predicted distribution based on 1988–1993 presence data.

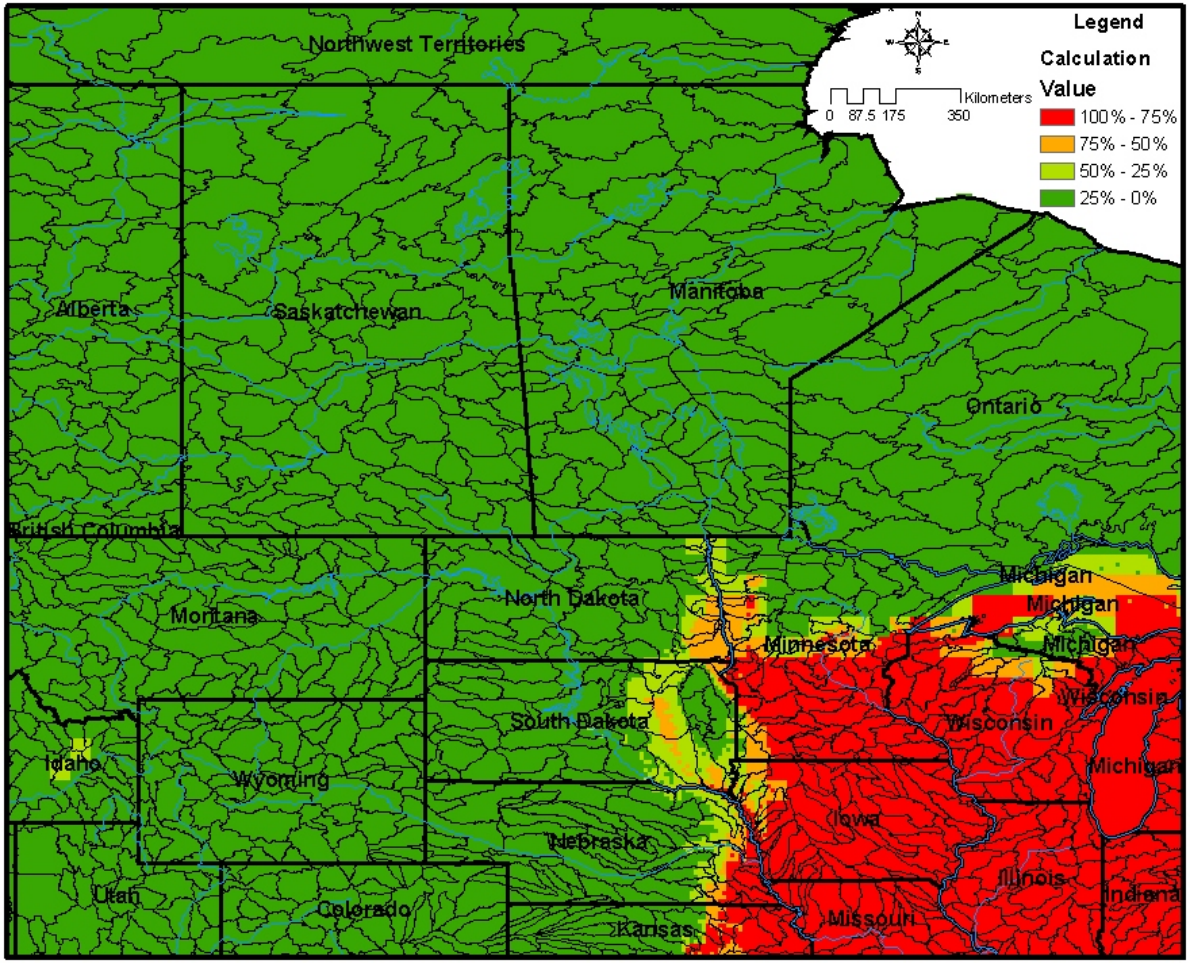


Figure 14. Zebra mussel predicted distribution based on logistic regression only.

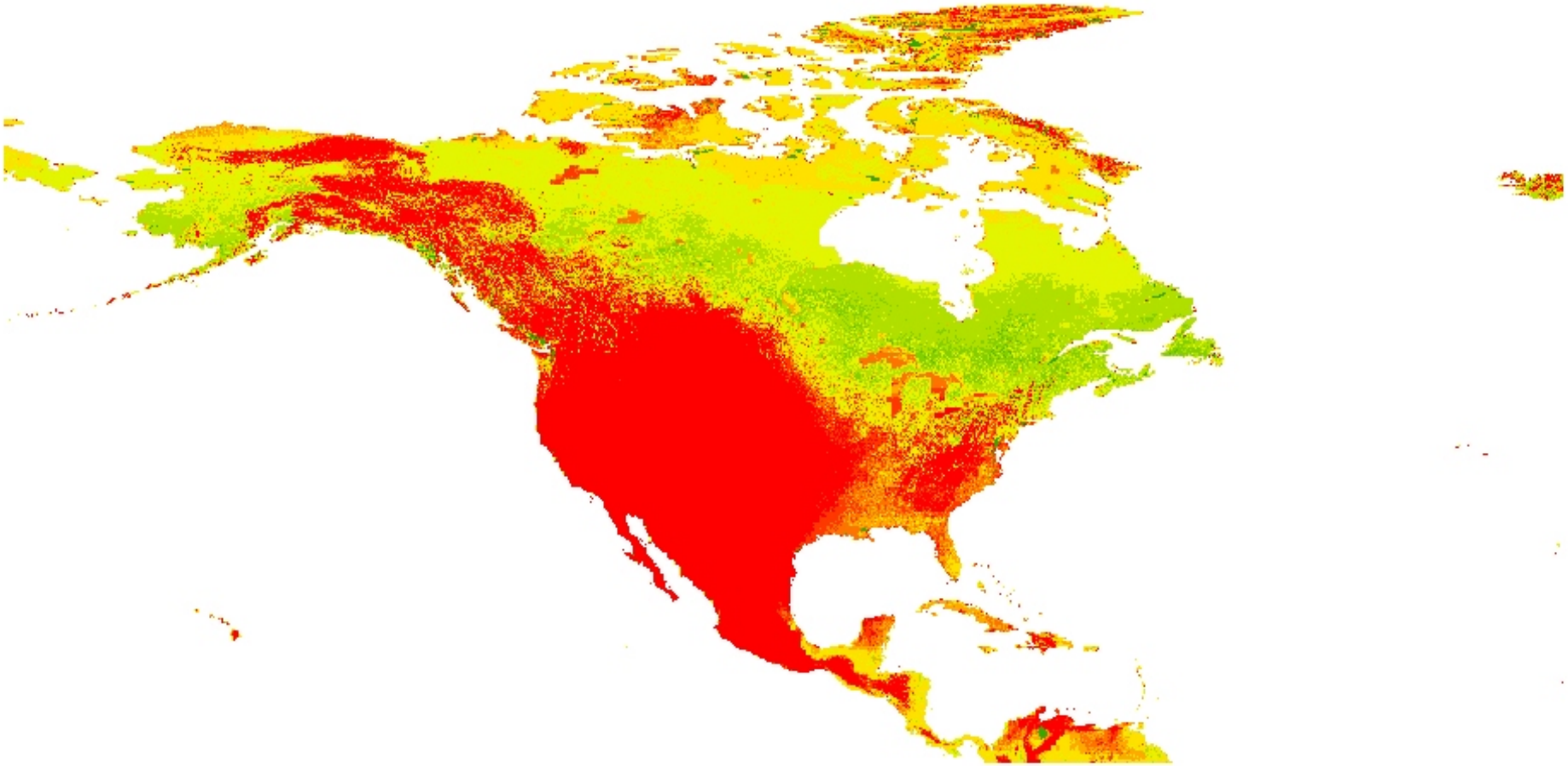
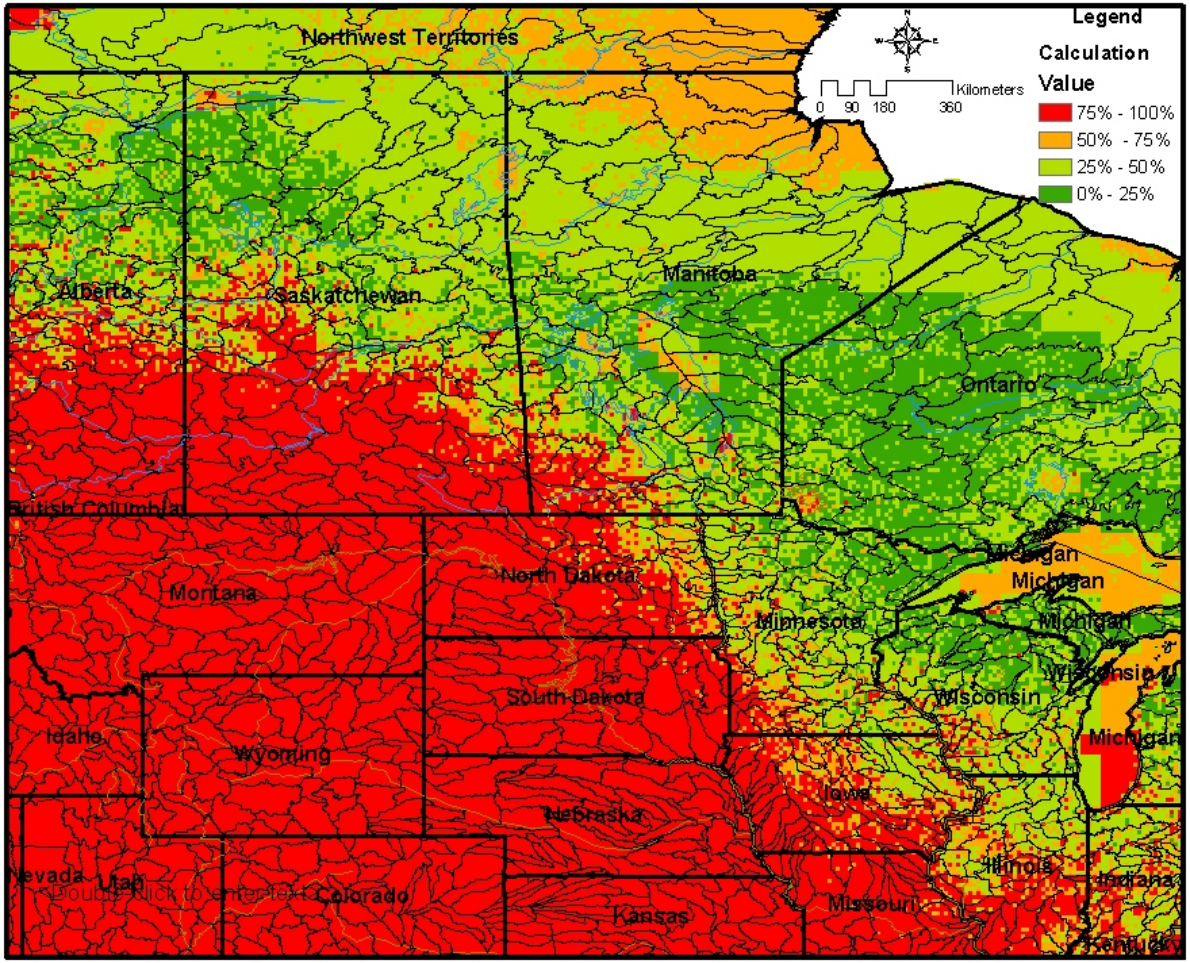


Figure 15. Zebra mussel predicted distribution based on logistic regression only.



Given this time-dependent character of data acquisition, Figure 16 through Figure 18 summarize GARP best subsets for predicted distributions of tamarisk. A simple sensitivity analysis targeted on aleatory uncertainty (as captured by on data completeness) suggests that predicted distributions for *Tamarix* spp. were very sensitive to spatial data compiled from various regional sources. Predictions of *Tamarix* spp. distributions derived from each of three data sets were poorly correlated (Table 9), and consequently data completeness markedly affected interpretations of risk associated with *Tamarix* spp. invasions in North Dakota and potential biota transfers to the Red River basin. The extend of data compilation reflected various "updates" that should be acknowledged as likely events for data compilations for other species that are gathered from multiple sources.

Table 9. Summary correlation table for comparisons of spatial-censored data for predicting tamarisk distributions using GARP.

	Correlation Coefficient (r)[1]		
Species and data support[2]	Tamarisk-all	Tamarisk-061104	Tamarisk-space
Tamarisk-all	1	0.75	0.55
Tamarisk-061104	na	1	0.68
Tamarisk-space	na	na	1

[1]see Appendix 14 for detail.

[2]Tamarisk-all = presence data includes over 5,000 point-data; Tamarisk-061104 = presence data includes greater than 100 point data; Tamarisk-space = presence data includes less than 100 point data; each data set a collection of *Tamarix* spp.; na = comparison not applicable.

[3]Correlation analysis completed for identical cases serving as quality control check on calculation.

4.9 Risk associated with unknown biota and extirpation process consequent to invasion

Provided input from Reclamation and Technical clearly identified interbasin transfers of "unknown biota" was a recurring issue among stakeholders, and a technical analysis of risks associated with these "as yet to be identified" species of concern for invasion are considered in the

following discussion focused along with a general discussion on the extirpation process critical to both establishment of a successful "invader" or the demise of a target species effectively displaced by an invading species.

4.9.1 Unknown biota. While the list of biota of concern generated by Reclamation and Technical Team was ambitious, especially for analysis of species-specific risks representative of those associated with biota transfers consequent to interbasin water diversions, those species identified in Section 1, Table 1 may be regarded as a "drop in the bucket" relative to number of species on Earth that vary between 1.2 and 1.6 million for low estimates to high estimates that range 25–30 million, depending on authority (see, e.g., http://www.enviroliteracy.org/ article.php/58.html last accessed December 4, 2004; and Wilson 1988). That species of "unknown biota" will be recognized as species of concern for invasion in future investigations clearly is certainty. Yet, historically and currently, ecologists and biologists focused on biological diversity have developed "short lists" of species that expert judgment and past experience suggests are likely to become "problem species" in the future. Hence, "virtual organisms" or "virtual species"[4] targeted on invasive-species concerns have not received sufficient level of effort in methods development to support an analysis of risks comparable to that completed for the biota of concern generated by Reclamation and Technical Team in collaboration with CERC. However, life history attributes of invasive species have been well documented, and would serve a function comparable to that of the virtual species in a narrative analysis of risks associated with "as yet to be identified" species that will very likely come to future discussions of biota transfers potentially realized if water diversions between Missouri River and Red River basin occur. Secondarily, these life-history attributes could be incorporated into the design of a virtual species, e.g., computational algorithms, that could be applied to future investigations focused on species invasion.

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[4]See, e.g., http://ecospat.unil.ch/, and recent publications, e.g., Hirzel, A.H., and Arlettaz, R., 2003, Modeling habitat suitability for complex species distributions by environmental-distance geometric mean, Environmental Management, published online November 2003, DOI: 10.1007/S00267-003-004-3, and Hirzel, A. H., Helfer, V., and Me´tral, F., 2001, Assessing habitat suitability models with a virtual species, *Ecol. Model.* 145:111-121.

Figure 16. Tamarisk distribution-censored through historic snapshots of presence data (limited to early records in SW US).

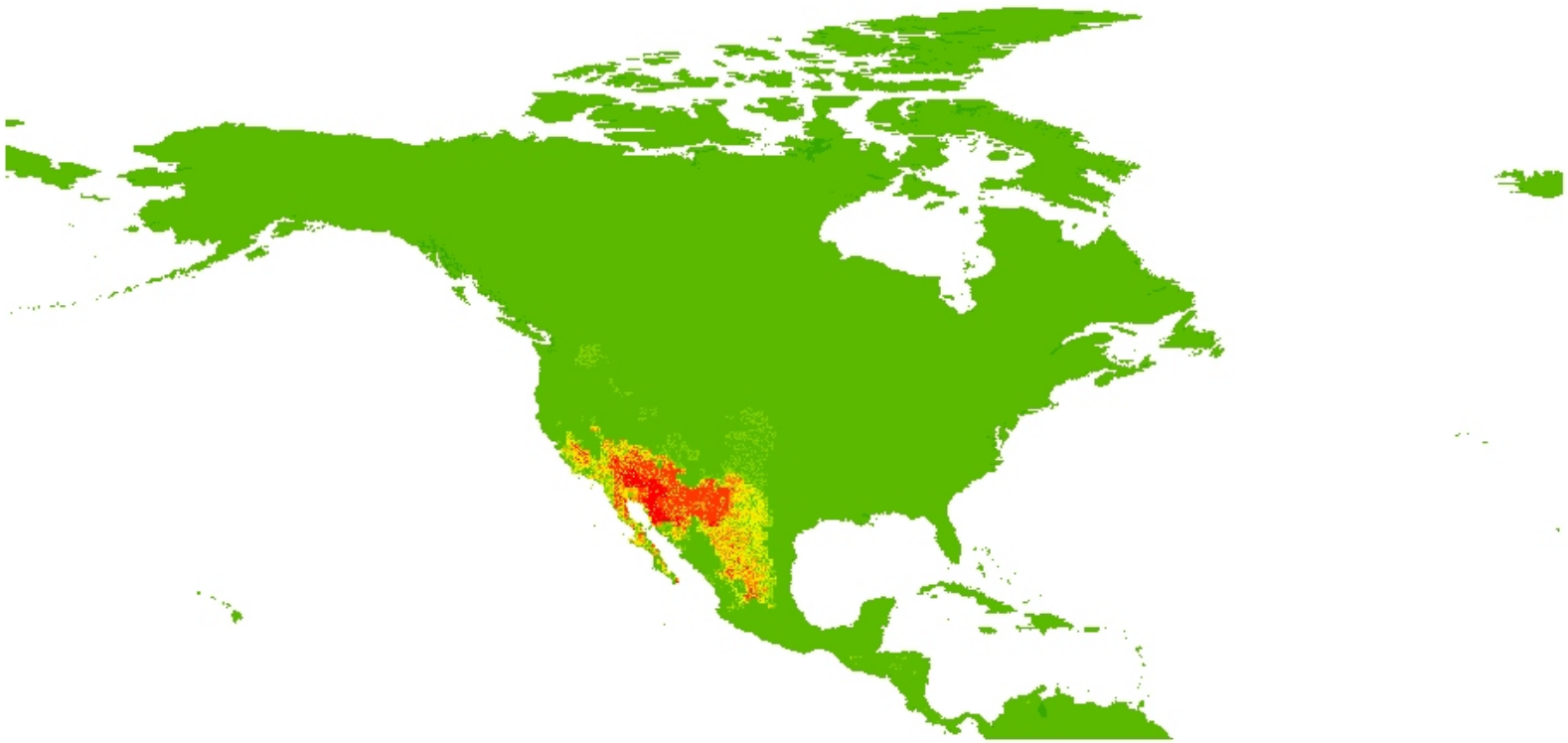


Figure 17. Tamarisk distribution censored through historic snapshots of presence data (limited to presence data extending to southwest and intermountain west of US).

