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.

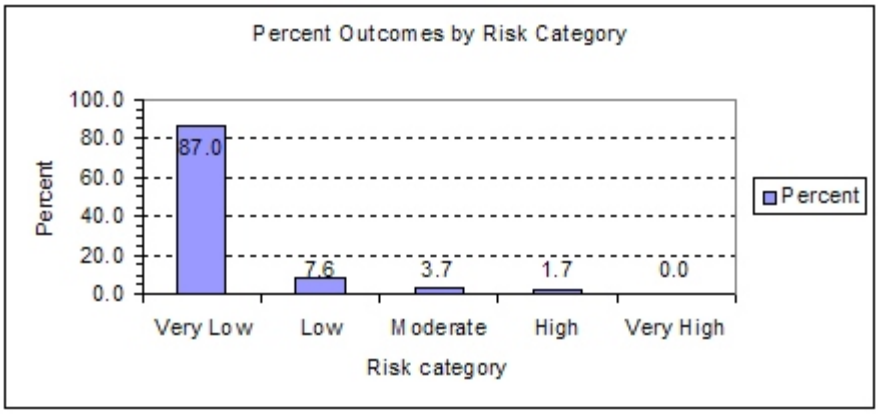

Figure 1. Categorical assignments of risk ranging from "Very low" to "Very high" derived from iterative analysis summarized in Section 3.

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).

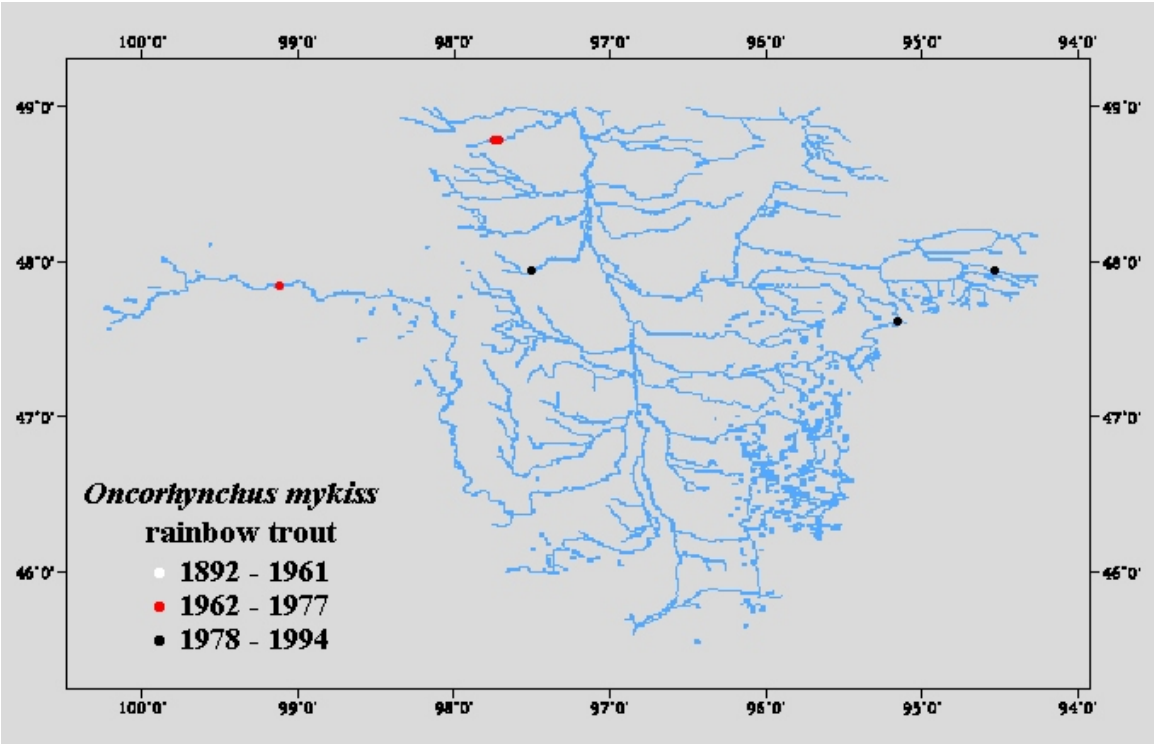


Figure 9. Distribution of the rainbow trout in streams of the Red River of the North basin (from Peterka and Koel 1996).

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.

