RECLAMATION

Managing Water in the West

Development of an Adaptive Management Workshop Manual to Assist in the Prevention and Management of Water Resource Conflicts

Proposal 9132 —
Review of Literature and Identification of Adaptive Management Expert Consultants

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado, *and*
Upper Colorado Region
Salt Lake City, Utah

September 2009

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Submitted to

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Contents

Literature Review

The roots of adaptive management lie in the desires of scientists and managers to improve the decision making process for environmental management through interjection of science and stakeholder participation. (Holling 1978, Williams et al. 2007). As the adaptive management process has grown in use, and has been expanded to enjoin with adaptive governance and collaborative processes (Brunner and Steelman 2005, Wondolleck and Yaffee 2000), there has been a growing emphasis on the inclusion of stakeholders throughout the adaptive management cycle. Pahl-Wostl et al. (2007) identified that this transition is part of a major paradigm shift in natural resources management, and particularly in water resources management.

Williams et al. (2007) provide an encompassing and very useful introduction to adaptive management for the Department of the Interior, including the importance of stakeholders, but the generalities in their guidebook need to be expanded and detailed for implementation of this important process at the field level. Our objective in this project is to produce a manual for setting up and implementing adaptive management workshops for Reclamation employees and stakeholders with whom they engage in addressing water resource conflicts. The manual will expand and provide detail on the concepts introduced in the Department of the Interior's manual. It will be focused on addressing water resource conflicts that arise in the course of Reclamation employee's activities as they fulfill the agency's mission to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public. We believe that many of the water resource conflicts in which Reclamation managers are engaged, which are often associated with impacts from Reclamation projects on major rivers, fall within the criteria identified for adaptive management by Williams et al. (2007).

Important steps in the iterative adaptive management process (Figure 1) can be facilitated through a series of workshops that bring together managers, scientists, policymakers and stakeholders. The first of these workshops is particularly critical because it is here that issues are defined, problems are focused, information needs are determined, alternative actions are described, a model of the system is created, and participants learn of one another's value systems with regard to the resources that are in dispute (Holling 1978, British Columbia Forest Service 1999).

During such a workshop, joint fact finding is employed to place the emphasis for discussion on better understanding of the system being considered, rather than the issues that separate people into opposing groups. An important outcome of the initial workshop is a crude version of a conceptual model of the system,

preferably in the form of a computer model. Even if lack of expertise, facilities, or time prevent a model from being developed, the techniques of organizing elements in preparation for a formal modeling effort are of fundamental value. The important point here is that, at the very beginning of the study, all elements — variables, management acts, objectives, indicators, time horizon, and spatial extent — are jointly considered and integrated. Even a crude model developed at this stage can be a powerful device to explore what is known and not known about the system in question.

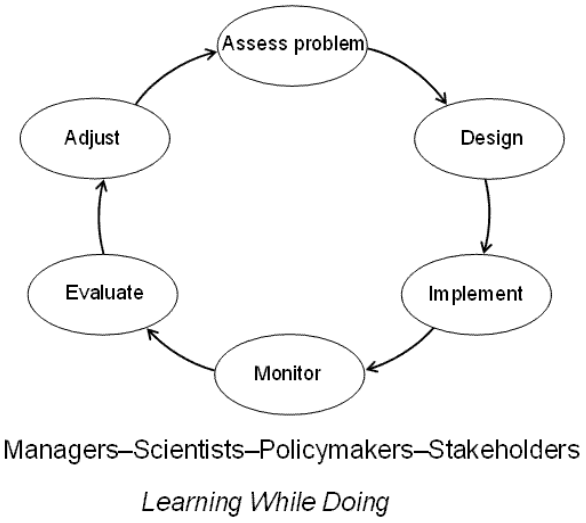

Figure 1. The six steps in the idealized classical adaptive management process (Source: The Adaptive Management Framework. Figure 1 from Nyberg, 1999, copyright Queen's Printer for Ontario, 1999. Reprinted with permission.).

Subsequent workshops at the evaluation and adjustment stages are very important to ensure that knowledge gained through research and monitoring is incorporated into changes in management and that there is buy-in by all represented groups.

Determination of who should be represented at workshops is a task that must be undertaken as part of the planning process, but it is important that the identified major interests all are represented. Policy people and managers provide a balance to the scientist's desire for minute detail and high precision. Scientists provide a concentration on rigor of the analysis and an understanding of fundamental physical, ecological, and economic forces. Stakeholders provide a range of values, local perspectives, and vested interests for the resources that are at issue.

Workshop steps identified by British Columbia Forest Service (1999) include:

(1) Prior to the workshop identify key participants and define the initial scope of the problem and key problem features;
(2) During the workshop:

(a) Define the scope of the management problem,
(b) Define measurable management objectives,
(c) Identify key indicators for each objective,
(d) Identify possible management actions,
(e) Draw impact hypothesis diagrams for given groups of actions and indicators,
(f) Identify and assess key information gaps,
(g) Modify an existing simulation or develop a new one,
(h) Test and validate the model by doing sensitivity analysis on model parameters,
(i) Explore alternative scenarios/management options, and
(j) Make explicit predictions about responses of the indicators to management actions.