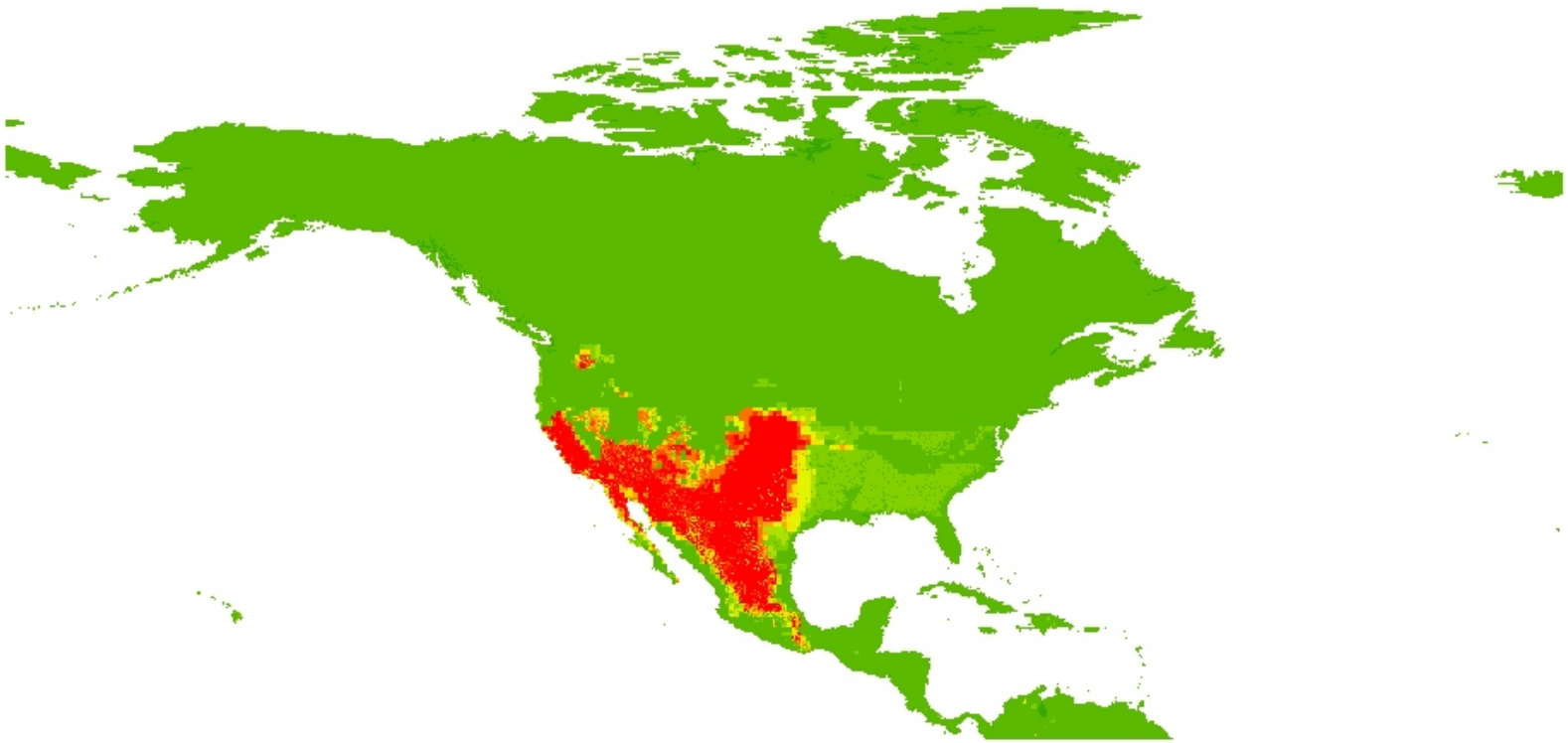
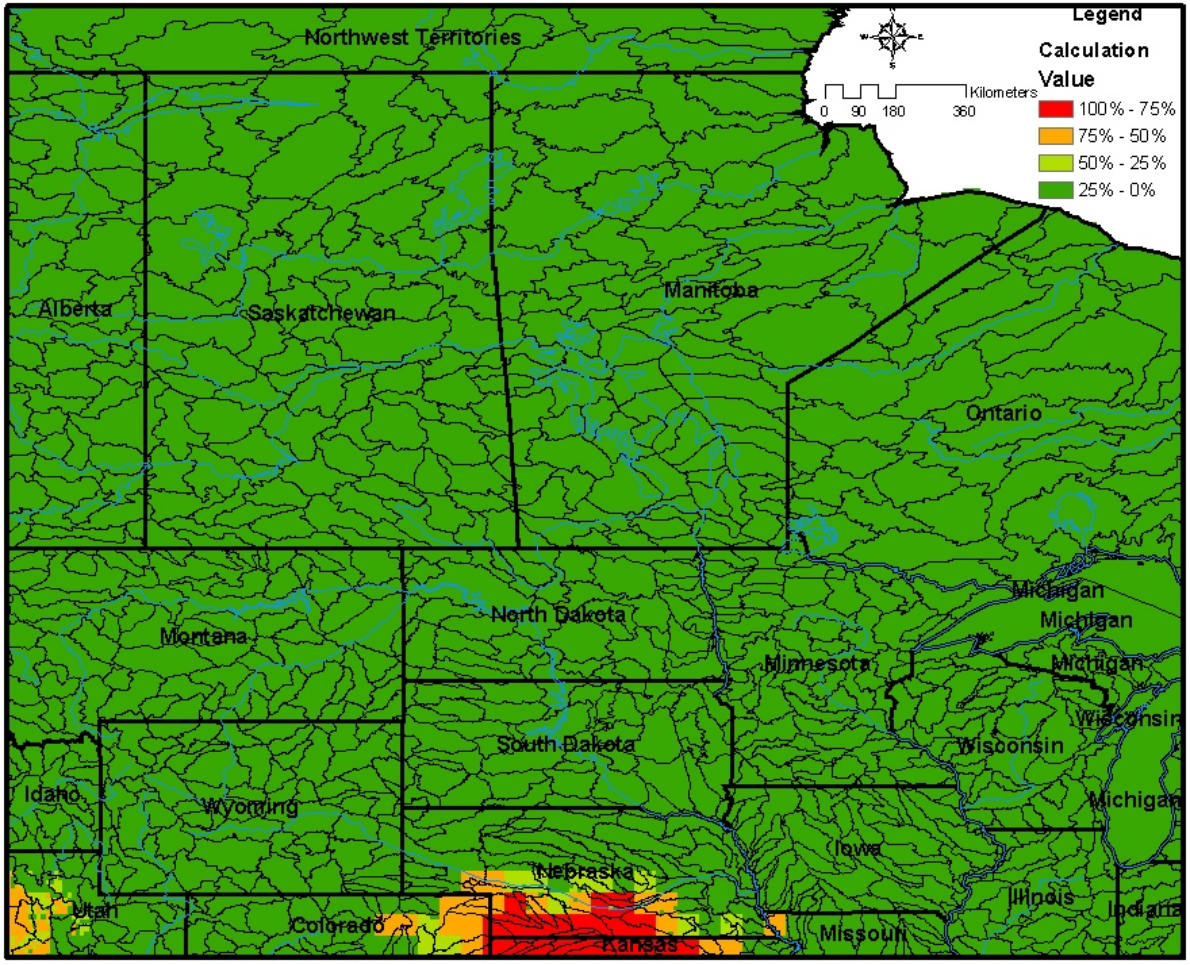


Figure 18. Tamarisk zoom of SW and intermountain west presence data.



Attributes of invasions species. Regardless of the geographic location, invasive species successfully established in previously unoccupied landscapes exert adverse effects on challenged systems (e.g., disrupt community structure and function in systems previously not occupied by the invasive species) or members of those systems (e.g., directly or indirectly gain competitive advantage over indigenous biota). These adverse effects range from relatively limited, but direct interactions that result, e.g., in reduced populations of target species or groups of closely related species (e.g., zebra mussel's adverse impacts on native Unionidae mussels) to widespread effects that reflect not only these direct species-level interactions but indirect effects manifest by alterations in community structure (e.g., purple loosestrife's impacts on wetlands). When adverse effects of invasive species exist singly or in combination with other environmental stressors such as land-use practices or chemicals released to the environment, loss of native species is a recurring effect widely documented in the literature (see, e.g., Heinz Center 2002). Population declines may follow the time course of the invasion process, wherein initial conflicts between targeted-native species and invasive species result in decreased populations of natives through direct competition which in turn may be exacerbated by predation that ultimately leads to extirpation or extinction by cumulative effects of competition-predation. Effects are also manifest by modification of the habitat, especially for invasive species that exert a dominant effect on habitat structure and function. These adverse effects are commonly indirect in their action, e.g., invasive purple loosestrife directly alters wetland vegetation community structure, which then adversely effects insect communities formerly linked to the native plant community. Mechanisms to increase the "invasiveness" of a species range from those life-history attributes that ensure a species' capability to modify, e.g., physically alter, previously unoccupied communities, rendering habitats amenable to their continued colonization, to genetic capacities to hydridize with native species and in the process expand a species range at the expense of another. In general, attributes of highly successful invasive species may be considered as

- having high fecundity and reproductive rates, e.g., "pioneer species" that characteristically have relatively young-age at first reproduction, and may have relatively long reproductive life, if not bearing great numbers of propagules with each generation,
- having high dispersion rates,
- being successful as a "single parent," e.g., parthenogenic species, species with limited parental investment, or asexual species,
- having vegetative or clonal reproduction as a common life-history attribute,
- presenting high phenotypic plasticity,

- presenting a wide physiological tolerance to environmental stressors, including life history traits to assure passage through relatively long periods (in life-times) of dormancy, encystment, or similar adaptations,
- presenting a large native range, e.g., having relatively wide latitudinal or altitudinal range in its native setting,
- being characterized as a habitat generalist,
- being omnivorous in food habit, and
- tending toward abiotic mechanisms (e.g., wind and water) or phoretic mechanisms (e.g., hitchhiking) for dispersal.

Attributes of systems prone to invasion. Invasive species accidentally or intentionally introduced to a previously unoccupied landscape generally are more likely to be successful as invaders if land masses are small and isolated, e.g., classic invasion biology focused on islands, or insular habitats characterized by small areas isolated from recolonization sources. History also suggests that invasions are more likely to be successful in receiving areas are characterized by high endemism, a condition typical of "islands" or disturbance communities. In general communities most vulnerable to invasion are characterized by

- having climates similar to those of the invading species source area,
- having attributes characterized of "early-succession stage" communities, e.g., disturbance communities,
- having low species diversity within the native species currently occupying the target area,
- having a relatively low abundance, if not absence, of predators and parasites that might limit success of invasive species, if the species was successful in reaching the previously unoccupied area,
- having relatively "simple" predator-prey systems characterized by food webs having few interconnections,
- having few species that would directly compete with candidate invasive species (e.g., receiving areas lacks ecological equivalents), and
- having the previously unoccupied area present a history of past invasions, e.g., because of relative absence of wildfire which may lessen likelihoods of successful plant invasions or increase presence of carriers with the capacity to transport invasive species as "hitchhikers," e.g., pathways linked to corridors of human transportation and migratory animals.

Community response to invasion varies, depending upon the species' composition and the extent to which invasion succeeds, e.g., from complete extirpation of members of the community to relatively slight impact of the invasion. Often, the extent to which invasive species dominate the landscape depends on the location's previous history of disturbance; highly disturbed habitats present greater risks for invasion than habitats that are relatively undisturbed. Habitat fragmentation and increased human activity (e.g., construction) foster increased risks of establishment of invasive species as does reduced habitat heterogeneity.

Invasion success is often low, ranging between 5% and 40% success, again, depending on the system at risk (see "ten-ten" rule; Section 4.4 and references therein). The likelihood of a successful invasion increases when target species occur at low density, and the invading species encounters limited resistance, e.g., competitors and disease agents are few, if any, in the area invaded. In contrast to species being displaced, invasive species tend to be less vulnerable to endogamy; species likely to be displaced generally display low viability under conditions reducing population size. Target species also tend to be more likely to display adverse effects when confronted with an invasive species if their populations display marked oscillations and their life history is characterized by limited variation and trophic specialization, e.g., relatively limited food choice. Successful invasions depend on population-level responses of both the species entering the previously unoccupied landscape and the target species most likely displaced by the invader. Hence, species' attributes that would characterize the "as yet to be identified" invasive species should also focus on the extirpation process.

4.9.2 Generalized extirpation process. Population viability is a problem common to both the invader and the species likely to be displaced consequent to invasion. As a general rule, population viability most often becomes a limiting factor for insular species, or species occupying habitat "islands" in a fragmented landscape, subject to demographic and population genetic problems associated with reduced populations and changes to their environment, e.g., habitat alteration, including releases of chemical stressors and increased predation or competition from other species such as invasives or disease agents. As such, the extirpation or extinction process results from reduced population viability. Reduced population viability reflects an integrated response often times initiated by a limited number of events (such as a species invasion), but ultimately, reduced population viability is the manifestation of multiple interacting factors yielding population declines bounded by extinction (see Beissinger and McCullough 2002; Newman and Palmer 2003).

Regardless of whether the invading species or the species likely to be displaced is concerned, demographic factors are a dominating influence on a population's viability. A species "intrinsic rate of increase" (referred to as *r* in the population ecology literature) reflects a composite value of birth and death rates and is subject to a wide range of environmental factors (see, e.g., Vandermeer and Goldberg 2003). Initial population size influences how a species will respond to challenge; hence, the inherent differences between the successful invader and the "unsuccessful" target species, wherein the invasive species is characterized by a capacity to thrive at low populations characteristic of founding groups that establish beachheads in previously unoccupied landscapes, and the target species is challenged, perhaps sufficiently to face extirpation or extinction (see, e.g., Elton 1958).

Stochastic events threaten the persistence of small populations regardless of their status as founding populations of an invasive species or the waning numbers of a species in the process of being displaced by a species whose arrival heralds the establishment of a species in previously unoccupied territory. Four general classes of threats may influence population viability:

- Demographic stochasticity
- Environmental stochasticity
- Natural catastrophes
- Genetic stochasticity

Demographic stochasticity is generally unlikely to be a problem in populations with more than 50 to 100 individuals. In contrast, environmental stochasticity requires population sizes on the order of 1000 to10,000 to buffer against adverse effects of such an event on the population, and natural catastrophes, depending on the specific events being considered, may be such that no single population can ever be large enough to buffer against natural catastrophes. Genetic stochasticity tends to be problematic only when initial population size is less than 100 to 300 and is not likely to be a problem in populations large enough to buffer environmental stochasticity (see, e.g., Beissinger and McCullough 2002; Newman and Palmer 2003). These generalized values for populations size critical to specific threats are generally applicable to those vertebrate species included on the list biota of concern, although these threats may be equally applied to other biota and only a species-specific analysis would yield population values comparable to those ranges listed here. Similarly, stochasticity captured in jump events within stratified diffusion processes resulting in long distance dispersal events may be considered within the context of "Markov Jump" (see, e.g., Breuer 2003; Asmussen 2003; Durrett 1996) and incorporation of these

concepts in future analyses of selected species, e.g., zebra mussel and New Zealand mudsnail may be warranted.

Attributes of a species' life history are critical to the evaluation of a population's viability, with the most critical stages of an organism's life cycle likely yielding the greatest impact on population dynamics. For example, attributes of an organism's life history that limit population size, population growth rate, or species distribution are generally most critical in projecting whether a founding population will become established and invasion ensured.

Within the context of population biology and conservation biology, two guiding principles influence population viability analysis: (1) any finite population will eventually go extinct and (2) population size cannot be predicted with absolute certainty but can only be specified as probabilities of particular outcomes. Population viability analysis (PVA) concerns a naively simple question, "How large must a population be for it to have a reasonable chance of survival for a reasonably long period of time?" The term viability considers the persistence of the population over some reasonably long period of time, with a particular focus on characterizing population levels associated with the population being self-sustaining. Both founding populations of invasive species and remnant populations of species on the decline potentially share a common problem, i.e., if their population reaches some "minimum value" and gets too small, it may no longer be able to sustain itself if its population numbers go below some threshold which leads to extirpation or extinction. For a native species confronted by a challenge such as a species invasion, its survival to date does not necessarily imply continued population numbers and avoidance of future declines, given the multiple threats the species encounters. Threats to population persistence are systematic, and analysis of life history, e.g., through simulations using deterministic and probabilistic models should identify the life-history stages that are most critical in determining abundance of biota as yet to be identified, so risk-management efforts to control interbasin biota transfers can be focused where they are likely to be most successful.

4.10 Risk reduction and control systems technology

As suggested by the previous discussion regarding general traits of invasive species, the analysis of species invasions or shifts in metapopulations associated with interbasin water diversions should be incorporated into risk management activities pursued by Reclamation and Technical Team. A similar role should be given to evaluations of control system technologies

potentially serving to reduce risks associated with interbasin water diversions. While the current investigation's focus has been on competing risks as those are reflected in project and nonproject pathways, a similar process of analysis could be fully developed in regard to the evaluation of risks associated with the range of mitigation options available to the design and implementation of control systems serving water diversion needs. For example, classical competing risks approaches could be applied to the analysis of water treatment options as those related to risk reduction.