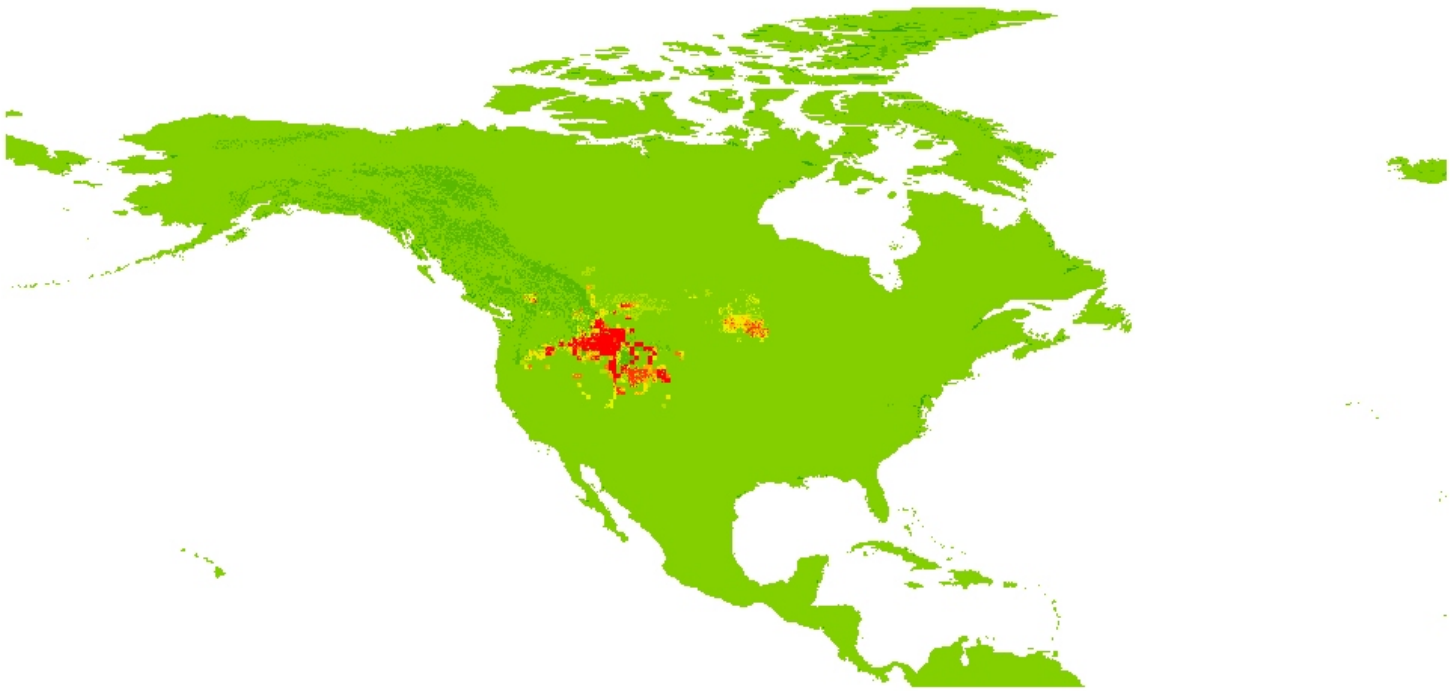


Figure 11. New Zealand mudsnail based on presence data from HUC10 only.

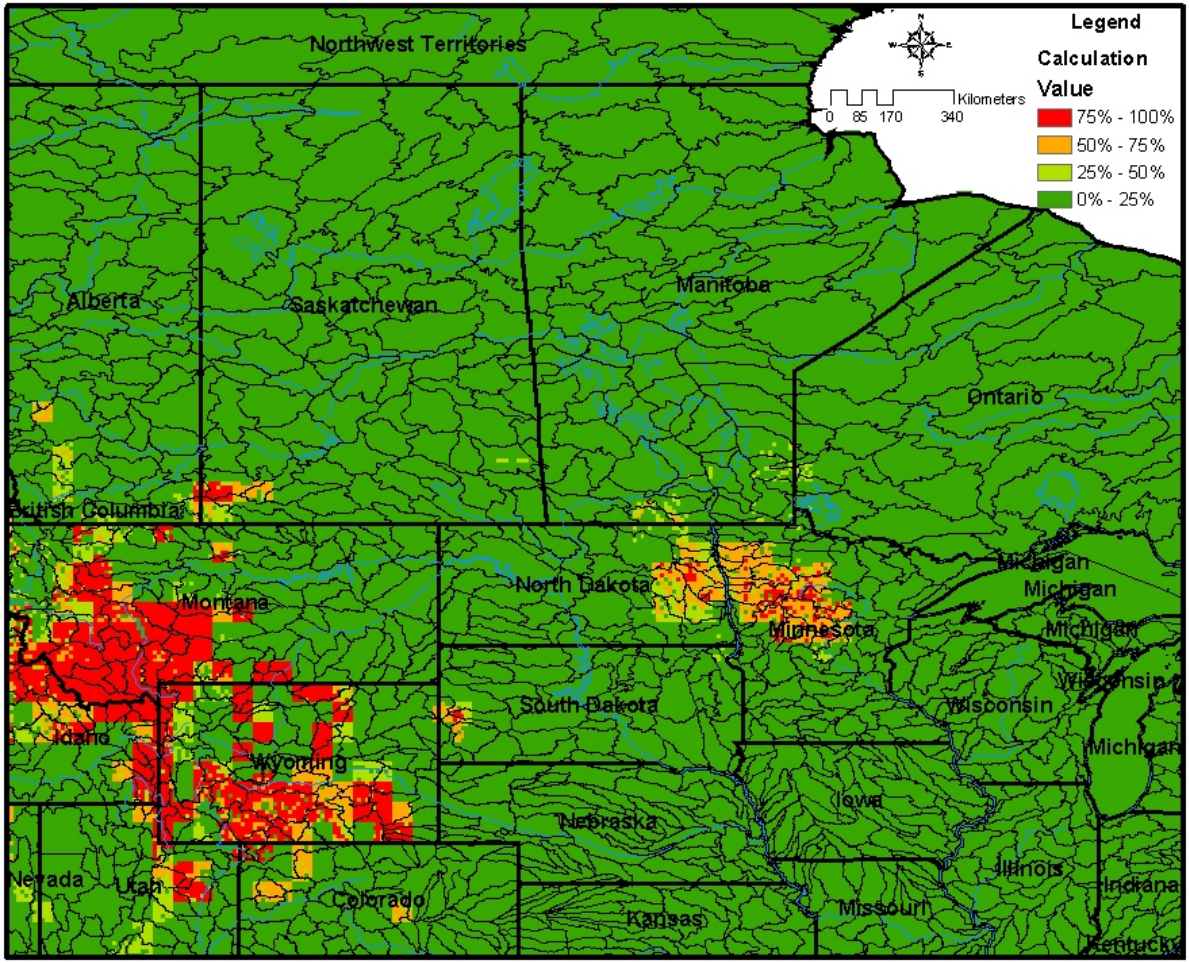


Figure 12. Zebra mussel predicted distribution based on 1988–1993 presence data.