Brown (1999) recognized the complexities of water resource disputes and advocated for a process of negotiated adaptive management in which the conflict is defined not as a legal violation, but as a divergence of interests and a competition of interests among parties. He identified that one-step legal solutions are seldom lasting, and that iterative, negotiated approaches are more persevering. Adler (2000) revealed that water resource disputes are often large in scale, broad in impacts, and laden with values that are at odds with each other. They fit in the broad category of "wicked problems" that are complex in nature, in which win-lose situations are common, and where solutions require the cooperation of parties who are by nature at odds with one another (Scholz and Stiftel 2005).

Adler (2000) also noted that people dread and hate meetings as forums to address controversies. He advocated for improvement of the ways in which we engage each other when we hold meetings about water controversies. Good process and good working relationships are necessary, but not sufficient. Very high quality information must be present, then substance, process, and working relationships must be brought together for a triangle in which all three sides are critical and dependent on each other. This advocacy opens the door to adaptive management and the science that it brings to the collaborative process.

Wallkerden (2005) has concentrated on adaptive management workshops as part of a conflict resolution process. He noted that adaptive management has developed planning processes that combine dialogue amongst stakeholders and experts, systems analysis, and exploration of uncertainty and options. Part of the processes are carried out through multiparty, multidisciplinary workshops and simulation modeling to facilitate dialogue, negotiation, and planning, but these processes have been criticized for failure to provide adequate forums for the creation of shared understanding among stakeholders. Walkerden (2005) advocated that adaptive management processes be combined with processes derived from bargaining traditions such as principled negotiation (Fisher et al. 1991) and sequenced negotiation (Susskind 1994) that engage conflict much more successfully than they do uncertainty.

Gilmour and Walkerden (1999) portrayed three case studies on watershed conflicts in Australia as a means of addressing the application of adaptive management to conflict resolution. They used workshops heavily in their assessment and made important discoveries that have high value in setting up future workshops. The following issues were evaluated for their importance in workshop success:

- Performance of the facilitators;
- Success of the process in facilitating the analysis of the environmental system;
- Understanding of other people's points of view';
- Use of working groups;
- Value of a field trip;
- Workshop notes; and
- Effectiveness of the model notes in documenting participants' understanding of management issues

From their evaluation, Gilmour and Walkerden (1999) identified the following prerequisites to success for the planning process:

- A transparent, community based process for selection of stakeholder participants in the workshops;
- A hypothesis in the form of a conceptual systems model, sometimes expressed as a computer-based simulation, that represents the understanding, as agreed to by stakeholders, of the system elements, structure, and processes;
- A set of strategies that represents management policies or actions that recognize the uncertainties inherent in the system, designed to test assumptions about the data and the processes incorporated in, and the responses of, the modeled system;
- A set of criteria for judging the success of management actions and policies tested in the model and implemented in the real system;
- A process and preferred set of management responses to be implemented at defined stages as the post-workshop project progresses;
- A clearly defined suite of responsibilities for implementing management actions and policies with an explicit, public reporting procedure.

Wondolleck and Yaffee (2000) identifed tests for credibility and accountability to the broader public interest of collaborative processes and public decision-making outcomes:

- Is it legitimate? Legitimacy includes the critics' concerns about the devolution of agency power. Is it tied to existing law and regulation through the direct involvement of responsible officials? Does it provide for normal public review and comment opportunities for those who care about the issues but are either unable or uninterested in participating directly?

- Is it fair? Fairness ensures that all parties have a chance to have their concerns heard by decision makers. Does it involve credible representatives of those who will be affected by its decisions and recommendations? Is it open, accessible, and transparent so that no individual is excluded except by his or her own choice, and no decision is imposed without agreement? Are decisions made in a manner that encourages consensus and not capitulation?
- Is it wise? Wisdom involves scientific grounding as well as a focus on the effectiveness of agreements. Does the process encourage participants to focus on the problems needing to be solved? Does it promote creativity and flexibility to allow effective management direction to be framed? Are decisions well rooted in current scientific understanding? Are there direct links between participants in the process and the appropriate sources of knowledge, expertise, and information that will enable those at the table to understand and act consistent with this current understanding? Moreover, does the process ensure that decision making is consistent with scientific knowledge or highlight where it is not? Does it recognize areas of uncertainty and provide credible opportunities for learning and adaptation?