For example, chlorination of drinking water supplies as a standard disinfection tool has a relatively long history and has greatly decreased mortality from waterborne infectious disease in the 20th century (see http://www.awwa.org/Advocacy/learn/info/HistoryofDrinkingWater.cfm last accessed December 4, 2004). However, adverse effects associated with various chlorination practices have been identified that suggest an unintended competing risk process has been ongoing since the chlorination became a tool common to water treatment technologies. Finished water resulting from chlorination contains chemical constituents associated with the disinfection process (referred to as disinfection by-products, DBPs; see Appendix 11 and Appendix 12). Under the mandate of the Safe Drinking Water Act Amendments of 1996, US EPA has published the Contaminant Candidate List (CCL; see Embrey et al. 2002 and regulatory updates available online at http://www.epa.gov/safewater/ccl/cclfs.html last accessed December 4, 2004) and identified regulated water constituents or candidate constituents that are currently unregulated (e.g., chemicals or biological organisms), including DBPs. Similar issues surface for alternative disinfection processes, e.g., ozonation yields bromate, which presents carcinogenic risks to finish water derived from such a disinfection process (http://www.epa.gov/safewater/mdbp/dbpfr.pdf). See Appendix 12 for a brief characterization of water treatment and control system alternatives potentially applicable to risk reduction tools amenable to preventing or controlling biota transfers collaterally occurring with interbasin water diversions.

From a competing risk perspective, the benefits of water disinfection to manage risks associated with biota transfers must be considered within the context of these process-derived constituents presenting potentially adverse effects on the water consumer; that is, these competing risks must be considered to gain the benefits of water disinfection while minimizing the potential for chemical-related adverse effects associated with disinfection. For example, risks associated with exposure to DBPs varies across the range of DBPs, the source of water, and time of year which influence the presence and relative concentrations of these chemicals. One family of DPBs includes the trihalomethanes which are found in chlorinated water. Chloroform is the most prevalent trihalomethane, is carcinogenic in rodents, and bromodichloromethane has also been

shown to be carcinogenic in rodents. A second important family of DBPs, the haloacetic acids, includes dichloroacetic acid and trichloroacetic acid which have both been causally linked to liver tumors in mice when exposed to high concentrations. Dihalogenated and trihalogenated acetic acids (such as dibromoacetic acid, dichloroacetic acid, bromodichloroacetic acid and bromochloroacetic acid) appear to differ in their mechanisms of toxicity; hence, their risks vary and influence the analysis of competing risks, even in well-specified systems. A third family of DBPs, the haloacetonitriles, are also unintended derivatives of water disinfection, but little toxicity data are available for these constituents. Alternative chlorination process present different risks. For example, disinfection with a strong oxidant such as chlorine dioxide yields low trihalomethane concentrations in drinking water but high levels of chlorate. Toxicity data on chlorate are limited, but studies completed by US EPA and National Institute of Environmental Health Sciences (NIEHS) have demonstrated adverse effects with exposure to chlorate, particularly with respect to thyroid function (see, e.g., US EPA 2004, 2002, 2000).

4.10.1 Generalized scenarios supporting preliminary risk reduction analysis. The analysis of risks associated with interbasin biota transfers focused on three general scenarios viewed within the context of baseline condition, viz., no water diversion implemented and within-basin water supply serving water needs. Essentially, risks of species invasions or shifts in metapopulation dynamics under this “no water diversion” scenario reflect the past history of species invasion in the Missouri River basin and Red River basin, wherein species foreign to either basin have entered the area and failed to establish a sustainable population, or have entered the area and subsequently established a sustainable population and currently flourish to varying extents within the region(e.g., Eurasian water milfoil, purple loosestrife in both HUC09 and HUC10). As indicated by the listing of exotic species collected in Missouri River and Red River basins (see Appendix 7 and Appendix 8), there have been many “visitors” from outside these areas of concern collected in the relatively recent past, and the history of successful invasions in either the Missouri River basin or Red River basin is replete with examples of intentional or accidental releases of species not native to the areas of concern, e.g., zander, rainbow trout, various plant species such as leafy spurge and other noxious weeds, and Eurasian water milfoil and purple loosestrife in aquatic and wetland habitats.

Although concerns related to shifts in metapopulations as envisioned occurring in Missouri River and Red River basins could be broken out along lines similar to biota transfers that represent species invasions, the level of data available for such resolution is not available; hence, conceptual arguments must be developed in recognition of this aleatory uncertainty. Best-

available data for considering a shift in metapopulations relative to an interbasin water diversion is currently illustrated by records of disease occurrence maintained by regional organizations, e.g., public health agencies of North Dakota, Minnesota, and Manitoba (see Appendix 3B). Unless an outbreak occurs characterized by records sufficient to time-series comparisons, e.g., point data nested within the usual by-county records, statistical analysis focused on within-basin and between-basin comparisons is highly unlikely to identify differences presumptively assigned to causal linkages to waters stemming from interbasin diversions. Quantitative arguments either supporting or refuting these linkages would necessarily be developed following epidemiological methods, which would best be served through designed monitoring programs.

At the present time, however, data collected regarding the occurrence of waterborne disease in counties within Missouri River basin or Red River basin (Appendix 3B) are inadequate to serve as an illustration of a spatially-linked quantitative evaluation of risks associated with biota transfer (i.e., based on 2- or 4-digit HUCs). Nevertheless, those data support a qualitative analysis of risks that could support risk-management decisions, especially in light of the categorical analysis summarized in Section 3. Many of those representative biota summarized and highest ranking in Section 3 (see Table 1 through Table 8 and Figure 9) represent species that currently occur in both Missouri River and Red River basins, which suggests "invasions" from sources areas to receiving areas occurred in the near to distant past, and for some species, occurrence was clearly established from the start of record keeping. For example, the agents of zoonotic disease (e.g., *E. coli* and *Salmonella* spp.) present a relatively well-defined historical data compilation, and from a "screening level" perspective (see Appendix 3B), presumptive linkages between sources of disease agent and disease outbreaks can be eliminated (if warranted by a specific analysis), using available epidemiological methods (see, e.g., Lawson 2001). In contrast, direct linkages between biota originating from Missouri River sources and disease outbreaks in Red River basin would be difficult to establish, given the data most likely available in the event that outbreak occurred. Characterizing indirect causal linkages between biota currently residing in both basins, but whose linkage to adverse effects in the Red River basin stems from its origins in source waters in the Missouri River basin would be practically intractable unless sufficient forethought were given to a monitoring program intended to address this level of causal analysis.

4.10.2 Open-conveyance water transfer between Missouri River basin and Red River basin. An alternative initially developed under the auspices of earlier versions of legislation supporting interbasin water diversions (e.g., Garrison Diversion Unit; see Section 1), the open-conveyance scenario, e.g., water diversion via canal, is only briefly considered, given the

existing stakeholder input regarding options most likely to be implemented to support water supply needs. From the technical perspective, systems such as that originally envisioned for an open conveyance would be suspect with respect to establishing a presumptive linkage between biota transferred to the Red River basin from the Missouri River basin as a consequence of interbasin water diversion. Historic concerns voiced by IJC (see Section 3) were not unfounded and represented an early implementation of the "precautionary principle" (see, e.g., Raffensperger and Tickner 1999; but also see Goklany 2001), and open conveyance (e.g., canals) for implementing water transfers would have yielded a series of relatively uncontrolled collateral events beyond those summarized in the fault-probability trees supporting the development of the simple simulation model focused on biota transfers occurring between Missouri River sources and Red River receiving areas. An open system as originally envisioned and historically initiated would have allowed multiple inputs in the transfer system via multiple pathways. While an open canal would have served as a "preferred pathway" or pathway of convenience, potential linkages between basins of concern would have been more highly diffuse (nonpoint) in character relative to closed-conveyance systems, making predictive (*a priori*) or forensic (*a posteriori*) studies intractable with respect to identifying unequivocal linkages between Missouri River sources and Red River receiving areas. Systems incorporating open conveyance will likely be characterized by moderate to high risk, of biota transfers, if used to implement interbasin water diversions.

Given the outcomes from the simulation completed for the simple probability model focused on the flow of events characterizing biota transfers consequent to interbasin water diversions (see Appendix 13), distinctions between risks anticipated for open-conveyance transfers and closed-conveyance transfers of untreated water cannot be quantitatively characterized. Yet from an conceptual perspective of risks, the simulation and supporting analysis seem sufficient to develop a line of argument for considering closed-conveyance transfers of untreated source waters. While the number of inputs into an open-conveyance system would be fewer than those inputs into a closed conveyance (e.g., pipeline), closed-conveyance transfers of untreated source waters from the Missouri River would be associated with risks that differed only marginally from those risks associated with an open-conveyance transfer, especially within the context of a point estimate of probability bounded by an estimate of error as derived from a Monte Carlo analysis (see Section 4.8.2 and Appendix 4). For example, untreated waters from the Missouri River piped from source areas to a discharge point, e.g., on the Sheyenne River would do little to reduce risk of interbasin biota transfer, especially for those biota presenting life-history attributes (such as small propagule size or having propagules resistant to rigors of piped transfer). At the least, piped transfers of untreated source waters would reduce the likelihood that causal

linkages, e.g., in a forensic analysis, would be less confounded than in an analysis of open systems, since the number of inputs to the system would be reduced. Risks associated with biota transfers realized collateral to an interbasin water diversion implemented via closed conveyance of untreated source waters then would also be regarded as a moderate to high, dependent on organisms most likely to succeed in the biota transfer process. Not all organisms will be equally likely to successfully complete the transfer process, if piped but untreated waters were realized.

4.10.3 Closed-conveyance water transfer between Missouri River basin and Red River basin. Piped-water transfers of source water appear the most likely alternatives for reducing risks associated with interbasin water diversions. Under this general scenario, alternatives were briefly considered that focused on piped transfers of untreated source waters, as noted previously, and treated source waters (see Section 4.10.2). Moreover, the location of control systems facilitating water treatment, i.e., control system located in Missouri River basin or control system located in Red River basin, was considered, although quantitative evaluations of risks were not completed, since the control system's specification is currently being identified. Distinctions between risks associated with control systems located in either Missouri River or Red River basins, and technological differences available to that system's design (e.g., including media filtration or pressure-driven membrane filtration technologies) were considered analytically with lines of argument based upon available literature and simulation output.

Source waters from the Missouri River transferred to Red River basin via intervening control system are characterized by low to very low risks. Costs reflected in risk reduction relative to alternative control systems have not been characterized, given the design options currently being considered. Water treatment alternatives potentially contributing to risk reduction under this general scenario would entail various chemical and physical treatment options such as chlorination or chloramine treatment, ozonation, media filtration (e.g., slow sand filters), and pressure-driven technologies (e.g., microfiltration or ultrafiltration; see Mallevialle et al. 1996; Duranceau 2001; Schippers et al. 2004). To minimize risks associated with interbasin water diversions, the control system should incorporate multiple technologies, e.g., conventional pretreatment, chemical or physical treatment, and filtration. To further reduce risks associated with trans-basin water distribution, the control system should reside within Missouri River basin then treated water piped to end-users in the Red River basin. If treated waters are contained within the control system from "point-of-acquisition to point-of-use," biota transfer becomes an engineering-design issue, wherein system efficiency and system failure become critical issues in risk reduction.

For example, differences in risks associated with a control system's geographic location, e.g., within the Missouri River basin or within the Red River basin) primarily reflect the distribution-related outcomes that result from interactions of "status of source water" (i.e., treated or not treated) and failure in distribution system, e.g., pipeline failure. Failures of water distribution systems such as pipeline breaks or water leakage have been characterized (see Deb et al. 1995) and provide empirical values that could guide system design and maintenance schedules to support a particular level of risk associated with interbasin transfers, e.g., less than 20 breaks/100 miles/year and less than 4,000 gallons/day/mile for water loss due to breaks. From a risk reduction perspective, whether the pipe is buried or not buried also must be considered (see Moser 2001), since pipe breaks and subsequent water loss occurring in systems of buried pipe would be less likely to lead to completed pathways for biota transfers than systems where pipes are located aboveground.

While the simulation outputs reported in Section 3 were based on a simple probability model of the biota transfer process, those results do provide insight to risk reduction and the role that a designed, multiple-step control system would play in achieving a level of risk acceptable to Reclamation and Technical Team. Again, a goal of "zero risks" cannot be achieved. Any designed control system will only attain performance that yields risks that at best approach "practically zero," given the stochasticity of the invasion process and the inevitable failure in components of the control system. Depending on the control system's design, e.g., level of redundancy and selection of technologies incorporated into the treatment and distribution network, risks may be reduced to "practically zero," although the simulation outputs at the extremely low end of the range of probabilities (Section 3, Figure 2) likely capture violations of assumptions of strict independence among the constituent events in some instances, e.g., biota transfers may reflect dependence within the flow of events charactering biota transfers of disease agents.

Tracking the inevitable failure of any control system (e.g., through "short circuiting" of pressure-driven membrane devices yielding incomplete removal of microbiological agents from process streams; see Schippers et al. 2004), biological tenacity significantly contributes to characterizing a "practically zero" performance criteria of any control systems. The nearly infinite number of trials (e.g., as number of propagules competing for transfer or the time allowed for competition) becomes a critical aspect of the invasion process that is captured by output from the simulation but not readily apparent on casual observation of the fault-probability tree that illustrates the invasion process.

The range of risks displayed in output from the simulation (see Appendix 13) must also be interpreted within the context of seasonal and daily dynamics of water transfers, e.g., risks may vary as a function of in-stream flows characteristic of the Missouri River and the volume of water withdrawn from the source. As a source for biota of concern, especially for disease agents whose environmental concentration will vary as a function of season, sources waters from the Missouri River will challenge a control system to varying extent during a system's annual performance cycle. While a quantitative comparison of time-dependent risks are not included in this initial evaluation of risks, seasonal changes in the quality of source water should be considered in the control system's design.

Biological invasions are not a "snapshot" process but occur continually within a dynamic ecological setting. Hence, our characterization of risks associated with biota transfers realized with control systems in place is "practically zero," but will never equal zero. The selection of component technologies within the control system's final design will influence the contribution of engineering failures to the invasion process, and as such, can be pursued once an acceptable risk is determined by Reclamation and Technical Team.

4.10.4 Risk reduction, risk minimization, and risk management. Identifying acceptable risks, in part, relies upon resolution of differences in resource valuation among stakeholders (see, e.g., Field 2001). Once acceptable risk is characterized, technical support within a resource management program can be fully tasked to develop control systems whose performance criteria attain that level of acceptable risk. To initiate discussions among Reclamation and Technical Team, a preliminary risk reduction analysis was completed as part of the current investigation. Risk reduction was considered relative to the generalized scenarios briefly profiled in the preceding section and is illustrated using output from the simulation completed in the analysis of risks associated with biota transfers potentially realized as a consequence of interbasin water diversions (Figure 12).

With guidance from Reclamation and Technical Team, control systems potentially serving to reduce risk were identified and represented by "off the shelf" technologies that could serve as candidate risk reduction tools for this preliminary evaluation. Selected technologies have been briefly considered in Appendix 12, including alternatives for chemical treatment (e.g., chlorination and chloramination), physical treatment (e.g., ozonation and UV disinfection), and pressure-driven technologies (e.g., microfiltration, ultrafiltration, and nanofiltration). In addition to the brief overviews of these alternatives in Appendix 12, slow sand filtration was briefly considered

early in Section 4 as an alternative media filtration technology. Each of these technologies may be used independently, but increasingly, each occurs as combined technologies, e.g., pretreatment of coagulation-flocculation followed by chemical treatment and filtration steps (see, e.g., Schippers et al. 2004), which enhances risk reduction capabilities for target constituents in source waters (e.g., disease agents).

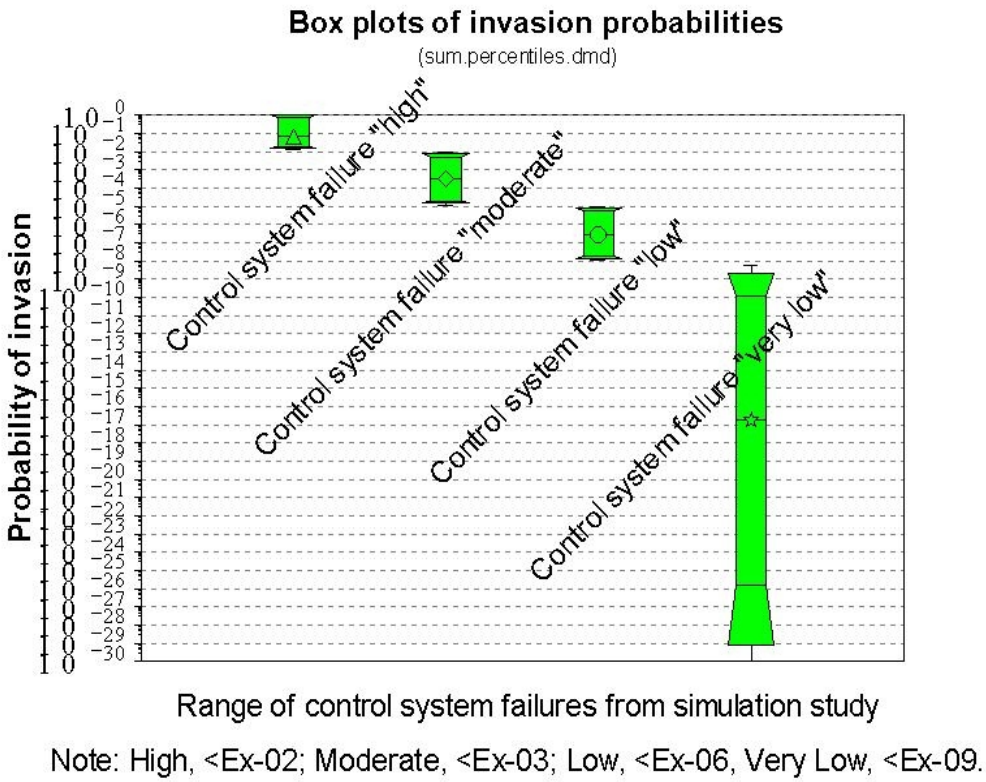


Figure 12. Probability of successful invasion given specified failure rates in control systems mediating interbasin water diversion.

As illustrated by a cursory review of the existing literature, there are a range of tools pertinent to technical support, e.g., as screening tools and simulation models pertinent to biota transfer and predictions of species invasions, but given our overarching conceptual model (Section 2, Figure 7) and the fault-probability trees guiding the analysis of risks (Section 2, Annex Figure 1through Annex Figure 5), output from the simulation was considered from the spectrum of control system performance. To tie the characterization of risks developed from the analysis detailed in Section 3 with a preliminary evaluation of risk reduction alternatives available to

resource management, the output of simulations (Section 3, Figure 2) based on the simple probability model of biota transfer and species invasion was considered within the context of system failure, or more generally, the system's incapacity to always eliminate biota of concern from its process stream. System failure yielding biota transfers and the potential for establishment of sustainable populations in the receiving system were considered as two mutually exclusive categories: (1) those associated with system breakdown (e.g., pipe breaks within the distribution system, membrane dysfunction consequent to aging) and (2) those associated with incapacity to achieve 100% efficiency in disinfection or removal of biota of concern in the process stream (e.g., short circuiting in ultrafiltration systems; see Schippers et al. 2004). Control system performance was broken down into categories based on failure rates consistent with those risk categories in Table 1 through Table 3 in this section.