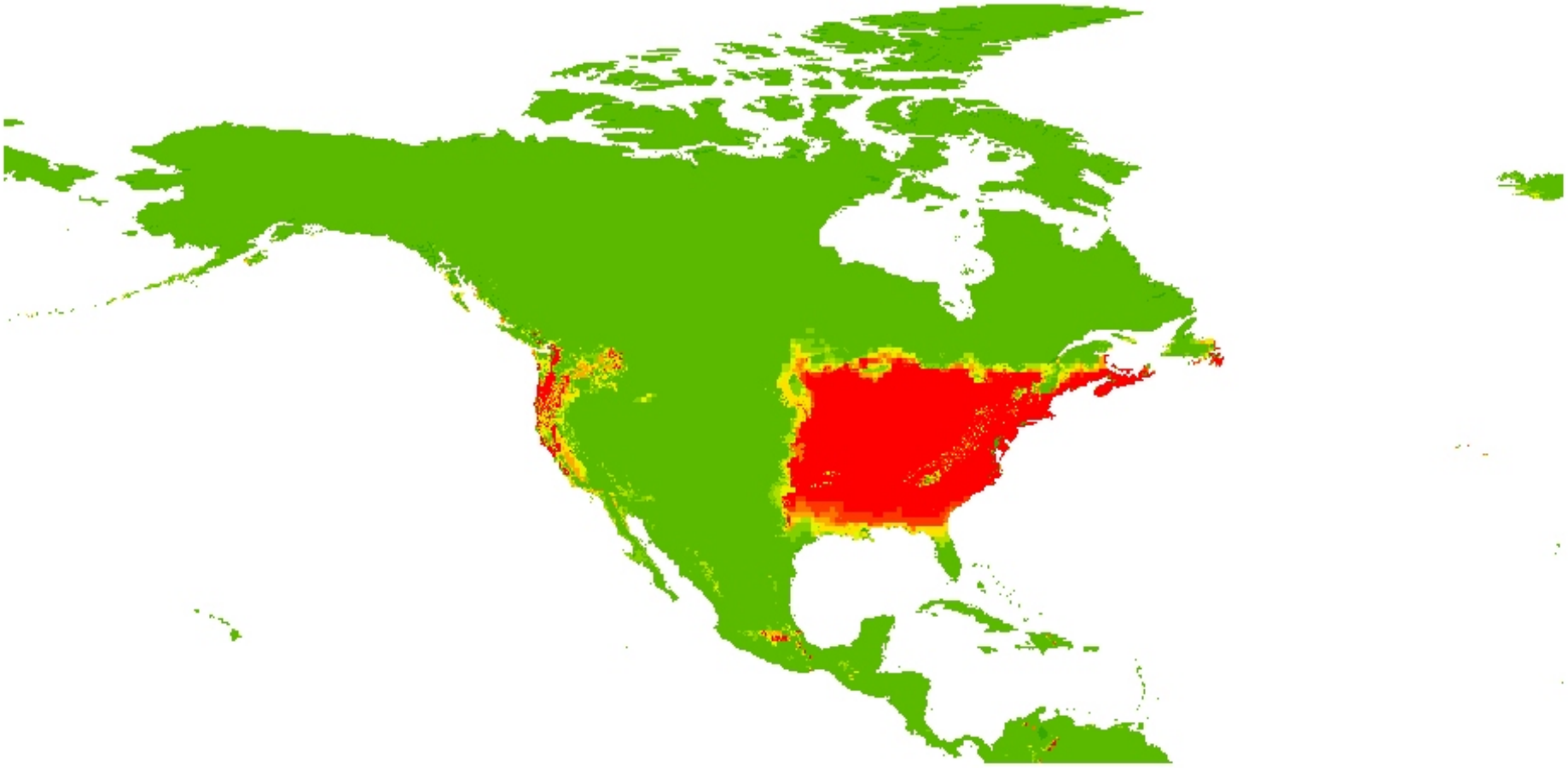


Figure 13. Zebra mussel predicted distribution based on 1988–1993 presence data.