Within the context of risk reduction, the box plots on Figure 12 suggest that if control systems meet performance criteria, e.g., provide for "best available technology"[5] to achieve elimination of biota of concern, then risk associated with interbasin biota transfers and their subsequent establishment as invasive species (or significant increases in populations of species currently resident in the receiving basin) are substantially reduced relative to risks associated with a control system that does not meet these performance criteria such as piped transfers of untreated source waters. Again, it must be emphasized that even under specifications of "control system failure very low," invasions may occur, although those probabilities of successful invasion are orders of magnitude less than those observed in the simulation outputs characterized by control system failure rates ranging between "near certainty" and 10^{-6}.

Given current drafts of pending reports[6] and required NEPA documents, options presently being considered by Reclamation and Technical Team reflect a range of alternatives that capture the range of risks identified in this investigation. For example, any option lacking a biota water treatment plant (WTP) would be considered a relatively high-risk option, given current outcomes in our risk reduction analysis. Any biota WTP options, however, would reflect a reduction in risks

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[5]Distinctions between "best available technology" and "best available technology not exceeding excessive costs" are not considered in this characterization but may be pertinent to discussions among Reclamation, Technical Team, and other stakeholders.

[6]Bureau of Reclamation, Dakota Area Office, Bismarck ND; "Needs and Options Report" (Chapter 4, Options; excerpt reviewed May, 2005) and Bureau of Reclamation, Technical Services Center, Denver CO; "Water Treatment Plant for Biota Removal and Inactivation, Preliminary Design and Cost Estimates – Draft Report").

of biota transfers directly associated with interbasin water diversions. At present, options incorporating biota WTP into preliminary designs afford a range of control system technologies, most often multiple technologies, that bring a range of risk reduction tools forward for consideration. Technologies considered for removal of biota from source waters range from primary treatment processes (such as coagulation and settling) to pressure-driven membrane processes (such as membrane- or media-based filtration devices). In parallel with these physical-barrier systems, various options for biological inactivation are potentially applicable to the implementation of an interbasin water transfer, most notably combined chemical treatment (e.g., chloramination) and UV inactivation. By looking at the biota WTP options in view of potential for risk reduction, selection of a biota WTP integral to a control system serving a water diversion can be based on performance criteria, e.g., specified to reject particles at a particular molecular weight cut-off, that can be fully incorporated into future engineering designs.

In parallel with discussions on options for infrastructure potentially supporting an interbasin water diversion, Reclamation and Technical Team may focus on siting of biota WTP, especially within the context of engineering failure analysis targeted on water distribution systems as components of the control system serving any interbasin water diversion. For example, location of the biota WTP in the Missouri River basin near source waters would reduce risks associated with water transfers from river sources to biota WTP. If source waters are treated to specifications, then biota transfer risks will be minimized. In contrast, if biota WTP were located in the receiving Red River basin, an engineering analysis would necessarily consider risks associated with, e.g., pipeline failure in conveying untreated source waters to a biota WTP in the receiving basin. These risks may be considered negligible, depending on designs serving the interbasin water transfer, e.g., buried pipelines conveying untreated waters to a biota WTP in the Red River basin may be considered by Reclamation and Technical Team as a low-risk means of transferring untreated waters from one basin to another. Again, a control system including a biota WTP and sited to reduce risks may present sufficient safeguards to ensure biota transfers are higly unlikely to occur.

4.11 Topics of concern and limits of time and scope

During problem formulation, Reclamation and Technical Team had voiced concerns regarding (1) risks associated with sludge disposal as that related to Missouri River source waters being treated and disposed in the Red River basin, (2) risks associated with genetically modified

organisms potentially being released to Red River basin subsequent to water diversions from the Missouri River, (3) risks associated with emerging diseases potentially linked to interbasin water transfers, and (4) risks of biological invasions or shifts in metapopulation dynamics associated with indirect pathways affected by interbasin water transfers. Although each of these topics may warrant a comprehensive analysis subsequent to this current investigation, the project's scope did not allow for the level of effort required for such an analysis at this time. However, a brief overview of the issues and existing summary of resource management options currently in place to address these concerns are included in the following sections, so discussions among stakeholders can be continued, and if warranted, subsequent iterations of the risk-assessment process may consider these topics comprehensively.

4.11.1 Risks and consequences associated sludge disposal. Water quality, including the management of wastewater and sewage sludge associated with wastewater treatment, has a long regulatory history, which would become a prominent factor in analysis of risks associated with sludges derived from source waters delivered to Red River basin from the Missouri River. Recent focus on sludge (see, e.g., NRC 2002c) would suggest future efforts could be narrowed to technical issues directly applicable to Reclamation and Technical Team questions regarding risk associated with biota transfers associated biosolids derived from waters diverted to Red River basin from the Missouri River. Sewage sludge is the solid, semisolid, or liquid residue generated during treatment of domestic sewage, and its disposal is regulated under the auspices of the Clean Water Act (CWA). Currently, sludge disposal is generally managed by incineration, landfilling, or disposal at certified surface facilities. Of these alternatives, the practice most likely directly linked to biota transfers would be disposal in upland disposal sites, landfills, and land application.

The use of sewage sludge as soil amendments (soil conditioners or fertilizers) or for land reclamation has been increased markedly since 1992[7] in efforts to reduce the volume of sewage sludge that must be landfilled, incinerated, or disposed of at surface sites (see Sopper 1993). Depending on the extent of treatment, sewage sludge may be applied where little exposure of the general public is expected to occur such as on agricultural land, forests, reclamation sites, or on public-contact sites, e.g., parks, golf courses, lawns, and home gardens.

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[7]While not directly relevant to issues focus on disposal practices in the northern Great Plains, ocean disposal of wastewater residuals was prohibited in 1992 and drove wastewater management agencies to seek alternative disposal practices.

Regulations governing land application of sewage sludge were established by US EPA in 1993 in the Code of Federal Regulations, Title 40 (Part 503), under Section 405 (d) of CWA. Sewage sludge conforming to the Part 503 rule standards is termed "biosolids." Under the purview of CWA, biosolids and their management in the US must conform to practices accepted by US EPA as alternatives for handling sewage sludge (e.g., incineration). The Part 503 rule has established management practices for land application of sewage sludge, including concentration limits and loading rates for selected chemicals, and treatment and use requirements designed to control and reduce pathogens and attraction of disease vectors (e.g., insects or other organisms that can transport pathogens). While regulations focused on chemicals would necessarily be considered in any future evaluation of risks associated with land application of biosolids, land-application standards for pathogens would likely be the most pertinent to an evaluation of risks associated with biota transfer. Land-application standards for pathogens specified in the Part 503 rule are not risk-based concentration limits for individual pathogens, but are technologically-based requirements aimed at reducing the presence of pathogens and potential exposures to them by treatment or a combination of treatment and use restrictions. Monitoring biosolids is required for indicator organisms (i.e., certain species of organisms serve as indicators for the presence of a larger set of pathogens).

Land application of biosolids is a widely used, practical option for managing the large volume of sewage sludge generated at wastewater treatment plants that otherwise would largely need to be disposed of at landfills or by incineration. There is no documented findings that the Part 503 rule has failed to protect public health; however, additional technical work is required to reduce uncertainty about the potential for adverse human health and ecological effects from exposure to biosolids. For example, there have been anecdotal accounts of increased disease occurrence in areas where land-applied biosolids has been completed. To ensure the public and to protect public health, there is a critical need to update the scientific basis of the rule to (1) ensure that the chemical and pathogen standards are supported by current scientific data and risk-assessment methods, (2) demonstrate effective enforcement of the Part 503 rule, and (3) validate the effectiveness of biosolids management practices (NRC 2002c). For our immediate consideration, risks of biota transfers directly associated with sewage sludge have not been determined.

4.11.2 Interbasin water transfers and genetically modified organisms. Evaluating biota transfers potentially involving genetically modified organisms (GMOs) far exceeded the time and level of effort identified in the original scope of the technical support activities for this initial

evaluation of risks. Yet the potential for such an evaluation of risks may be indicated in future iterations of the risk-assessment process, depending on discussions among Reclamation, Technical Team, and other stakeholders. Risks assessments for GMOs have increasingly been the object of many national and international workshops and "expert panels" (e.g., NRC 2002b; Letourneau and Burrows 2002). Risks of GMOs linked to biota transfers would be conditioned, in many instances, on outcomes from studies such as the current effort, and the role of indirect pathways would likely be prominent drivers in the analysis, given pathways for transgene transfers that were not operational in this investigation. Given the relatively sparse empirical data, when considered in future studies, initial estimates of risks for biota transfer of GMOs should be considered categorically, e.g., as "high-," "moderate-," and "low-risk" events, at least until specific scenarios are considered.

Within the context of our current focus on biota transfers associated with interbasin water diversions, risks associated with GMOs would mostly likely be directly linked to aquaculture and agricultural practices throughout the northern Great Plains. And given the dependence of GMOs on dispersal mechanisms similar to those for the biota of concern in this current investigation, a focus on risks associated with GMOs would largely reflect conditional events, e.g., with risks characterized for biota of concern, then GMOs might exists as a subset of those representatives. Evaluations of risks of GMOs, then, could be viewed as derivative risks of biota that have not been genetically modified, and a qualitative analysis of conditional probability could be implemented for organismic-level analysis, e.g., for genetically modified fishes escaped from aquaculture facilities (see Muir and Howard 2002) or genetically modified plants increasingly common in agricultural practices (see NRC 2002b; Rissler and Mellon 2000). Unfortunately, complex pathways not at play in the current investigation are likely to confound interpretations of risks, if the focus on GMOs goes beyond these relatively simple "whole propagule" scenario. Gene dispersal opens an entirely underdeveloped field in the evaluation of risks associated with biota transfers, since genetic materials become the "transferred unit of concern." While a comprehensive treatment of risks potentially associated with GMOs is not the focus of this investigation, the potential resource management issues reflecting an interaction between biota transfers associated with interbasin water diversions and GMOs is briefly considered through broad categories of "sources" and "target and nontarget receptors" in agriculture and aquaculture where future investigations might be pursued.

Agriculture. Interactions between GMOs and their wild or cultivated relatives cannot be avoided, given the modes of gene transfer in the field. Depending on one's perspective, transfer of

transgenes from GMOs to wild relatives may be perceived as "genetic pollution" or as a natural process, depending on whether such a gene transfer poses a threat to species or communities in the environment.

Gene transfers, e.g., through pollen or seed dispersal, have been illustrated in studies over the past 10-20 years. For example, gene transfer from radish crop to wild weedy relatives was characterized in early studies completed by Klinger et al. (1992) where dispersal of genetic material occurred over distances of one kilometer (Klinger et al. 1992). "Transgene x Wild" crossbreeds showed significantly greater fruit and seed production, and in all other measured characteristics the hybrids were like weeds. Results from these field studies suggested that neutral or advantageous transgenes introduced into natural population tend to persist in wild populations (Klinger and Elstrand, 1994). Field tests with various transgenic crops have demonstrated both a high frequency and wide range of gene flow (Skogsmyr 1994), although modes of dispersal commonly reflect pathways that are not directly related to interbasin water diversions, e.g., wind-dispersed pollen from genetically engineered crop species mediates hybridization with wild relatives which assures an increased liklihood for transfer of transgenes such as herbicide resistance genes to wild weed populations (Jørgensen and Andersen 1994; Mikkelsen et al. 1996). Gene transfer may also occur between plants and microorganisms, as demonstrated in studies wherein antibiotic-resistance genes were transferred from genetically engineered oilseed rape, black mustard, thorn-apple and sweet peas to the fungus *Aspergillus niger* (Hoffmann et al. 1994). Microorganisms can transfer genes through several mechanisms to other unrelated microorganisms and eukaryotic biota (see Hurst 2000; Watson et al. 2003).

Aquaculture. As with biological invasion in general, anthropogenic introduction of GMOs into natural communities is an ecological concern, because GMOs could adversely affect communities in many ways, including adversely affecting, possibly eliminating, populations of other species (see Mooney and Drake 1986; Lodge 1993). In contrast to anthropogenic introductions—intentional or accidental—the release of transgenic organisms into natural environments poses additional ecological risks because they may also possess some novel advantage, e.g., exogeneous genetic material not occurring in wild-type counterparts in the environment. As a consequence, transgenic organisms might threaten the survival of wild-type conspecifics as well as other species in a community (see Letourneau and Burrows 2002). For example, escape of domesticated fish, whether transgenic or not, into feral populations might adversely affect wild-type populations by introducing alleles that are poorly adapted to natural environments. If the wild population is sufficiently large, these alleles would eventually be

eliminated by natural selection; however, stochastic events could fix the alleles in small populations (see Muir and Howard 2002).

Risks manifested from interactions between interbasin biota transfers and releases of GMOs. Sources most likely to contribute to scenarios focused on interbasin transfers of GMOs would come from agricultural and aquaculture operations in the Missouri River system, although potentially confounding sources would necessarily be derived from other areas. Evaluations of risks associated with GMOs potentially entering Red River basin as a consequence of a water diversion from Missouri River sources would initially involve assessing the conditional risks associated with biota transfers. Then, events such as gene dispersal and the molecular pathways mediating transfer of genetic material would be of concern.

Spread of transgenes into natural populations may occur by a number of mechanisms: (1) vertical gene transfer as a result of matings with feral animals, (2) invasion of new territories as with introduction of invasive species or shifts in metapopulations between areas of concern, and (3) horizontal gene transfer mediated by microbial agents. Ecologically, field conditions favor a combination of these factors mediating transfer of genetic materials. The importance of each factor is species dependent, which complicates an analysis focused on a range of "most likely species of concern."

Vertical gene transfer is highly dependent on the species that has been genetically modified. For example, highly domesticated animals may not be as well adapted to the natural setting and may not be able to survive and reproduce, if individuals escape confinement. Yet if feral populations are locally available, then local adaptation is not a major barrier to gene spread, as the domesticated GM stock may be able to mate with the highly adapted native populations. Vertical gene transfers may be of greater concern for cultured aquatic species such as fishes, because aquatic environments are highly interconnected within a watershed and wild-types occur for nearly all cultured species.

Risks of GMOs realized as a consequence of biological invasions depend on the transgene-specific functions. Transgenic organisms released to natural environments poise risks beyond those of invasive species expanding their distributions and entering previously unoccupied areas. For example, transgenic individuals retain most of the characteristics of their wild-type counterparts in addition to the novel genetic material incorporated into their genome. The novel genetic material may confer advantages to the transgenic individuals, and effectively displace their

nonmodified counterparts, e.g., transgenes may enhance environmental adaptation such as heat tolerance that would allow cold water fish with this gene to invade cool and warm water environments while maintaining populations in current habitats. Genetically modified fish possessing such a transgene might threaten the survival of wild-type conspecifics as well as other species in a community. Horizontal gene transfer occurs naturally through viruses and transposons. If a virus or transposon used to construct a GMO, e.g., to mediate the insertion of transgenes, that virus or transposon, or a closely related virus or transposon, may enable recombination with other biota and dispersal to "new" hosts could occur.

This brief consideration of GMOs and the role that interbasin biota transfers may play in realizing risks of GMOs in the environment barely scratches the surface of a widely diverse topic. However, from a risk assessment perspective the current investigation contributes to evaluations of conditioning events focused on biota transfers that would necessarily be included as part of future efforts focused on GMOs and gene transfers, which will ultimately require an analysis of molecular mechanisms of dispersal that were not directly related to evaluations completed for those biota of concern identified by Reclamation and Technical Team. From a technical perspective, a comprehensive risk analysis focused on GMOs may be warranted, yet its justification may go beyond the scope of analysis. Discussions among stakeholders may point toward technical support activities that goes beyond the immediate concerns of Reclamation, as it responds to water needs.

4.11.3 Interbasin water transfers and emerging diseases (plant, wildlife, and human). Infectious diseases whose incidence in host populations has increased in the past 10 to 20 years or threatens to increase in the near future have been defined as "emerging" or "reemerging" diseases (see Brown and Bolin 2000; NRC 2004). Biota of concern focused on for this analysis of risks associated with biota transfers realized as a consequence of interbasin water diversions included disease agents regarded as emerging or reemerging disease agents.

In general emerging or reemerging infectious diseases reflect (1) new infections resulting from changes or evolution of existing organisms, (2) known infections spreading to new geographic areas or populations, (4) previously unrecognized infections appearing in areas undergoing ecological change or "jumping" to new host species, and (5) long-known and relatively well-characterized diseases that appear to be reemerging as a result of declining health in host populations (e.g., through diminished immune responsiveness associated to exposure to environmental chemicals), altered antimicrobial resistance in known agents (e.g., antibiotic

prophylaxis and livestock management), or breakdowns in preventive health measures (e.g., nutritional deficiency-disease interactions). Many factors contribute to the emergence of disease, including:

- microbial adaptation and environmental change (e.g., changes in weather and climate, alteration of habitats,
- human-induced changes in land and water use
- changing demographics of host populations
- changing migratory patterns and immigration/emigration of host populations
- increased interconnections between hosts and infectious agents, and
- increased host and disease agent exposures to multiple environmental stressors such as chemicals and physical agents (e.g., UV radiation).

Outbreaks of existing diseases or the emergence of new ones typically involve several of these factors acting simultaneously, and predicting and controlling emerging infection ultimately requires incorporating interrelationships between biological systems and their physical environments. By selecting biota of concern that included zoonotic disease agents tracked by public health organizations (e.g., Centers for Disease Control and Prevention and departments of health in states encompassed by the areas of concern), Reclamation and Technical Team ensured the analysis of risks would include a range of infectious disease agents with a host range from aquatic vertebrates to terrestrial vertebrates, including humans, and sources that potentially link these agents with point- and nonpoint source inputs into the Missouri River. The analysis and subsequent characterization of risks completed as part of the current investigation at best captures a narrow range of potential agents that may warrant future investigations.

4.11.4 Risks of biological invasions or shifts in metapopulations associated with indirect pathways affected by interbasin water transfers. Indirect effects associated with interbasin water transfers were not considered as part of the current investigation, primarily owing to stakeholder focus on biota transfers directly linked to water diversions. Nonetheless, a narrative analysis of indirect effects of interbasin water diversions and the role such water-management practices would play in managing risks potentially realized by biota transfers will be briefly considered, with a particular emphasis on indirect effects potentially associated with within-basin water-supply alternatives.