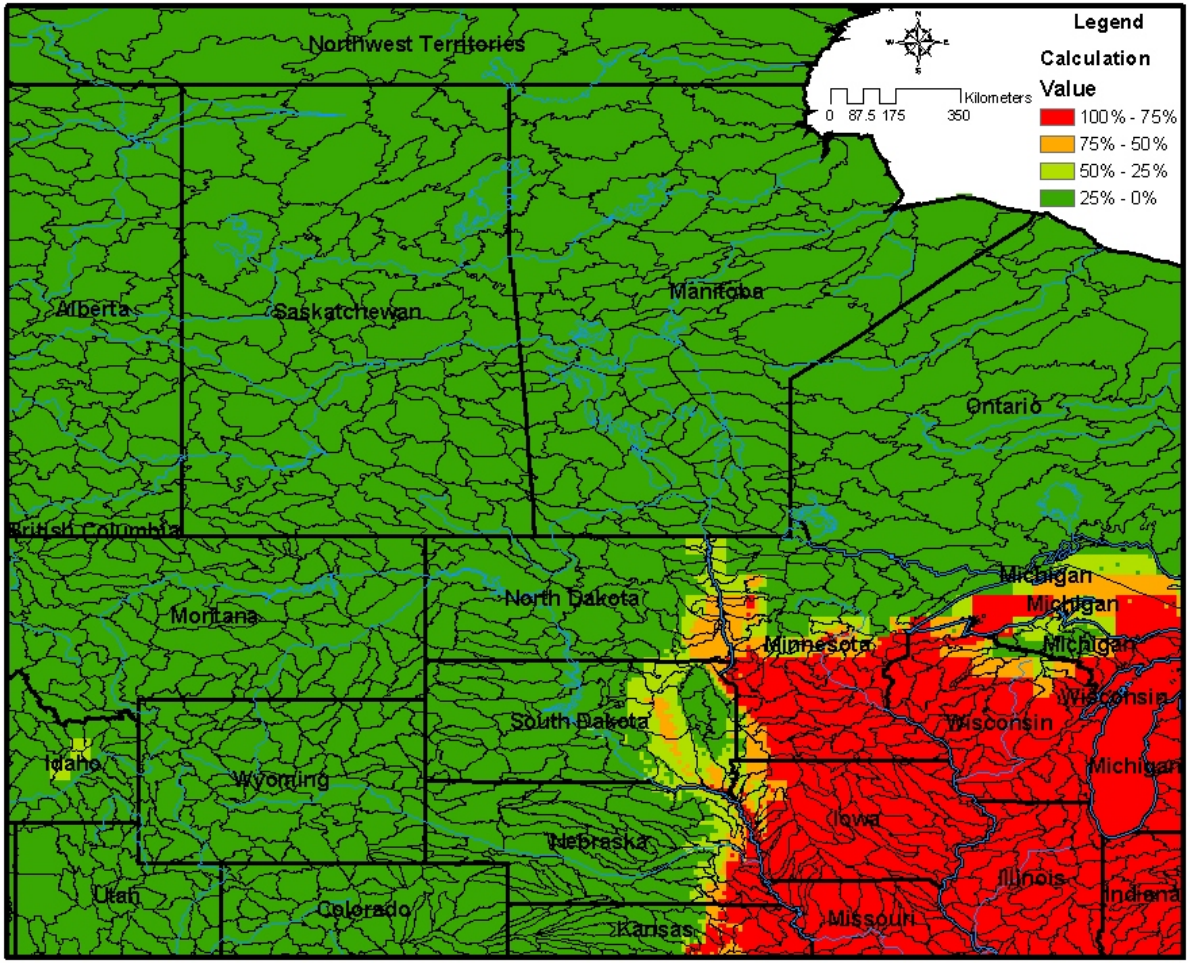


Figure 14. Zebra mussel predicted distribution based on logistic regression only.

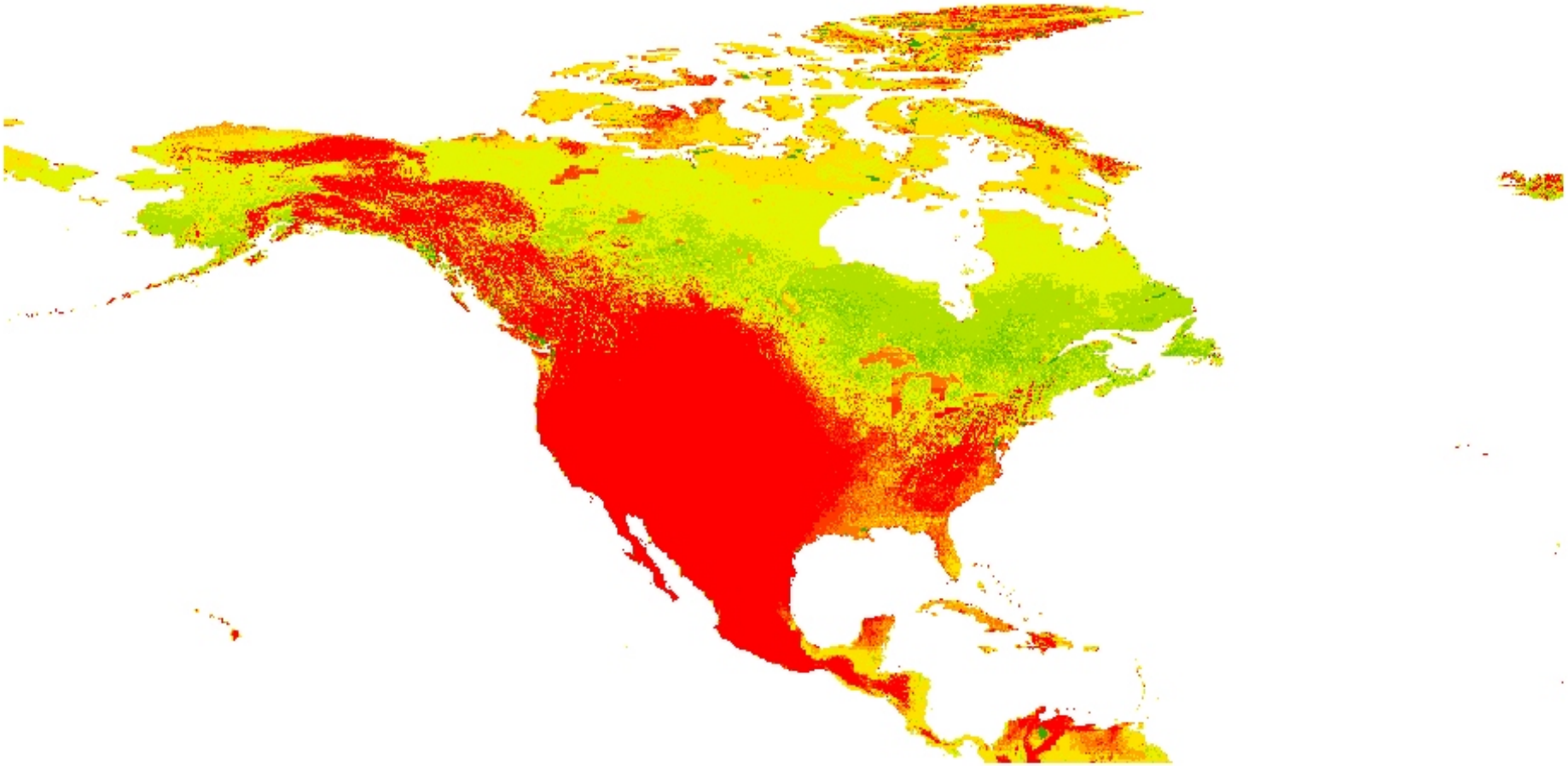
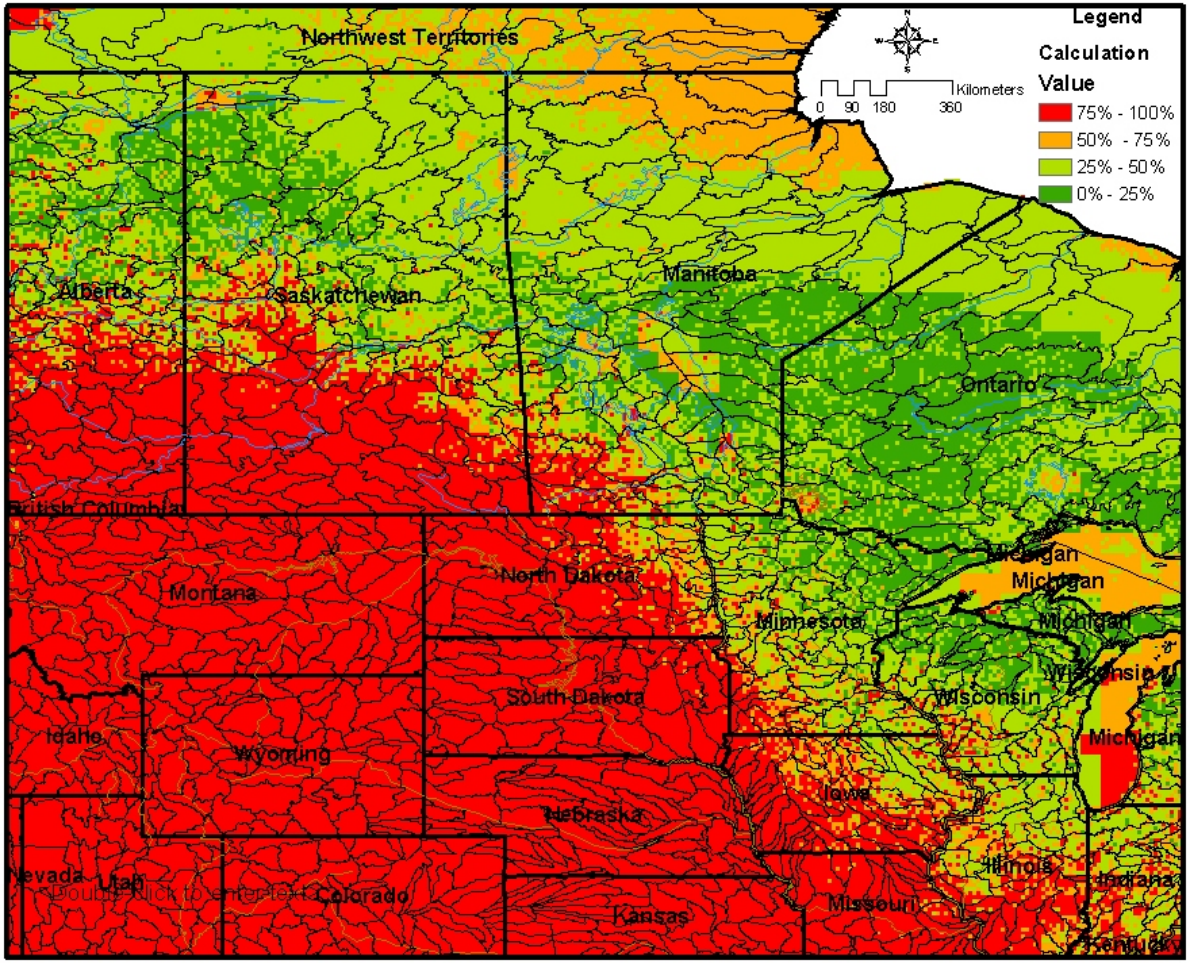


Figure 15. Zebra mussel predicted distribution based on logistic regression only.



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).