Within-basin water supplies. If no interbasin water transfers were realized in satisfying water needs of the Red River valley, competing risks associated with gaining needed water supplies from within-basin water sources for the Red River basin would eliminate even the relatively low risks characterized for closed-conveyance interbasin transfers of treated source waters from the Missouri River. However, the relatively small reduction in risk of species invasion or shift in metapopulation that may be realized if a closed conveyance of treated Missouri River waters were not diverted would likely not significantly effect the ecological affects potentially associated with using within-basin water supplies as an alternative.

Within-basin water sources must be considered recognizing that estimates of future water demands for human uses (while maintaining a sustainable system) is fraught with uncertainty, given the many factors playing a role in determining within-basin water withdrawals (e.g., state of water supply technology, including conservation; environmental regulations; changing nonhuman uses, seasonal and long-term trends in water inflows and outflows). Place water needs of the human population and their associated uncertainties within a dynamic ecological context reflecting near-term requirements (e.g., instream flows) and long-term trends (e.g., climate change), and value of management practices should be apparent (see Environment Canada 2004; Mitchell 2002). For example, updated projections of water withdrawals and consumption by end users must be an ongoing technical support activity, given the potential biological, physical, and socioeconomic factors influencing water use in the Red River basin.

While Reclamation and Technical Team's focus in this current investigation has focused on potential interbasin biota transfers, opting for within-basin water sources as a solution to that problem must be pursued within the context of competing risks (e.g., for pathways of species invasion other than interbasin water diversions, unintended habitat effects associated with using within-basin water sources). Multiple parties are part to water supply and water-use decisions, and interbasin biota transfers are but one component of many that reflect biological responses to different and changing circumstances related to physical habitat. As noted in Environment Canada (2004), water resource problems

> "extend beyond the scope of any single government agency and level of government, and are associated with high levels of change, complexity, uncertainty and conflict. Differences of opinion over the goals to be achieved, and uncertainty and disagreement about the means to solve meta-problems are common. Problems can be chronic or acute, and may be bound or framed in technical, economic, legal, political and social ways. Proposed

solutions will be multifaceted; hence information concerning human use and biophysical aspects of water and related resources will be required if decision making is to be adequately informed."

Satisfying water needs using within-basin sources to avoid risks associated with interbasin biota transfers must be pursued with competing risks in mind. From a resource management perspective, those competing risks may be categorized as being outcomes realized because of integrated and cumulative threats to water resources (Environment Canada 2004). Integrated threats emerge when combinations of stresses occur (e.g., conjunctive groundwater and surface water problems, expected changes in climate and population with associated changes in water demand, simultaneous changes in water uses), and cumulative threats are those that develop slowly and evolve over long periods. Cumulative threats are often integrated threats that variously impact water resources (see, e.g., Foran and Ferenc 1999).

A general framework for generating policy and management responses to integrated and cumulative threats is shown in Figure 13.[8] The process includes a wide range of technical, economic and social analyses, with measures of performance for management activities including ecosystem health, human health, economic measures, long-term sustainability, and whether expectations of stakeholders have been met.

As competing risks, within-basin water supplies would necessarily have to be considered with respect to integrated and cumulative ecological effects beyond species invasions. For example, alterations in flow, water levels, or system geometry and hydrology in the course of withdrawing or diverting within-basis water sources would produce ecological effects in a serial manner. The withdrawal affects the physical and/or chemical environment, which in turn affects specific populations or groups of populations (i.e., communities), including potential interactions that influence habitat's vulnerability to species invasions. For example, potential alterations in structure and function riparian habitats may be realized through reliance on surface water sources, if within-basin supplies are tapped to meet demands.

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[8]Source: Environment Canada, 2004, Threats to Water Availability in Canada. National Water Research Institute, Burlington, Ontario, NWRI Scientific Assessment Report Series No. 3 and ACSD Science Assessment Series No. 1. 128 pp.

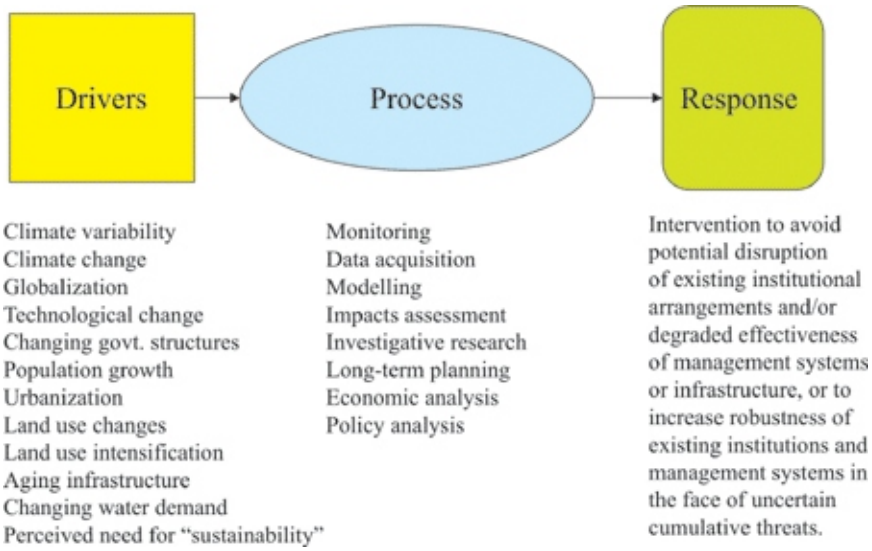

Figure 13. Process for evaluating threats and risks associated with within-basin alternatives for Red River basin water supply.

Cumulative effects associated with taps to water sources within Red River basin would parallel an ongoing analysis being completed by Reclamation under the auspices of NEPA for an evaluation of effects associated with interbasin water diversions from the Missouri River. Differences between Missouri River and Red River basins, e.g., volume of water flows, in-stream flow requirements, and percent withdrawals, may be associated with critical differences in forecasting integrated and cumulative effects associated with scenarios developed as part of that broader scope of analysis.

4.12 Risk Management: The Role of Monitoring and Mitigation Plans as Part of Implementation

The brief consideration of the conceptual setting for evaluating ecological effects associated with alternative within-basin water sources illustrates the significant role that monitoring and mitigation planning plays in resource management, particularly within the context of managing risks. Folding the ideas of integrated and cumulative effects into a framework of competing risk is operationally simple, since it merely extends the existing framework available for evaluating risks associated with multiple stressors (see Foran and Ferenc 1999; Ferenc and Foran 2000). Developing monitoring and mitigation plans for managing risks associated with biota transfers (if interbasin water diversions are selected to meet water needs of Red River basin) or

with species invasions as components of integrated and cumulative effects (if within-basin water sources are selected to meet water needs of Red River basin) could start with a revised conceptual model based on that derived from problem formulation (Figure 14; see also Section 1 and Section 2).

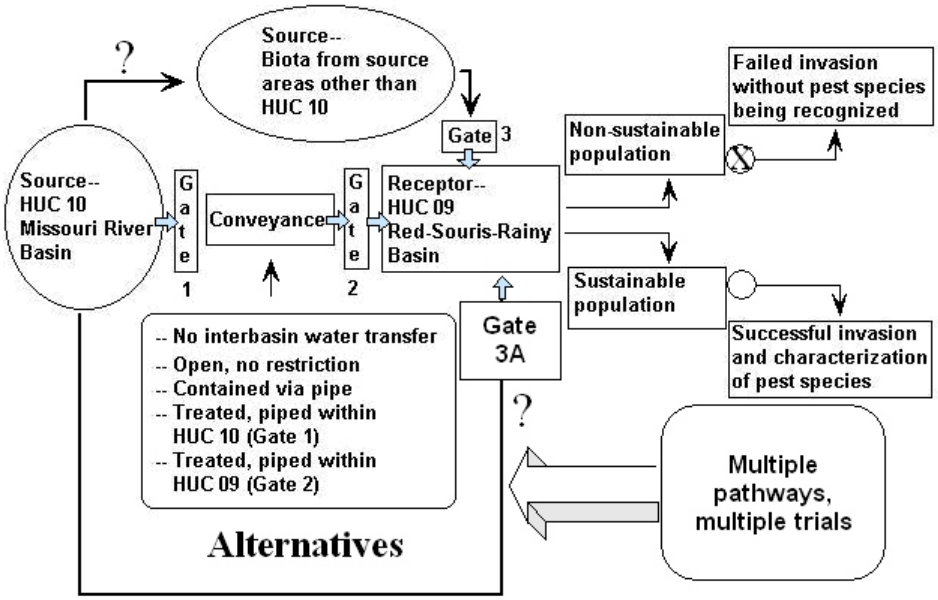

Figure 14. Proposed conceptual model of reflecting multiple pathways influence on the evaluation of risks potentially associated with biota transfers collateral to interbasin water diversions.

Regardless of decisions related to interbasin water diversions or selection of alternative water sources for satisfying water needs of Red River basin, resource management plans should be developed, including monitoring and mitigation activities designed with a particular emphasis on their roles in ministering to uncertainty (see Walters 1986; Wittenburg and Cock 2001). Technical support developed as part of ongoing assessment and monitoring activities could help focus mitigation plans developed as a consequence of risk analysis completed under the auspices of resource management.

A solitary focus on interbasin biota transfers uniquely linked to water diversions from the Missouri River technically oversimplifies the species invasion process and reflects political and socioeconomic drivers influencing the risk assessment process more than is technically justified.

Risks exists in a changing landscape of time and space, and the risks associated with interbasin biota transfers illustrate such an observation. International Joint Commission's findings of unacceptable risks associated with biota transfers consequent to water diversions envisioned in the mid-1970s and early 1980s (see Section 1; IJC 1977) were amply justified given the "best management practices" available at that time, yet given the control technologies developed in the intervening 30 years, revisiting those findings may be warranted. Depending on the definition of acceptable risk used by Reclamation, Technical Team, and other stakeholders, the current investigation characterizes risks for interbasin biota transfer consequent to diversion of source waters from the Missouri River as low to very low for those biota of concern identified, as long as control systems are sufficient to the task of risk reduction (e.g., multiple-step control systems involving pretreatment, chemical and physical treatments, and filtration). Even then, however, risks of biota transfer will never be zero. Competing pathways will likely lead to interbasin biota transfers and subsequent species invasions in the near future, following the trend that has lead to species invasions of Red River basin in the past, even in the absence of waters from the Missouri River basin having entered the basin through human agency.

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5.0 Consequence Analysis

Abstract. Analysis summarized in Section 5 estimated the potential consequences associated with interbasin water transfers between the Upper Missouri River and Red River basins. Two economic approaches were used to estimate these consequences. Habitat equivalency analysis was used to estimate consequences throughout the assessment area including the Red River and Lake Winnipeg. That analysis indicated risk consequences ranging from 0.6 to 3.1 river-miles of offsetting restoration on the Red River and from 1.9 to 27,750 acres of offsetting restoration on Lake Winnipeg. While those results suggest potentially significant consequences for Lake Winnipeg, their interpretation depends on the feasibility and availability of appropriate restoration measures.

Since the feasibility and availability of those restoration measures is not clear at this time, a second economic approach was used to focus the consequence analysis on Lake Winnipeg. Regional economic impact analysis was used to estimate the impacts on output (sales revenue) and employment in the Lake Winnipeg commercial fishery. The invasion scenarios with the largest consequences (slow and fast invasions given a jump dispersal event) indicated a total expected present value between $33,000 and $136,000 in direct and indirect output impacts for all Canadian provinces. All other invasion scenarios indicated smaller output impacts. Expected employment impacts in the very high risk category (i.e., certainty) reach 331 full-time equivalent (FTE) jobs. The average expected employment impacts weighted by the percent outcomes of respective risk categories is zero FTE for all invasion scenarios.

Given the quantitative results from the habitat equivalency analysis and the regional economic impact analysis, the following three conclusions can be drawn. First, the overall results are sensitive to the distribution of probabilistic outcomes from the risk characterization. Consequence levels for the individual risk categories vary substantially. That variance reflects the different probabilities of successful invasion. A different distribution of probabilistic outcomes would change the weighted averages of the consequence levels. Therefore, this consequence analysis is sensitive to the results of the risk analysis. In this particular case, the weighted average consequences are heavily weighted toward the lowest risk category (87% of outcomes in the very low-risk category). A distribution more heavily weighted toward the higher-risk categories would yield substantially higher-weighted averages of consequences.

The second conclusion of this consequence analysis is that the speed of invasion significantly affects the quantitative results. As many as four orders of magnitude difference in offsetting restoration levels exists between the two invasions speeds assumed in this analysis, and one order of magnitude difference is captured by output impacts. A much more detailed analysis would match individually estimated invasion speeds to respective organisms, and then aggregate the indicated consequence levels over the species of concern. However, the information regarding species-specific invasion speeds was not available to conduct that level of analysis. Therefore, this analysis

indicates not only the significance of this analytic factor but also the need for additional research in this area.

This consequence analysis also concludes that the anticipated distribution of the method and number of dispersal events substantially affects the quantitative results. This analysis considered only a limited set of potential dispersal scenarios. No information was available to inform the distribution of these scenarios to include in the analysis. However, the limited number of potential dispersal scenarios analyzed here indicated as many as four orders of magnitude difference in offsetting restoration levels between them. Similar to the conclusion regarding the speed of biotic invasion, this analysis indicates a significant analytic factor and a need for further research.

5.0 Consequence Analysis: Introduction

This section presents a consequence analysis of specific risks that are potentially associated with interbasin water transfers between the Upper Missouri River and Red River basins. The specific risks addressed involve the possibility of biological invasions between the two river basins. The analysis presented in the previous sections of this report resulted in a risk characterization that integrates exposure and effects information to estimate and describe the risks of adverse effects resulting from these potential biological invasions. As an integral part of watershed management, consequence analysis interprets a risk characterization to illustrate the significance of risk in meaningful terms that promote public understanding and involvement in risk management. The specific goals of this consequence analysis include the following:

- Present the consequences of risk in a meaningful way that is easily understood by stakeholders
- Estimate a relevant range of the magnitude of risk consequences
- Determine critical factors that influence the magnitude of risk consequences

This consequence analysis uses two economic approaches to illustrate the significance of risk. The integration of ecological risk assessment and economic analysis in watershed management is a relatively new concept with little empirical application (US Environmental Protection Agency 2003). However, economic analysis typically forms a key element of policy analysis for decision making (Loomis and Helfand 2001). That is because economic analysis is often required in governmental decision processes (e.g., promulgation of federal regulations), and because the public in a market-oriented society is generally familiar with economic indicators.

One economic approach used in this analysis, habitat equivalency analysis (HEA), borrows from the established field of natural resource damage assessment. Natural resource damage assessments are conducted to determine the specific restoration measures needed to address injuries resulting from hazardous substance releases and discharges of oil. A key assumption of the HEA method is that appropriate restoration measures are feasible and available. This application of HEA was useful in quantifying the relative consequences within the assessment area and indicated potentially significant

consequences for Lake Winnipeg. Nevertheless, whether appropriate restoration measures are feasible and available either now or in the future is yet another level of uncertainty that was not addressed in this analysis.

Recognizing the possibility that appropriate restoration measures may not be feasible or available, a second economic approach, regional economic impact analysis, was used to describe potential consequences for Lake Winnipeg in terms of their impacts on the economy (sales revenue and employment). Regional economic impact analysis does not assume the feasibility or availability of appropriate restoration measures.

This section first provides a brief background of various economic approaches to establish the context for this consequence analysis. The particular economic approaches selected for this analysis are then presented, followed by descriptions of their application in this consequence analysis. Finally, the conclusions of this consequence analysis are presented.

5.1 An Economic Approach to Consequence Analysis

Policy analysts commonly employ economic approaches to present relevant information to the public and ultimately to decision makers. For example, federal agencies are required to conduct cost/benefit analyses of proposed government regulations.[1] Those analyses present the estimated costs and benefits that can be attributed to the particular regulations under consideration. Such economic analyses present the consequences of policies in terms that are relevant for people in evaluating their tradeoffs of current and future resources. While these tradeoffs are frequently presented in monetary terms, they can also be cast in terms of other resource needs such as habitat restoration.

The presentation of consequences in terms of resource tradeoffs is also appropriate for watershed management issues (Bruins and Heberling 2005). In the event of an adverse ecological impact resulting from a watershed management action, individuals and firms may lose income, affected habitats may require restoration, and the recreational services provided by those habitats may be diminished. Recognition of these tradeoffs is an important part of communicating the consequences of risk to the public and to decision makers.

An economic approach to this consequence analysis was chosen in order to recognize some of the potential tradeoffs resulting from interbasin water transfers. The field of economics is wide and provides a number of approaches to estimating tradeoffs. These various approaches are briefly described below and specific approaches are selected for the consequence analysis.

[1] See Executive Order 12866 on regulatory planning and review in the October 4, 1993, issue of the *Federal Register* (Volume 58, Number 190).

5.1.1 Background of economic approaches. A key distinction among different economic approaches is the type of economic values they are designed to address. One economic approach frequently encountered involves estimating "regional economic impacts." These impacts describe the domino effect of spending (by commercial fishers for example) that reverberates through a local economy. Such impacts are experienced in the form of jobs, wages, tax revenues, and output or sales revenues.

These regional economic impacts are often *gross* economic values, meaning that their associated costs have not been subtracted. Examples of associated costs include the wages and taxes that businesses must pay out of their sales revenues. Since those costs have not been subtracted, regional economic impacts double-count to some extent. For example, the regional economic impacts of wages and tax revenues are also included in the regional economic impacts of sales revenues. Therefore, the interpretation of gross values like regional economic impacts must be cautioned by the potential for double-counting and by the fact that certain costs must be paid out of them. However, the regional economic impacts of various projects are frequently reported in the popular press and are easily understood by the public.

Another type of economic value is *net* economic value. Net values are gross values minus their associated costs. An example of net value is equity in real estate, which is the sales value of property in excess of all claims against it. Another example is business profit, which is sales revenue minus the costs of capital and labor. Since all costs or claims have been subtracted, net values reflect the true worth of a resource since its owner is free to spend or invest that amount at will. Further, net values do not double-count and can therefore be aggregated meaningfully in a cost/benefit analysis.

A number of methods have been developed to estimate net economic values.[2] These methods frequently rely on public surveys, which require significant investments in time and budget to design and implement.[3] Therefore, expedited methods have been developed for use in a number of contexts including public policy analysis and natural resource damage assessment. These expedited methods either estimate net economic values or incorporate their consideration in the analysis of management actions.

Expedited economic methods appropriate to watershed management include benefits transfer and HEA. Benefits transfer involves using economic values that have been previously estimated and reported in existing studies to address similar issues in other contexts. Specifically, per-unit value estimates from existing economic studies are combined with site-specific resource information to estimate total costs and benefits. For example, suppose a management action results in the loss of 150 angler-days of fishing along a river. Then, per angler-day value estimates from studies of comparable resources could be obtained from the economics literature and multiplied by 150 to estimate the

[2] See Freeman (1993) for a comprehensive survey of economic methods that are applicable to natural resources.
[3] If conducted by or for federal agencies, surveys must also be approved by the Office of Management and Budget.

total cost of that action. Some original research may be required to obtain the necessary site-specific resource information such as the number of affected angler-days.[4]

The habitat equivalency analysis method does not estimate net economic values, but HEA does incorporate its consideration in quantifying the impacts of management actions. This method is widely used in natural resource damage assessments, which determine compensation for lost or diminished ecological services.[5] In that context, compensation is provided by restoration projects that provide replacement services with an economic value at least as great as the economic value of the lost services. That is, the size of the restoration project must be sufficient to offset the economic value of lost services. Therefore, the impacts are quantified as the size or cost of the required restoration project. For example, replacement services could include the monitoring and removal of existing invasive species that are not related to the project. Those replacement services would improve habitat and represent real economic value. Obviously, a key assumption of the HEA method is that appropriate restoration measures are both feasible and available for implementation.

HEA employs other assumptions in order to avoid explicitly estimating economic value. One assumption is that the unit economic values of the replacement services are comparable to those of the lost services. This assumption is required because HEA determines the size of the restoration project such that the total quantity of replacement services provided through time is sufficient to offset the total quantity of lost services.[6] These services are quantified in physical units of measure such as acre years.[7] Given the offset of the total physical quantity of lost services, the restoration project will be sufficient to offset the total economic value of lost services if the unit economic values of the replacement services are comparable to those of the lost services. This is reasonable if the replacement services are comparable in type and quality to the lost services. Therefore, to apply HEA, selected restoration projects must provide ecological services that are comparable to those lost as a result of the resource impact. For example, if aquatic habitat services are diminished as a result of an impact, then restoration must provide similar aquatic habitat services in replacement.[8]

The simplifying assumptions of HEA impose certain restrictions on its application. However, the method also has the distinct advantage of focusing on environmental restoration measures rather than on the estimation of economic values. In

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[4] See Kaval and Loomis (2003) and Desvousges et al. (1992) for a more detailed description of the benefits transfer method. Also, see page 499 of the January 5, 1996, issue of the *Federal Register* (Volume 61, Number 4) for a description of the application of benefits transfer in natural resource damage assessment.
[5] Ecological services are the functions performed by a natural resource for the benefit of other resources. For example, habitats provide food and refuge for wildlife populations.
[6] Services lost or provided at different times are discounted at an appropriate rate to reflect time preference considerations. See Brennan (1999) for a discussion of discounting.
[7] An acre year refers to all the resource services provided by one acre of habitat for one year. This measure of resource services is specific to habitat since different habitats provide different services. Other metrics, such as river-mile years, can also be used.
[8] See Unsworth and Bishop (1994), Jones and Pease (1997), and Allen et al. (2005) for a detailed description of the HEA method. See Penn and Tomasi (2002) for an example application of this method.

natural resource damage assessments, this restoration focus is more easily understood by a wider audience than the more theoretic valuation approaches.

5.1.2 Selection of specific economic approaches. Two economic approaches were selected for this consequence analysis: habitat equivalency analysis and regional economic impact analysis. HEA was selected for two reasons. First, HEA is a relatively transparent economic approach. It describes consequences in terms of the amount of restoration that would be needed to address potential impacts. The analytic inputs and results of HEA are directly associated with the potentially affected resources and their services. Because of that, the results of HEA are easily understood by a broad range of interested parties.

The second reason HEA was selected is because it is readily available in terms of the time and budget resources required for implementation. Unlike methods relying on public surveys, HEA can be conducted relatively quickly and at a modest cost. Therefore, HEA was considered to be the most cost-effective approach for describing the consequences of risk throughout the entire assessment area. In that capacity, HEA was used to quantify potential consequences for both the Red River and Lake Winnipeg.

This application of HEA indicated potentially significant consequences for Lake Winnipeg. However, that indication of consequences relies on the feasibility and availability of appropriate restoration measures. Since the feasibility and availability of appropriate restoration measures is not clear at this time, a regional economic impact analysis of the Lake Winnipeg commercial fishery was also conducted. Regional economic impact analysis describes potential consequences in terms of their impacts on the economy (output or sales revenue and employment) and does not assume the feasibility or availability of restoration measures. Additionally, regional economic impact analysis can be conducted quickly and at a modest cost since the necessary data are readily available from Statistics Canada. Therefore, regional economic impact analysis was used to focus the consequence analysis on the area indicated by HEA as potentially most affected by the risks of biological invasions.

5.2 Habitat Equivalency Analysis: Model Development

In this section, the habitat equivalency analysis model is developed for the consequence analysis. This model is essentially the same used in natural resource damage assessments with one significant difference. Damage assessments are conducted after the occurrence of an ecological injury. Therefore, that analysis is of a *certain* event. Ecological risk assessments, on the other hand, address *uncertain* events in the future. To accommodate this uncertainty, the probability of successful biological invasion is introduced into the HEA model development. This probability is applied to the future ecological losses that would occur given a successful invasion. This analysis presents the consequences of this risk as the *certain* level of restoration that would be required to address these *uncertain* losses. That is, a certain level of restoration is calculated to offset

an uncertain risk of successful biological invasion. This quantification of risk consequences is termed *offsetting restoration*.

The fundamental criterion behind this application of HEA is characterized by the following relationship:[9]

$$aV^{L}\sum_{t=t_0}^{t_1} L_t\left(1+i\right)^{(P-t)} \quad = \quad V^{R}\sum_{s=s_0}^{s_1} R_s\left(1+i\right)^{(P-s)} \qquad [1]$$

where a = Probability of successful biological invasion

L_t = Lost services in time period t

V^L = Net economic value per unit of lost services (assumed to be invariant with respect to the scale of loss and time over a relevant range)

R_s = Replacement services in time period s

V^R = Net economic value per unit of replacement services (assumed to be invariant with respect to the scale of restoration and time over a relevant range)

t_0 = Time period when lost services first occur

t_1 = Time period when lost services last occur

s_0 = Time period when replacement services are first provided

s_1 = Time period when replacement services are last provided

P = Present time period (when the analysis is conducted)

i = Periodic discount rate

The expression on the left-hand side of equation [1] is the expected present value of lost services and the expression on the right-hand side is the present value of replacement services provided by restoration. This criterion requires that sufficient replacement services, R_s, be provided through time to generate a present value that is equal to the expected present value of lost services.

[9] This relationship is consistent with the expected value criterion for decision making under risk (Thusesen and Fabrycky 2001).

HEA is a specific application of this criterion. The simplifying assumption that is required for HEA is that the replacement services provided by restoration are comparable to the lost services. Specifically, HEA assumes that V^R equals V^L, which simplifies equation [1] as follows.

$$a\sum_{t=t_0}^{t_1} L_t\left(1+i\right)^{(P-t)} \quad = \quad \sum_{s=s_0}^{s_1} R_s\left(1+i\right)^{(P-s)} \qquad [2]$$

Thus, the value terms cancel out, avoiding explicit economic valuation while continuing to satisfy the fundamental criterion.

If a constant level of replacement services, R, is provided through time, then equation [2] can be modified to allow for the unique solution of the restoration requirement.

$$\begin{aligned} a\sum_{t=t_0}^{t_1} L_t\left(1+i\right)^{(P-t)} &= \sum_{s=s_0}^{s_1} R\left(1+i\right)^{(P-s)} \\ &= R\sum_{s=s_0}^{s_1} \left(1+i\right)^{(P-s)} \end{aligned}$$

$$R \quad = \quad \frac{a\sum_{t=t_0}^{t_1} L_t\left(1+i\right)^{(P-t)}}{\sum_{s=s_0}^{s_1} \left(1+i\right)^{(P-s)}}$$

Replacement services are often quantified by geographic area (e.g., acres of habitat or miles of river). Given that metric, varying levels of effective service provision can be accommodated by assigning varying proportional weights, Q_s, to a constant land area, R, through time. For example, such weights could reflect the increasing efficacy of restoration as planted vegetation grows or is succeeded by the intended climax community. These weights are sometimes referred to as relative productivity.

$$\begin{aligned} a\sum_{t=t_0}^{t_1} L_t\left(1+i\right)^{(P-t)} &= \sum_{s=s_0}^{s_1} Q_s R\left(1+i\right)^{(P-s)} \\ &= R\sum_{s=s_0}^{s_1} Q_s \left(1+i\right)^{(P-s)} \end{aligned}$$

$$R = \frac{a\sum_{t=t_0}^{t_1} L_t (1+i)^{(P-t)}}{\sum_{s=s_0}^{s_1} Q_s (1+i)^{(P-s)}} \qquad [3]$$

Where Q_s = Relative productivity (proportional equivalence of the net ecological services provided in time period *s* by restoration relative to the baseline productivity of the injured habitat)

Equation [3] is used to determine the scale of offsetting restoration when both lost services and replacement services occur over finite time horizons. Modifications of that equation include situations where some level of lost services continues into perpetuity and where restoration provides some level of replacement services into perpetuity. These modifications are incorporated below.

$$R = \frac{a\sum_{t=t_0}^{t_1} L_t (1+i)^{(P-t)} + \frac{L_{t_1}(1+i)^{(P-t_1)}}{i}}{\sum_{s=s_0}^{s_1} Q_s (1+i)^{(P-s)} + \frac{Q_{s_1}(1+i)^{(P-s_1)}}{i}} \qquad [4]$$

Where t_1 = Time period when a constant level of lost services is achieved

L_{t_1} = Constant level of lost services continuing from time period t_1 into perpetuity

s_1 = Time period when restoration achieves a constant level of replacement services

Q_{s_1} = Constant level of relative productivity continuing from time period s_1 into perpetuity

All other variables are as defined for equation [3] above.

This HEA uses equation [4] to calculate the consequences of the potential risks associated with biological invasions. That is, the adverse effects of a successful biological invasion are assumed to continue into perpetuity, and the offsetting effects of restoration are assumed to continue into perpetuity as well.

5.3 Habitat Equivalency Analysis: Model Estimation

This habitat equivalency analysis addresses two distinct but related water bodies that could be affected by a potential biological invasion: the Red River and Lake Winnipeg. For purposes of this analysis, the Red River habitat is defined as the 455.4 river-miles from the I-94 bridge in Fargo, North Dakota, to the southern shore of Lake Winnipeg (US Army Corps of Engineers 2004). The Lake Winnipeg habitat is defined as its 5,868,625 acres (23,750 square kilometers) of surface area (Manitoba Water Stewardship 2004). The consequences of risk are estimated separately for these two habitats.

Critical factors in this analysis include the method and rate of the dispersal of biological invaders. Two potential dispersal methods are considered: *progressive* and *jump*. The progressive dispersal method assumes a linear, geographically incremental advancement of a biological invasion. In this analysis, a progressive dispersal in the Red River is assumed to begin at the I-94 bridge and to progress incrementally northward toward the southern shore of Lake Winnipeg at a constant rate of advancement. In Lake Winnipeg, a progressive dispersal is similarly assumed to begin at its southern shore and to progress incrementally northward toward its northern shore at a constant rate.

The jump dispersal method is represented in this analysis by an instantaneous introduction of a biological invader into Lake Winnipeg. In this scenario, a progressive invasion of Lake Winnipeg is assumed to begin at its southern shore at the same time that a progressive invasion of the Red River begins at the I-94 bridge. Once these two invasions begin, they are assumed to progress incrementally northward to the northern extents of their respective habitats at a constant rate.

It should be recognized that the quantitative results of this analysis are significantly influenced by the particular assumptions adopted here regarding dispersal methods. For example, this analysis assumes that given a jump dispersal event, the introduction of a biological invader will occur at the southern shore of Lake Winnipeg, and that a progressive dispersion will subsequently proceed northward toward its northern shore. Alternatively, it could have been assumed that the introduction would occur at the middle of Lake Winnipeg with subsequent progressive dispersions both north and south. That assumption would yield higher-risk consequences as quantified by the HEA model.

The number of permutations of possible dispersal scenarios is large given the large geographic extent of the habitats considered in this analysis. The particular assumptions adopted here were chosen to illustrate risk consequences under two broad categories of dispersal methods, not to provide an exhaustive analysis of all potential events. This analytic approach was chosen to efficiently yield qualitative results that clearly communicate the nature of the risk consequences resulting from interbasin water transfers between the Upper Missouri River and Red River basins.

The rates of advancement of a biological invasion are assumed to range between 2.5 and 25 kilometers, or between 1.55 and 15.5 miles, per year.[10] Accordingly, a *slow* invasion would traverse the Red River in 294 years (455.5 river-miles divided by 1.55 miles per year). Lake Winnipeg extends 271 miles (436 kilometers) from its southern shore to its northern shore (Manitoba Water Stewardship 2004). Given that extent, a slow invasion would require 175 years, on average, to traverse the lake (271 miles divided by 1.55 miles per year). Alternatively, a *fast* invasion would require 29 years to traverse the Red River (455.5 river-miles divided by 15.5 miles per year), and 17 years to traverse Lake Winnipeg (271 miles divided by 15.5 miles per year). After these habitats have been traversed by biological invasions, the resulting ecological service losses are assumed to continue into perpetuity.

Assumptions must also be made regarding the nature of offsetting restoration. *Offsetting restoration* provides certain levels of ecological services to replace uncertain losses of similar services. That is, this HEA quantifies the consequences of risk as the quantity of a certain provision of restoration that is required to offset an uncertain risk of successful biological invasion. Offsetting restoration is quantified in the same terms that are used to quantify habitat losses: river-miles for the Red River and acres for Lake Winnipeg.

This analysis assumes that offsetting restoration begins five years after the onset of successful invasion, and requires 20 years to become fully functional. These assumptions are made to allow sufficient time for planning, implementation, and mid-course corrections under adaptive management. Once offsetting restoration becomes fully functional, it is assumed to provide replacement ecological services that are equivalent to those potentially lost from biological invasion. Further, these replacement services are assumed to continue into perpetuity.

As with the assumptions made regarding dispersal methods, alternative assumptions for offsetting restoration will also yield different quantitative results. For example, specifically designed restoration measures for different invasive organisms would likely have different timing requirements and different success levels. However, at its most basic level, this analysis quantifies risk consequences for a single representative organism. Consistent with that approach, this HEA incorporates a single representative description of offsetting restoration. This approach was considered the best way to determine useful qualitative results without an exhaustive description of applicable restoration methods.

Finally, an appropriate discount rate must be selected in order to meaningfully aggregate ecological services over time (the parameter i in the model specification). A 3-percent annual discount rate was selected for this analysis. The economics literature supports an annual 3% discount rate for natural resource valuation (e.g., Freeman 1993). Two federal rule-makings also support an annual 3% discount rate for lost natural

[10] See, for example, Pearce and Smith (2002; 2003), Skalski and Gilliam (2000), and Speirs and Gurney (2001).

resource use valuation[11]. Also see Peacock (1995) for a discussion of the theory and estimation of the discount rate.

The economics literature has recently addressed whether the discount rate used to analyze long-term projects should be adjusted to account for intergenerational equity concerns (e.g., Portney and Weyant 1999). Since the ecological service losses and replacements analyzed here occur over periods approaching 300 years, and into perpetuity, intergenerational equity is certainly a consideration. However, the literature is not conclusive as to whether such adjustments are appropriate. For example, Weitzman (1999) recommends applying a declining discount rate over time, while Arrow (1999) recommends using a positive and constant discount rate, even in the face of irreversible changes. In light of this unsettled controversy and the previous references cited, a constant 3% annual discount rate was selected as appropriate for this analysis.

The HEA was calculated for a single representative invasive organism given the progressive and jump dispersal methods and the slow and fast dispersal rates described above for the five different risk categories considered (very low, low, moderate, high, and very high risk). The results of those HEA calculations are presented in Table 1. Detailed HEA calculations are presented in Appendix 15.

Probabilistic outcomes from the risk characterization were incorporated in Table 1 by calculating the average of the HEA results for the different risk categories weighted by their respective percentage outcomes (Figure 1 in Section 4). These weighted averages were then aggregated to the 31 species of concern according certain assumptions regarding the number of jump dispersal events that might occur.

The number of expected jump dispersal events was not addressed in the foregoing analysis of risk. Therefore, the following three dispersal scenarios were assumed in order to estimate a range of potential risk consequences for the 31 species of concern.

- **0 Jump - 31 Progressive:** There are no jump dispersal events in this scenario. All 31 species of concern are assumed to begin their invasions at the I-94 bridge on the Red River, progress incrementally to the southern shore of Lake Winnipeg, and then progress incrementally to the northern shore of the lake. That is, the potential invasions of Lake Winnipeg by all 31 species of concern are assumed to begin only after their progressive invasions of the Red River have been completed. This dispersal scenario yields the lowest levels of risk consequences in present value terms since it has the longest time horizon for any potential biological invasion to traverse the Red River and Lake Winnipeg.
- **1 Jump - 30 Progressive:** There is one jump dispersal event in this scenario. One species of concern is assumed to begin its progressive invasion of Lake Winnipeg at the same time that it begins its progressive invasion of the Red River.

[11] See the January 5, 1996, *Federal Register* notice (61 FR 453) for damage assessments conducted under the Oil Pollution Act and the May 7, 1996, *Federal Register* notice (61 FR 20584) for damage assessments conducted under the Comprehensive Environmental Response, Compensation, and Liability Act.

- **10 Jump - 21 Progressive:** There are ten jump dispersal events in this scenario. Ten species of concern are assumed to begin their progressive invasions of Lake Winnipeg at the same time that they begin their progressive invasions of the Red River. This dispersal scenario yields the highest levels of risk consequences (in present value terms) since it assumes the greatest number of species that jump to Lake Winnipeg.