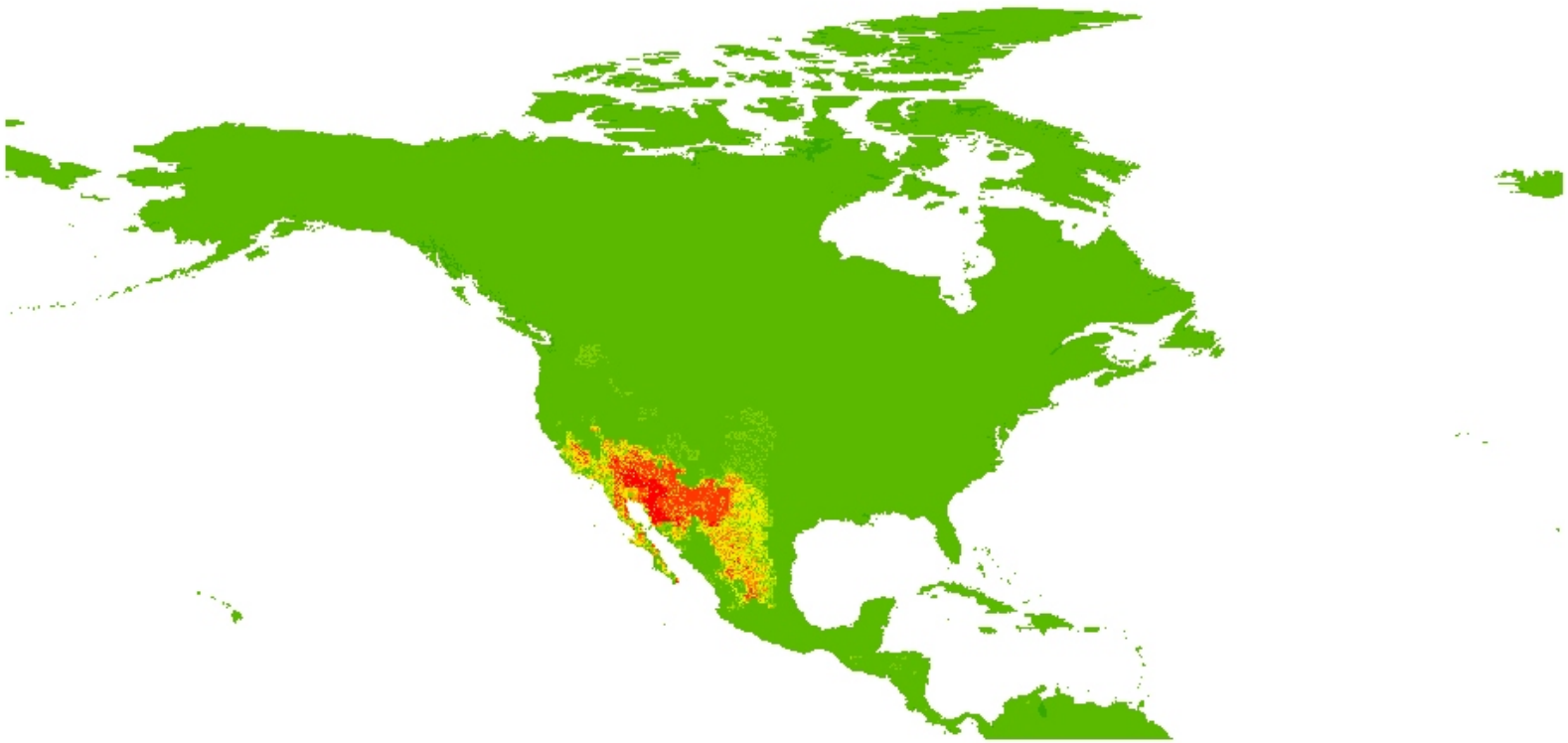


Figure 17. Tamarisk distribution censored through historic snapshots of presence data (limited to presence data extending to southwest and intermountain west of US).