Table 1
Offsetting Restoration for a Single Representative Invasive Organism

Red River from Fargo to Lake Winnipeg - Progressive Dispersal

Risk Category	Probability of Successful Invasion	Percent Outcomes	----Offsetting Restoration---- Slow Invasion (River-Miles)	Fast Invasion (River-Miles)
Very Low	1.00E-09	87.0	0.0000000805	0.000000470
Low	1.00E-06	7.6	0.0000805	0.000470
Moderate	1.00E-03	3.7	0.0805	0.470
High	1.00E-02	1.7	0.805	4.70
Very High	1.00E+00	0.0	80.5	470
Weighted Average			0.02	0.10

Lake Winnipeg – Jump Dispersal

Risk Category	Probability of Successful Invasion	Percent Outcomes	----Offsetting Restoration---- Slow Invasion (Acres)	Fast Invasion (Acres)
Very Low	1.00E-09	87.0	0.00173	0.00708
Low	1.00E-06	7.6	1.73	7.08
Moderate	1.00E-03	3.7	1,730	7,080
High	1.00E-02	1.7	17,300	70,800
Very High	1.00E+00	0.0	1,730,000	7,080,000
Weighted Average			358.24	1,466.10

Lake Winnipeg - Progressive Dispersal

Risk Category	Probability of Successful Invasion	Percent Outcomes	----Offsetting Restoration---- Slow Invasion (Acres)	Fast Invasion (Acres)
Very Low	1.00E-09	87.0	0.000000291	0.00301
Low	1.00E-06	7.6	0.000291	3.01
Moderate	1.00E-03	3.7	0.291	3,010
High	1.00E-02	1.7	2.91	30,100
Very High	1.00E+00	0.0	291	3,010,000
Weighted Average			0.06	623.30

The aggregations to the 31 species of concern are presented in Table 2. These aggregations simply combine multiples of relevant weighted averages of the offsetting restoration levels for a single representative invasive organism. For example, the aggregated offsetting restoration for Lake Winnipeg given a slow invasion and the 1 Jump - 30 Progressive dispersal scenario (360 acres in Table 2) was obtained by taking 1 times the offsetting restoration for a single representative invasive organism given a slow invasion and a jump dispersal (358.24 acres in Table 1) plus 30 times the offsetting restoration for a single representative invasive organism given a slow invasion and a progressive dispersal (0.06 acre in Table 1).

The results presented in Table 2 indicate potentially significant consequences for Lake Winnipeg and generally much lower consequences for the Red River. For example, measured widths of the Red River at Fargo during 2004 range from 55 to 180 feet (US Geological Survey 2005). Using the mid point of that range as an average width (117.5 feet) indicates 8.5 acres of offsetting restoration in the Red River given a slow invasion and 44 acres of offsetting restoration given a fast invasion.

Table 2
Offsetting Restoration for 31 Biota of Concern

Dispersal Scenario	------Offsetting Restoration*------ Red River (River-Miles)	Lake Winnipeg (Acres)
Slow Invasion		
0 Jump - 31 Progressive	0.6	1.9
1 Jump - 30 Progressive	0.6	360.0
10 Jump - 21 Progressive	0.6	3,583.7
Fast Invasion		
0 Jump - 31 Progressive	3.1	19,322.3
1 Jump - 30 Progressive	3.1	20,165.1
10 Jump - 21 Progressive	3.1	27,750.3

*Multiples of the weighted averages of the respective offsetting restoration levels for a single representative invasive organism (Table 1), combined according to the dispersal scenarios.

The indicated offsetting restoration levels for Lake Winnipeg are lower than those for the Red River only given a slow invasion with no jump dispersal events, the most conservative invasion scenario considered. Indicated offsetting restoration levels for Lake Winnipeg in all other invasion scenarios exceed those for the Red River by two or three orders of magnitude. These results suggest that the majority of the potential consequences from risks of biological invasion would likely occur in Lake Winnipeg.

This analysis indicates potentially significant consequences for Lake Winnipeg. However, the HEA method relies on an assumption that offsetting restoration is both feasible and available for implementation. Recognizing the possibility that appropriate restoration measures may not be feasible or available, a second economic approach, regional economic impact analysis, was used to describe potential consequences for Lake Winnipeg commercial fishing in terms of the impacts of risk on the economy (output or sales revenue and employment). Regional economic impact analysis does not assume the feasibility or availability of appropriate restoration measures. That analysis is described next.

5.4 Regional Economic Impact Analysis of Lake Winnipeg Commercial Fishing

Lake Winnipeg supports the largest commercial fishery in Manitoba, contributing 41% of total production and 58% of total landed value in the province (Manitoba Conservation 2003). From 1992 through 2002, the average landed value from the lake was $14,838,754 per year (Canadian 2003 $) and an average of 1,013 fishermen were employed in the fishery (*ibid.*). Commercial fishing is permitted at Lake Winnipeg only during specific seasons of the year (summer open water, fall open water, and winter).

The regional economic impacts of this fishery include both *direct* and *indirect* impacts. The direct impacts are the initial sales of the commercial fishing industry (an average of $14,838,754 per year). The indirect impacts arise as these initial sales reverberate through the economy from the purchase of necessary inputs from other industries (e.g., labor, fuel, and tackle).[12] While the direct impacts occur within Manitoba, the indirect impacts can occur throughout the entire Canadian economy. Therefore, this analysis calculates the direct and indirect impacts of the Lake Winnipeg commercial fishery for all Canadian provinces.

The direct and indirect impacts estimated in this analysis are for sales revenue (also called *output*) and employment. These impacts were calculated using data purchased from Statistics Canada specifically for this analysis. These data, called *multipliers*, were determined by Statistics Canada through economic modeling and relate the output and employment impacts to the initial sales of the commercial fishing industry. Statistics Canada did not have multipliers available specifically for the commercial fishing industry in Manitoba, but did have multipliers for the broader “fishing, hunting, and trapping” industry for that province. Therefore, this analysis relies on the fishing, hunting, and trapping multipliers provided by Statistics Canada.

For consistency, the same biological invasion scenarios that were used in the HEA were also used in the regional economic impact analysis. For Lake Winnipeg, the

[12] Regional economic impacts can also include *induced* impacts, which refer to the increased economic activity arising from household spending from income earned in either the directly affected or supporting industries. However, induced impacts were not quantified in this analysis due to data limitations.

relevant scenarios are defined by whether or not a jump dispersal event occurs. If a jump dispersal event occurs, a progressive invasion of Lake Winnipeg is assumed to begin at its southern shore at the same time that a progressive invasion of the Red River begins. If a jump dispersal event does not occur, the progressive invasion of Lake Winnipeg is assumed to begin only after the biological invasion has traversed the Red River.

The same slow and fast invasion rates used in the HEA were also used in the regional economic impact analysis. Therefore, a slow invasion would take 175 years to traverse Lake Winnipeg, and a fast invasion would take 17 years. Both the slow and fast invasions of Lake Winnipeg are assumed to begin immediately given a jump dispersal event. If a jump dispersal event does not occur, a slow invasion of Lake Winnipeg would begin after the 294 years it would take to traverse the Red River, and a fast invasion of Lake Winnipeg would begin after 29 years. See section 5.3 for an explanation of these invasion rates.

Once an invasion of Lake Winnipeg by *any* of the 31 species of concern begins, it is assumed to incrementally displace all commercial fishing at a constant rate. For example, a fast invasion is assumed to displace the entire commercial fishery in 17 years. This conservative approach recognizes the possibility that a single invasive organism might displace the entire fishery, and thereby sets an upper bound on the estimate of consequences for any invasion scenario considered.

Finally, since a potential displacement of the Lake Winnipeg commercial fishery would occur over a number of years, impacts occurring in the future are discounted to the present time so they can be added up in a meaningful way. This discounting applies to the output impacts since they are expressed in monetary terms. However, the employment impacts, which are expressed in terms of full-time equivalent jobs, are not discounted. For consistency, the same discount rate used in the HEA (3% per year) was used in the regional economic impact analysis as well.

The potential direct and indirect output (sales revenue) impacts for all Canadian provinces given a jump dispersal event are reported in Table 3. Biological invasion scenarios involving a jump dispersal event will produce larger impacts than other scenarios since they are assumed to begin immediately (i.e., the effects of discounting are minimized). These impacts were first calculated separately for each risk category (very low, low, moderate, high, and very high). The probabilistic outcomes described in the risk characterization were then incorporated by calculating the average of these separate impact calculations for the different risk categories weighted by their respective percentage outcomes (Figure 1 in Section 4).

Given a jump dispersal event, the average total expected present value of the direct and indirect output impacts for all Canadian provinces ranges between $33,000 and $136,000, depending on whether the biological invasion is slow or fast. It is important to note that these impacts are expected values. Similar to the lost services included in the HEA, the economic impacts for each risk category reflect the associated probabilities of successful invasion (e.g., 1.00E-03 for the moderate risk category). The indicated

magnitudes of these average impacts ($33,000 to $136,000) also reflect a strong weighting toward the very low-risk category since that category accounts for 87% of all risk outcomes. The calculations for the results reported in Table 3 are detailed in Appendix 16. Impacts for progressive dispersal scenarios are significantly smaller and are not reported here.

Table 3
Expected Direct and Indirect Output Impacts for All Canadian Provinces Given a Jump Dispersal Event

Risk Category	Probability of Successful Invasion	Percent Outcomes	Total Expected Present Value of Direct and Indirect Output Impacts -------(Canadian 2003 $)------- Slow Invasion	Fast Invasion
Very Low	1.00E-09	87.0	$0.160	$0.655
Low	1.00E-06	7.6	$160	$655
Moderate	1.00E-03	3.7	$160,000	$655,000
High	1.00E-02	1.7	$1,600,000	$6,550,000
Very High	1.00E+00	0.0	$160,000,000	$655,000,000
Weighted Average			$33,000	$136,000

The expected direct and indirect employment impacts for all Canadian provinces given a fast invasion and jump dispersal event are illustrated in Figure 1 for a single representative invasive organism in the very high risk category. These impacts are expressed as full-time equivalent jobs and are not discounted to the present time. After the biological invasion has traversed Lake Winnipeg and the commercial fishery has been completely displaced, an expected loss of 331 FTE in all Canadian provinces is indicated by this analysis for the very high-risk category. This number is less than the actual employment of 1,013 fishermen in the Lake Winnipeg commercial fishery because it is expressed in terms of full-time equivalent jobs. Actual employment in this fishery is seasonal; therefore, the associated number of full-time equivalent jobs will be less.

The expected direct and indirect employment impacts for the other risk categories are significantly less: three FTE for the high risk category and zero FTE for all other risk categories. When weighted by the associated percent of outcomes in the risk characterization (e.g., 87% in the very low-risk category), the average direct and indirect employment impacts over all risk categories is zero FTE. That result holds regardless of the invasion scenario considered.

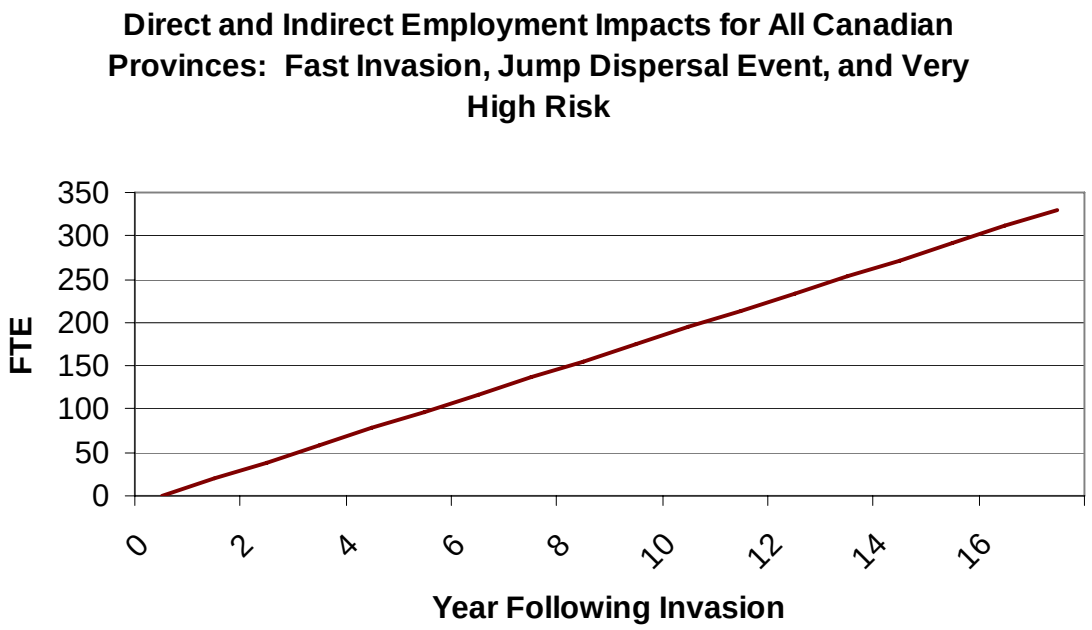

Figure 1. Direct and indirect employment impacts for all Canadian provinces given a fast invasion, jump dispersal event, and very high risk.

5.5 Conclusions

This analysis estimated the potential consequences associated with interbasin water transfers between the Upper Missouri River and Red River basins. Two economic approaches were used to estimate these consequences. Habitat equivalency analysis was used to estimate consequences throughout the assessment area including the Red River and Lake Winnipeg. That analysis indicated risk consequences ranging from 0.6 to 3.1 river-miles of offsetting restoration on the Red River and from 1.9 to 27,750 acres of offsetting restoration on Lake Winnipeg. While those results suggest potentially significant consequences for Lake Winnipeg, their interpretation depends on the feasibility and availability of appropriate restoration measures. Since the feasibility and availability of those restoration measures is not clear at this time, a second economic approach was used to focus the consequence analysis on Lake Winnipeg.

Regional economic impact analysis was used to estimate the impacts on output (sales revenue) and employment in the Lake Winnipeg commercial fishery. The invasion scenarios with the largest consequences (slow and fast invasions given a jump dispersal event) indicated a total expected present value between $33,000 and $136,000 in direct and indirect output impacts for all Canadian provinces. All other invasion scenarios indicated smaller output impacts. Expected employment impacts in the very high risk category (i.e., certainty) reach 331 full-time equivalent jobs. The average expected employment impacts weighted by the percent outcomes of respective risk categories is zero FTE for all invasion scenarios.

Given the quantitative results from the habitat equivalency analysis and the regional economic impact analysis, the following three conclusions can be drawn. First, the overall results are sensitive to the distribution of probabilistic outcomes from the risk characterization. From Tables 5-1 and 5-3, it can be seen that the indicated consequence levels for the individual risk categories vary substantially. That variance reflects the different probabilities of successful invasion. A different distribution of probabilistic outcomes would change the weighted averages of the consequence levels. Therefore, this consequence analysis is sensitive to the results of the risk analysis. In this particular case, the weighted average consequences are heavily weighted toward the lowest-risk category (87% of outcomes in the very low-risk category). A distribution more heavily weighted toward the higher-risk categories would yield substantially higher-weighted averages of consequences.

The second conclusion of this consequence analysis is that the speed of invasion significantly affects the quantitative results. Tables 5-1 and 5-2 indicate as many as four orders of magnitude difference in offsetting restoration levels between the two invasions speeds assumed in this analysis, and Table 3 indicates one order of magnitude difference in output impacts. A much more detailed analysis would match individually estimated invasion speeds to respective organisms and then aggregate the indicated consequence levels over the species of concern. However, the information regarding species-specific invasion speeds was not available to conduct that level of analysis. Therefore, this analysis indicates not only the significance of this analytic factor but also the need for additional research in this area.

Finally, this consequence analysis concludes that the anticipated distribution of the method and number of dispersal events substantially affects the quantitative results. This analysis considered only a limited set of potential dispersal scenarios. No information was available to inform the distribution of these scenarios to include in the analysis. However, the limited number of potential dispersal scenarios analyzed here indicated as many as four orders of magnitude difference in offsetting restoration levels between them. Similar to the conclusion regarding the speed of biotic invasion, this analysis indicates a significant analytic factor and a need for further research.

The questions raised about invasion speeds and the distribution of dispersal events are biological/ecological in nature and must be answered through additional biological/ecological research. However, additional economic research would also improve the estimates of risk consequences. For example, primary research and original economic modeling could be conducted to more accurately estimate the regional economic impacts associated with the Lake Winnipeg commercial fishery. Impact multipliers specifically for the commercial fishing industry in Manitoba were not available for the present analysis. Therefore, research to estimate those multipliers would improve the estimates of risk consequences.

Additional economic research could also be conducted to estimate other consequences than those related to commercial fishing. For example, biological invasions

could potentially impact the recreational fishing industry of Lake Winnipeg. Similar to commercial fishing, recreational fishing generates economic activity in Manitoba and throughout the Canadian economy. In addition to estimating the regional economic impacts on the recreational fishing industry, additional research could be conducted to estimate potential losses of net economic value to recreational anglers. That research would likely require public surveys and original economic modeling.[13]

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6.0 Summary and Conclusions

Abstract. In Section 6, risks directly linked to biota transfers potentially associated with interbasin water transfers between Missouri River basin and Red River basin are summarized, and conclusions are developed. Absent priority, a simple list of conclusions includes but is necessarily not limited to:

(1) Interbasin transfers of untreated waters implemented via an open conveyance (e.g., canals) have a very high likelihood of establishing pathways to potentially promote biota transfers and subsequent biological invasions. While most of these invasions will fail in the absence of establishment of sustainable populations, such precursors to invasion will occur with near certainty. Although interbasin transfers of water via open conveyance has been dismissed as an option of choice, if interbasin water transfers occur via such a mechanisms, species invasions will occur and some species will establish populations in the receiving system despite any implementation practice adopted by Bureau of Reclamation or other government or nongovernment organization.

(2) Given life-history attributes typical of invasive species, biota likely to be successful at establishing sustainable populations in the Red River basin can be identified, although there is relatively great uncertainty associated with identifying which specific species may be involved in a successful invasion, given the stochasticity of the pioneering event.

(3) Historically, interbasin biota transfers have occurred independent of any designed engineering project linking the Missouri River basin and Red River basin; these biota transfers will continue to occur as a consequence of existing pathways (both natural and anthropogenic) and extreme events (e.g., floods) that are independent of any future human intervention. Management practices focused on prevention and control of biological invasions may minimize adverse effects associated with such transfers, and more optimistically, lead to the eradication of relatively long-established invasive species.

(4) Rosters of biota considered to be invasive are continually updated and additional species are being characterized as “emerging” or “reemerging” species of concern. Hence, poorly characterized or newly described invasive species must be anticipated and managed accordingly, e.g., analysis of risks must be updated periodically by resource managers.

(5) Interbasin transfers of water via a controlled and contained conveyance (e.g., piped from source to receiving system) will have less risk of biological invasions associated with their transfer, although the degree of risk reduction will depend upon the engineering design selected for the conveyance. For example, simply transferring water via pipeline from the Missouri River to a "point of engineering convenience" in the Red River basin will likely present risks similar to those associated with transfers completed via open conveyance, if a multiple-stage control system is absent from the transfer system's design.

(6) Interbasin transfers of treated water via a controlled and contained conveyance will present the lowest risks of biological invasion, and depending on the control system selected for implementation of the transfer, the likelihood of biological invasions being successful are much less than the likelihoods associated with biological invasions occurring via alternative pathways (natural or anthropogenic).

(7) Biological invasions associated with treated waters transferred through a controlled and contained conveyance would be more likely to be successful as a function of life-history attributes of the biota being transferred and not highly dependent on mode of transfer alone.

(8) The establishment of sustainable populations is less dependent on stochastic events resulting in an invasion than it is on the life-history attributes of the biota being transferred.

(9) Interbasin water transfers are also likely to indirectly influence biota transfers, biological invasions, their attendant outcomes, and potentially affect both source and receiving systems. Quantitative estimates of risks characteristic of indirect effects are precluded from derivation in the current report of technical findings. Analysis and estimation of risks associated with indirect pathways for invasion require greater specification of systems "at risk."

(10) Attributes of complex systems, and especially those characterized by engineering designs layered upon an existing landscape of natural and anthropogenic features, likely mean that the indirect or contributory role that multiple, interacting factors may play in the process of species invasion (e.g., augmented water flows may influence species invasions of riparian habitats previously subject to the vagaries of season water flows) will yield numerous low-probability events, which through time may be expressed as long as the interrelationships among constituent nodes remains fully characterized.

(11) For complex systems, the analysis of indirect effects becomes idiosyncratic and highly

scenario dependent. The focus of the present report has been on risks potentially associated with direct effects attendant to interbasin water diversions.

(12) If interbasin water transfer occurs with a multiple-stage control system built to implement diversion, there is still likely a future misassignment of linkage between water diversion and species invasions.

6.1 Introduction

John Wesley Powell, second director of the US Geological Survey, had observed in his classic "Report on the Lands of the Arid Region of the United States" (1878) that water was the arid region's [1] most precious resource but that very little of the remaining public land was suitable for conventional farming and that only a small fraction of the arid land was characterized by soils amenable to irrigation. In the "Report on the Lands of the Arid Region of the United States" (1878), Powell also suggested that water was more of a sociopolitical than a scientific problem. Powell's observations over 125 years ago still ring true, and this report continues USGS efforts to bring science to the decision-making process. Water demands continue to increase throughout the Great Plains and the western US (see NRC 1992; Rogers 1993). In the case of the northern Great Plains, the recognition of water needs and the anticipation of solutions to meet those needs has been, and continues to be, a well-traveled road, water needs approach infinity while finite water resources continue to shrink.

Water transfers within a watershed or between watersheds are an increasingly common component of regional water systems and are being considered in many locations for meeting growing water demands and for managing the impacts of drought (see, e.g., NRC 1992, Rogers 1993). Water transfers have long been a concern of water-resource managers, and historically, the topic has gained national and regional attention not unlike the issues associated with various visions of the Garrison Diversion. The balance of this closing section of the technical report will focus on summaries of risks of biota transfers, control systems and their role in reducing those risks, and the larger adaptive management context in which these technical findings are intended to be used.

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[1] During Powell's tenure as director of USGS, "arid region" was the US west of the 100th meridian.

6.2 Control Systems and Reduction of Risks Associated with Interbasin Biota Transfers

If USGS were interpreting risks associated with biota transfers potentially linked to the proposed Garrison Diversion of the mid- to late-1970s, we too would have characterized risks as being "high," given the water control system proposed at that time to reduce risks of biota transfers associated with interbasin water diversions. Today, our analysis of alternative scenarios suggests that risks of biota transfers are high, if control systems are not sufficiently developed to offset the relatively high probability that biota transfers would occur if implemented via open conveyance (e.g., open canal) or contained conveyance serving to divert "raw" water (e.g., piped, but untreated water). A snapshot calculation of risk may appear relatively small to many observers, yet the range of risk estimates generated from the simulation study illustrates the uncertainty contributing to the decision-making process under which this, or any interbasin water diversion, operates. For interbasin water transfers completed in the absence of a multiple-stage control system (e.g., water pretreatment followed by stepwise water treatment using chloramination and ultrafiltration), risks of biota transfers approach "practically one" (that is, very likely to occur), given the number of trials that could inevitably occur through time. Seemingly an infinite number of trials would likely yield a "founding cohort" that breaches confining geographic barriers of exporting basin and subsequently establishes sustainable populations in the importing basin. In contrast, an interbasin water diversion completed using a multiple-stage water control system including pretreatment, chemical treatment, and ultrafiltration would be characterized as a low-risk venture where probabilities of biota transfers approached "practically zero," with species invasions or shifts in metapopulation dynamics strongly coupled with control system failure and stochastic processes that link independent steps within a flow of events that characterize the invasion process.

In order to reduce risks of biota transfers associated with interbasin water diversions, engineered systems designed to accomplish water transfers from Missouri River to Red River basins must consider our increasing, yet incomplete, understanding of technical issues related to invasion biology and the ecological perspectives that potentially influence water quality and quantity in Missouri River and Red River basins. Given the iterative character of the risk analysis and risk assessment process, the findings in this technical report reflect our initial foray into the interrelated issues of interbasin water diversions and the collateral effects potentially associated with biota transfers that occur consequent to that action. Three basic scenarios—transfer via open-water conveyance, transfer of untreated water via piped

conveyance, and transfer of treated water via piped conveyance—were considered using multiple tools: narrative analysis, quantitative analysis, and simulation. As a point of reference, the technical analysis considered these interbasin transfers relative to a narrative analysis of a "within-basin" water supply alternative, and a narrative analysis of risks associated with mode of conveyance. If outcomes to companion efforts currently being develop by Reclamation (e.g., preparation of an environmental impact statement being prepared under NEPA) warrant, subsequent iterations of this process may be focused on engineering needs that require a targeted analysis of risk reduction measures to support control system design and specification.

6.2.1 Single-stage control systems and risk reduction. As indicated in Appendix 12, candidate technologies to support a single-stage control system vary from those widely used in current water supply systems (e.g., chlorination) to those whose application is relatively underdeveloped in domestic markets of the US (e.g., ozonation). The intent of the technical report was to afford stakeholders with sufficient background with these technologies to consider their role as risk-reduction measures and not to advocate one technology's use over another. Previous Reclamation efforts to address water needs in the northern Great Plains (e.g., Northwest Area Water Supply (NAWS) project) proposed a control system that was single-stage in construction but multiple-stage in practice (see contrasting views related to NAWS, e.g., http://design.eng.umanitoba.ca/resources/garrison_full.html and http://www.houstoneng.com/ projects/naws/ last accessed December 6, 2004). As evidenced by water supply systems currently in operation throughout the US, control system designs may assume any of many configurations, which in part reflects various user needs (e.g., irrigation, rural and municipal use, industrial and high technology use) and their location relative to source water supply.

Regardless of technology of choice, no control system will be "risk free." Each of the water treatment technologies summarized in Appendix 12 have risks associated with their use as part of a control system; those risks cannot be avoided but can be minimized. And risks associated with single-stage control systems may be unacceptable for water resource managers, especially given the "competing risks." For example, chlorination has a long history of use in control systems as a water treatment technology with a performance history supporting its continued role in water disinfection (see Appendix 12). Yet the increasing awareness of risks associated with "disinfection by products" (DBPs, e.g., halomethanes) has required water users to revisit questions related to chlorination and competing risks related to health benefits associated with reduced occurrence of waterborne disease consequent to drinking water chlorination and increased risks associated with exposure to DBPs (e.g., increased cancer risks) in drinking water. Similar issues of competing risks exists for ozonation processes wherein

formation of bromide becomes an issue owing to the collateral increase in cancer risks associated with exposure to bromide in drinking water (see, e.g., http://www.epa.gov/safewater/mcl.html last access December 6, 2004).

Review of Appendix 12 suggests that risks of biota transfer can be substantially diminished, if a control system is designed with that contingency in mind and providing performance criteria are specified against which a single-stage system can be designed and constructed. However, single-stage systems may not afford risk reduction sufficient to ensure skeptical stakeholders that biota transfers would likely not occur, e.g., disease agents such as *M. cerebralis*, the causative agent of whirling disease, and *C. parvum* are relatively resistant to single-stage chemical treatments such as chlorination. From a technical perspective, multiple-stage control systems afford another level of risk reduction that may be warranted, if costs associated with these systems are not prohibitive.

While multiple-stage control systems are generally associated with less risk than those associated with a single-stage control systems, the concept of "zero risk" remains unattained even with this level of design (see Schippers et al. 2004). As noted in Appendix 12 and captured in the simulation analysis in Section 3 and Section 4, multiple-stage control systems will never be characterized by zero risk given the inevitable changes in a system's reliability through time (see Appendix 4). However, risks relative to a control system and its product waters (e.g., increased health benefits associated with water disinfection and reduction in DBPs in treated waters) can be minimized with attendant uncertainties related to system performance. Potential system failures, however, contribute to our inability to attain a "perfect system" having zero risks. Technical findings summarized in this report do not recommend one control system over another with respect to specification or configuration, nor do these findings specify whether risks are acceptable and not acceptable. This initial iteration in the analysis of risks, however, suggests that risk associated with biota transfers could be reduced through implementation of water diversion via a multiple-stage control system that incorporates a conventional pretreatment (e.g., coagulation and flocculation), followed by chemical treatment (e.g., with chloramine) in series with ultrafilation. Rejection values vary across available pressure-driven membrane devices (e.g., microfiltration, ultrafiltration, and nanofiltration membranes), but ultrafiltration (or the equivalent technology yielding similar performance characteristics) would reduce risks associated with resistant life stages of disease agents such as viruses, bacteria, protozoa, and other microorganisms potentially occurring in source waters from the Missouri River.

6.2.2 Control systems for sufficient risk reduction to support interbasin water diversions. By incorporating economic concepts such as the "willingness-to-pay" and "willingness-to-accept" (see, e.g., Field 1996, 2000) into the analysis of risks and consequences potentially associated with interbasin biota transfers, outcomes of risk analysis can be placed in perspective. The economic principles may be applied to natural resource issues where monetary and nonmonetary costs are viewed within the context of "risk reduction" to allay stakeholder concerns associated with adverse effects that might occur as collateral damage to resource management policy (see Walters 1986). For example, risks of biota transfer may be reduced provided multiple-stage control systems are used to implement interbasin water transfers, but alternative options may be preferred by stakeholders, owing to other monetary or nonmonetary concerns. Similarly, within-basin alternatives may be associated with reduced risks, if water allocations among competing users can be reprioritized depending on resources most sensitive to reduced water availability, e.g., voluntary transfer of water rights between willing buyers and sellers. Water marketing may be used to meet "new" water demands, because the process encourages voluntary transfers rather than forced reallocations, e.g., water may be reallocated from lower-valued uses to higher-valued uses. As Garrison Diversion's history would suggest, interbasin water transfers often times are associated with significant economic, political, social, cultural and environmental concerns, so public interest criteria are needed to assess the viability of transfers. These criteria should distinguish between large and pervasive effects and smaller ephemeral impacts, although finding common ground among stakeholders presents a challenge to the resource manager. If resource valuation can be determined, then a marketing approach to dispute resolution may be gained in the process and risks of biota transfer can be fully integrated into resource management plans. As such, the prospects of biota transfers consequent to interbasin water diversions should be integrated into basinwide plans that likely exceeds the scope of any single resource management agency such as Bureau of Reclamation.

Our technical findings indicate risks of biota transfers, be those aquatic nuisance species or other biota of concern, e.g., aquatic vascular, and riparian and wetland vascular plants, identified by stakeholders during problem formulation, will vary as a function of control systems designed and constructed to realize water diversions. Biota transfers and species invasions are also subject to inevitable stochastic events. While "high-risk alternatives" such as open-canal conveyance and untreated water transfers may be infrequently considered options for implementing water transfers, these options provided alternative scenarios for evaluating risks. And not surprisingly, risks of biota transfers under these alternatives were high, and in some instances approached near certainty. Hence, those options, or engineering alternatives strikingly similar to those considered by IJC (1977), still present technically unacceptable risks for biota

transfer. In contrast, risks of biota transfers associated with interbasin water diversion implemented with multiple-staged control systems in place present low, if not negligible, risks and do not appear as significant as those biota transfer risks forecasted over 25 years ago when control options considered by IJC (1977) were relatively limited. To a large extent, the observed "risk reduction" apparent between 1977 and 2004 stems from advances in water treatment control technologies, primarily the wider array of water treatment options currently available to reduce likelihoods that biota transfers occur, e.g., multiple control stages including traditional pretreatment, chemical treatment using chloramine, and ultrafiltration (see, e.g., Schippers et al. 2004).

6.3 Conclusions Regarding the Risks and Economic Consequences of Biota Transfers Potentially Associated with Interbasin Water Diversions

A simple summary of risks and conclusions suggested by technical findings of this report merely capture a snapshot of risks reflected by potential biota transfers directly associated with interbasin water transfers between Missouri River basin and Red River. Yet without priority, the dozen conclusions that follow may afford natural resource managers insights into biota transfer issues that presently challenge water management agencies and stakeholders focused on interbasin water transfers between Missouri River and Red River basins.

(1) Interbasin transfers of untreated waters implemented via an open conveyance (e.g., canals) have a very high likelihood of establishing pathways to potentially promote biota transfers and subsequent biological invasions. While most of these invasions will fail in the absence of establishment of sustainable populations, such precursors to invasion will occur with near certainty. Although interbasin transfers of water via open conveyance has been dismissed as an option of choice, if interbasin water transfers occur via such a mechanisms, species invasions will occur and some species will establish populations in the receiving system despite any "best management practice" adopted by Bureau of Reclamation or other government or nongovernment organization.

(2) Given life-history attributes typical of invasive species, biota likely to be successful at establishing sustainable populations in the Red River basin can be identified, although there is relatively great uncertainty associated with identifying which specific species may be involved in a successful invasion, given the stochasticity of the pioneering event.

(3) Historically, interbasin biota transfers have occurred independently of any designed engineering project linking the Missouri River basin and Red River basin; these biota transfers will continue to occur as a consequence of existing pathways (both natural and anthropogenic) and extreme events (e.g., floods) that are independent of any future human intervention. Management practices focused on prevention and control of biological invasions may minimize adverse effects associated with such transfers, and eradication of relatively long-established invasive species may attain limited success in the near future.

(4) Rosters of biota considered to be invasive are continually updated and additional species are being characterized as “emerging” or “reemerging” species of concern; hence, poorly characterized or newly described invasive species must be anticipated and managed accordingly.

(5) Interbasin transfers of water via a controlled and contained conveyance (e.g., piped from source to receiving system) will have less risk of biological invasions associated with their transfer, although the degree of risk reduction will depend upon the engineering design selected for the conveyance. For example, simply transferring water via pipeline from the Missouri River to a “point of engineering convenience” in the Red River basin will likely present risks similar to those associated with transfers completed via open conveyance, if a multiple-stage control system is absent from the transfer system’s design.

(6) Interbasin transfers of treated water via a controlled and contained conveyance will present the lowest risks of biological invasion, and depending on the control system selected for implementation of the transfer, the likelihood of biological invasions being successful are much less than the likelihoods associated with biological invasions occurring via alternative pathways (natural or anthropogenic).

(7) Biological invasions associated with treated waters transferred through a controlled and contained conveyance would be more likely to be successful as a function of life-history attributes of the biota being transferred and not highly dependent on mode of transfer alone.

(8) The establishment of sustainable populations is less dependent on stochastic events resulting in an invasion than it is on the life-history attributes of the biota being transferred.

(9) Interbasin water transfers are also likely to indirectly influence biota transfers, biological invasions, their attendant outcomes, and potentially affect both source and receiving systems. Quantitative estimates of risks characteristic of indirect effects are precluded from derivation in

the current report of technical findings, given the unspecified engineering designs proposed to mediate the transfer. Analysis and estimation of risks associated with indirect pathways for invasion require specification of systems with greater detail than currently available.

(10) Attributes of complex systems, and especially those characterized by engineering designs layered upon an existing landscape of natural and anthropogenic features, likely mean that the indirect or contributory role that multiple, interacting factors may play in the process of species invasion (e.g., augmented water flows may influence species invasions of riparian habitats previously subject to the vagaries of season water flows) will yield numerous low-probability events, which through time may be expressed as long as the interrelationships among constituent nodes remains fully characterized.

(11) For complex systems, the analysis of indirect effects becomes idiosyncratic and highly scenario dependent. The focus of the present report has been on risks potentially associated with direct effects attendant to interbasin water diversions.

(12) If interbasin water transfer occurs with a multiple-stage control system built to implement diversion, there is still likely a future mis-assignment of linkage between water diversion and species invasions.

Powell's observations on water in the western US have in part been addressed through policy statements that guide "how water needs should be satisfied." Yet at times these policy perspectives may conflict, e.g., precautionary measures vary with respect to implementation when encountering declarations with equally variable interpretation. Unfortunately, resolution of these conflicting views, or rather the interpretation of how these policies should be implemented, is not a technical problem even if technical solutions are sought. This technical report can only hope to bring an analytical perspective to the discussion of risks and consequences associated with biota transfers potentially occurring consequent to an interbasin water diversion. If the water diversion is realized, the risks of biota transfers range from "highly likely to occur" to "highly unlikely to occur," depending on how the diversion is realized and with economic consequences matching these technical findings focused on risk. Technical findings summarized in this report are predicated on the assumption that water from the Missouri River is transferred to the Red River basin. Yet, until an overarching set of sociopolitical and socioeconomic questions—the same questions identified by Powell over 125 years ago—are answered, the issue of biota transfer will very likely be addressed in another report prepared by future technical analysts whose findings will be damned or praised, depending on the "eye of the beholder."

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