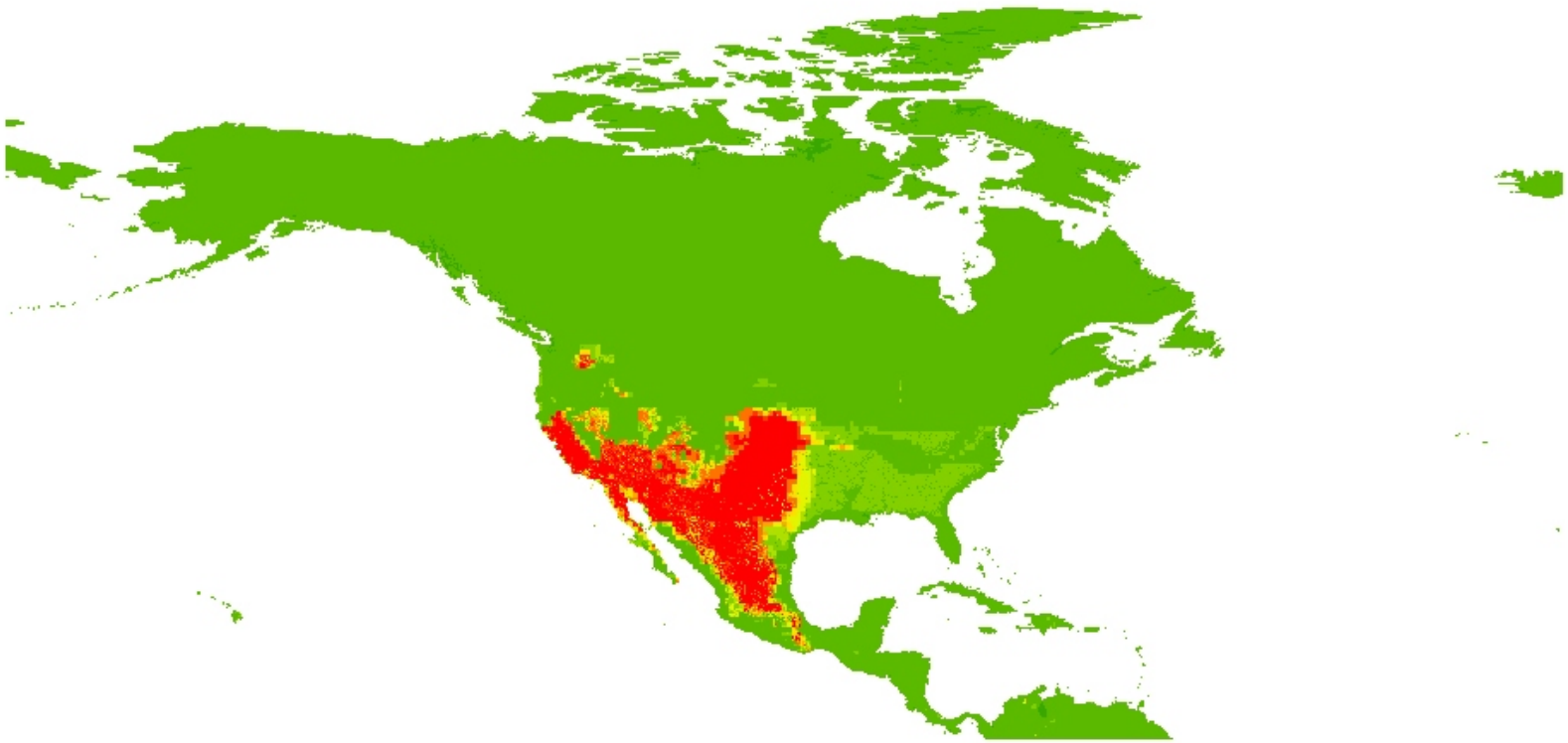
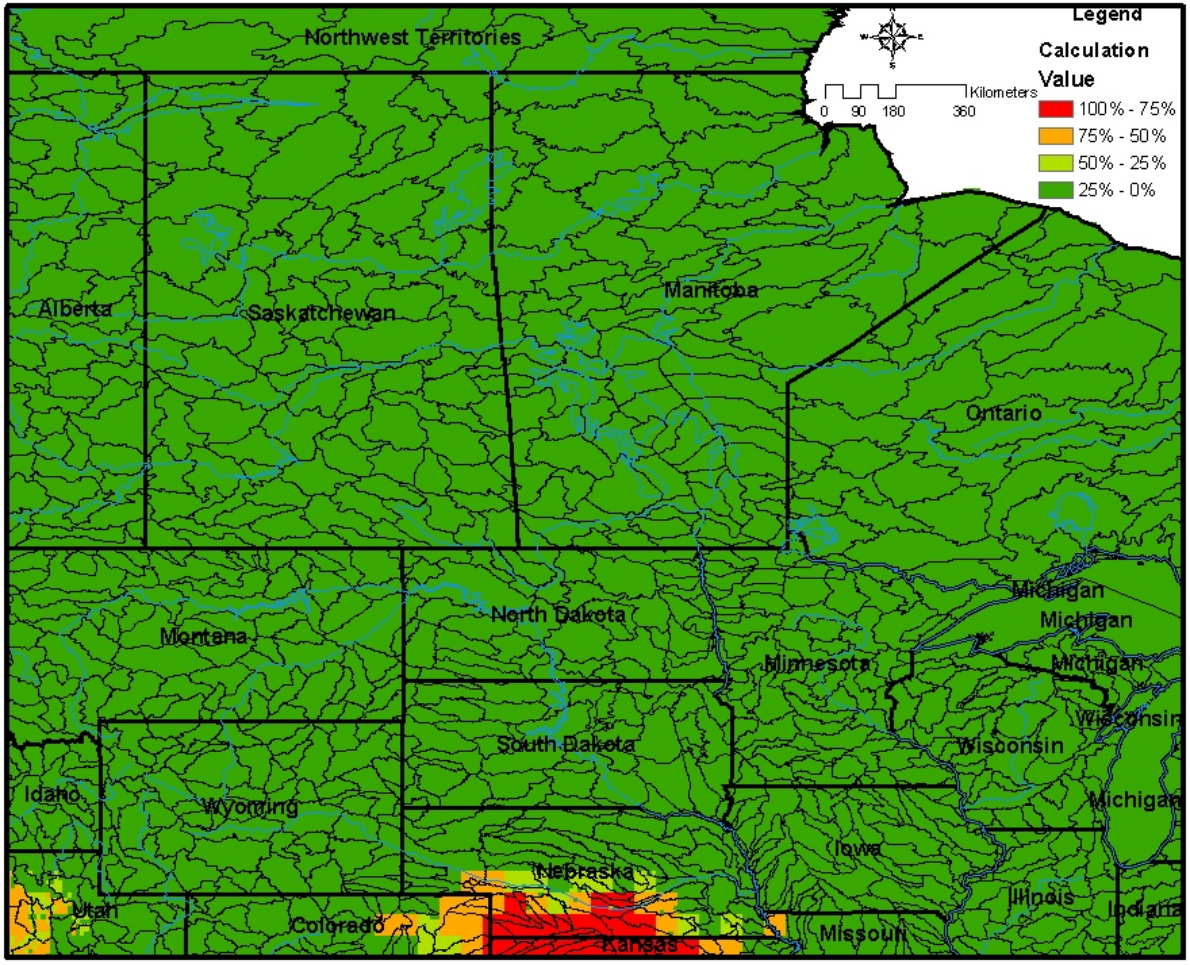


Figure 18. Tamarisk zoom of SW and intermountain west presence data.



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).

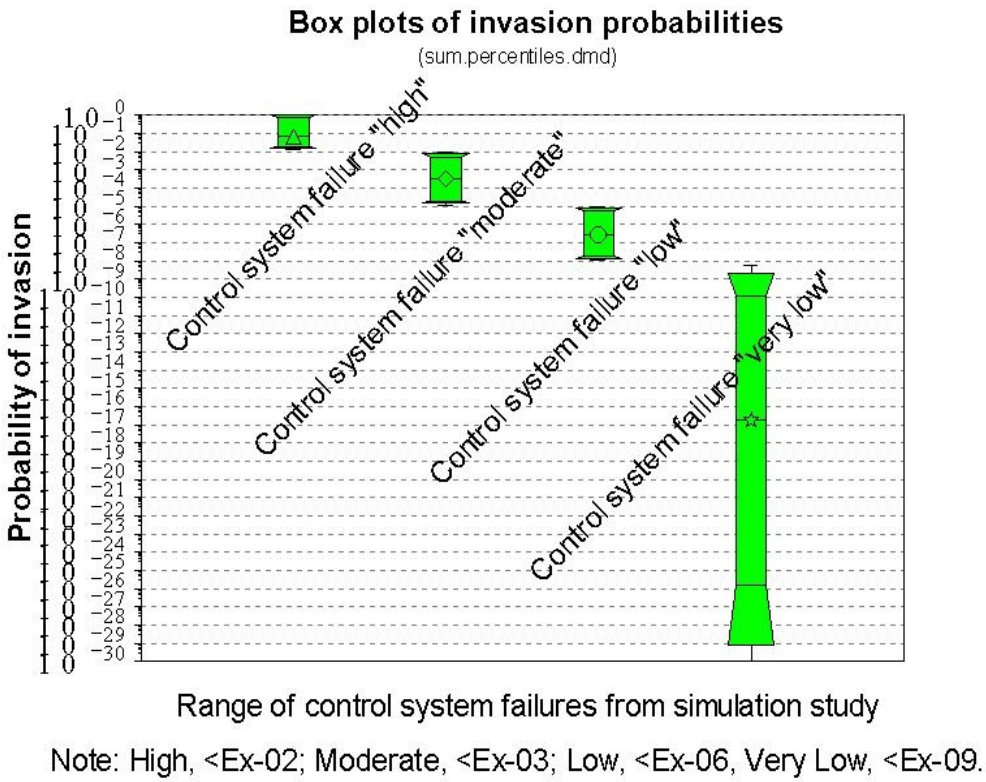


Figure 12. Probability of successful invasion given specified failure rates in control systems mediating interbasin water diversion.

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.

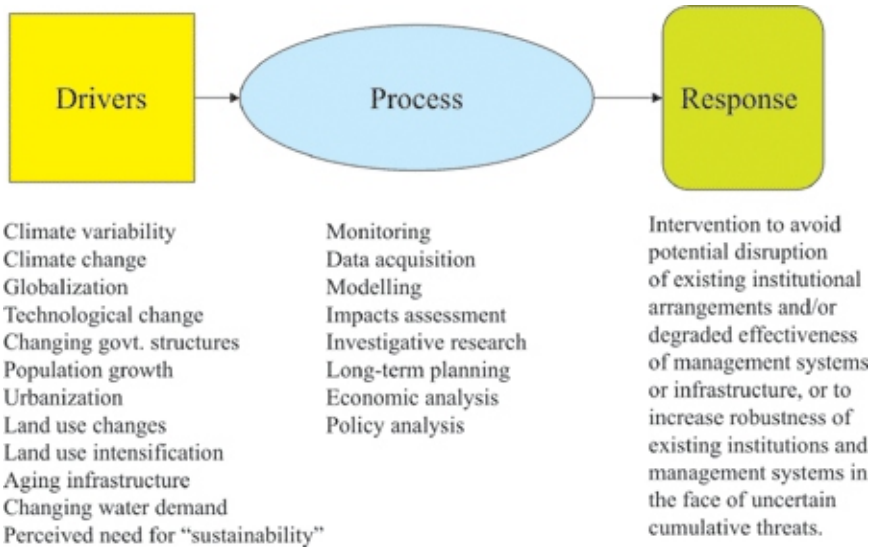

Figure 13. Process for evaluating threats and risks associated with within-basin alternatives for Red River basin water supply.

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).

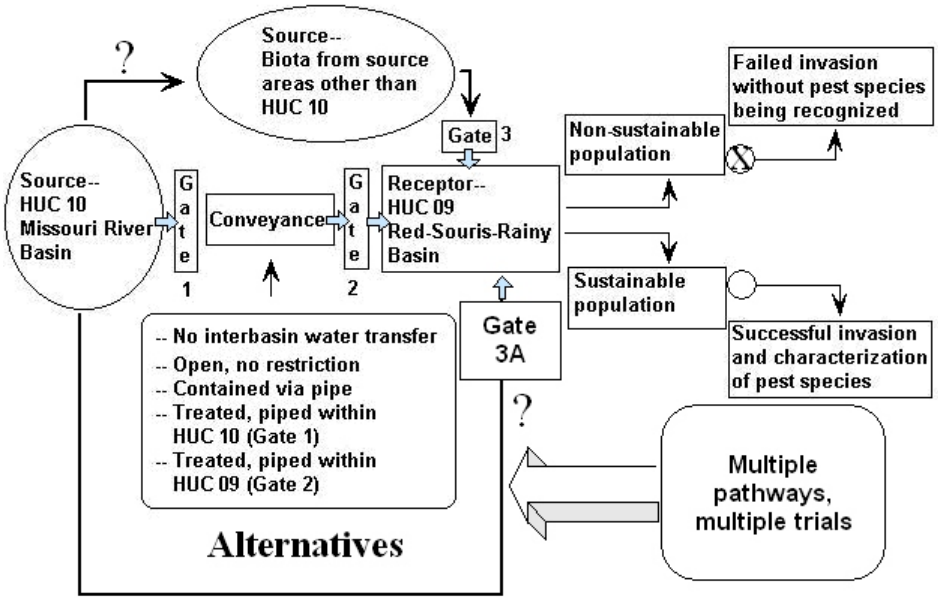

Figure 14. Proposed conceptual model of reflecting multiple pathways influence on the evaluation of risks potentially associated with biota transfers collateral to interbasin water diversions.

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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