Wondolleck and Yaffee (2000) discovered four factors involving stakeholders that are correlated with the success of collaborative decision making: (1) early, often, ongoing involvement; (2) real, substantive involvement; (3) consensus decision making, and; (4) inclusiveness and diverse representation of stakeholders. Walkerden (2005), using insights provided by Wondolleck and Yaffee (2000) identified a way to test his process design for adaptive management workshops to see if it supported collaborative decision making, thus a wedding of adaptive management and negotiation processes. He has provided a set of guidelines for adaptive management planning projects, including sections on scoping, structuring, and implementing workshops based on his findings. His proposed procedures are:

Project Establishment:

(1) Establish the process as a negotiation leading to a formal agreement that is to be conducted using adaptive management procedures to provide analytical rigor to the consideration of options;
(2) Identify a facilitator capable of facilitating negotiations amongst stakeholders in ways that will help them explore their underlying interests, using multiparty, multidisciplinary analysis of socioecological systems as a vehicle;
(3) Rough out the general scope of the project. This occurs in conversations between the lead agency and facilitators;
(4) Identify and invite stakeholder representatives and experts to participate in adaptive management workshops, and in shuttle diplomacy, or informal mediation if that proves helpful.

Scoping for Workshop Sessions:

(5) Why are we here? An exploration of the participant's sense of the intent of the project or issues.
(6) What are the management problems that need to be addressed?
(7) What boundaries in space and time, and in the range of issues considered, are appropriate?
(8) What actions might effectively deal with the problems?
(9) What indicators would measure success or failure in solving the problems?
(10) What interests underlie the choice of indicators?
(11) Review: Do we need to add to the lists of problems, actions, and indicators, or review the boundaries to explore possible impacts on stakeholders' interests?

Structure of Workshop Sessions

(12) Identify major subsystems;
(13) Describe interfaces between subsystems, with a flow diagram or detailed interaction matrix.
(14) Describe the structure of each subsystem as with the interfaces.
(15) Review subsystem descriptions in light of stakeholders' interests, and ask: Are there other creative ways in which we could look after stakeholders' interests, including the interests of other kinds of organisms that should be included?
(16) If a quantitative model is being built, describe processes quantitatively using equations that describe how outputs are derived from inputs.
(17) If a quantitative model is being built, build it incrementally, dialoguing frequently with stakeholders about what will add the most value to their investigations and negotiations.

Dynamics of Workshop Sessions

(18) Explore dynamics, and specifically the effects of alternative assumptions and alternative management choices, in a "scenario gaming" environment. Emphasize the conceptual model alongside the quantitative model so that out of box suggestions can be explored more easily by varying the conceptual model.
(19) Negotiate a path ahead, using "gaming" as a catalyst for, and point of reference in, negotiations.
(20) If a consensus is reached or there is widespread agreement, stakeholders formalize their commitments in a written agreement.

Adaptive Management Workshop Support Tools

Participatory Improvement

Adaptive management workshops can be improved by incorporating a number of technological and sociological tools. Much of the emphasis for these techniques is directed at improving communication among participants, reducing uncertainty and increasing knowledge of systems and affected resources, and facilitating higher quality outcomes through the decision making process.

Lynam et al. (2007) reviewed several participatory tools that have been used in forest management and that likely can assist in stakeholder participation in adaptive management workshops dealing with water resource conflicts. They are especially important in eliciting the knowledge, values, and preferences of stakeholder communities. We repeat their assessment of capabilities in Table 1. Lynam et al. (2007) also provided assessments of these techniques based on experience from their use and the products that they generate.

Technical Validity

The interjection of science and identification of uncertainty are important components of adaptive management workshops. Participants need to achieve a better understanding of the system that is at issue, including what is known or held to be true about relationships between management actions and resource responses. A generalized view of the system being investigated can be gained from maps, particularly if they are georeferenced and attributed in a geographical information system. Using commonly available information on the landscape, natural resources and human demographics, workshop participants can begin to jointly build a conceptual model of the system. Thus, by using the combination of participatory techniques and technical information, workshop participants, preferably with the aid of one or more skilled facilitators, can begin to undertake the process of achieving a better understanding of their individual values, the resources at issue, and potential management actions that might be undertaken to further that understanding and reach agreement on management of the system.

Table 1. Evaluation criteria applied to tools for improving stakeholder involvement capabilities (Adapted from: Lynam et al. 2007)

Tool	What does it do?	What does it not do?	Methods
Bayesian belief network system dynamic model (Cain 2001, Lynam et al. 2002, Lynam 2003)	Simplifies complex systems through key variables and their relationships	Capture all details and nuances	Individual or group setting; usually requires quantitative estimation of relationships
Discourse-based valuation (Wilson and Howarth 2002)	Develops a common (group) representation of importance	Develop causal relationships among variables or entities	Facilitated group interactions
4Rs framework (Dubois 1998)	Assesses stakeholder roles and resilience in forest management	Reveal causal relationships	Carefully facilitated individual or group setting
Participatory mapping (Lynam 1999, 2001, Sheil et al. 2002)	Represents spatial relationships	Represent spatial interactions	Individual or group setting
Pebble Distribution Method (Colfer et al. 1999a, Sheil et al. 2002, 2002)	Rates alternatives (items) and encourages examination of the underlying reasons for these ratings	Represent, clarify, or reveal relationships or processes	Individual or group setting supervised by a facilitator who must carefully introduce and guide the process
Vision/pathway scenario (Wollenberg et al. 2000)	Envisions and articulates an ideal future as a basis for planning and decision making or developing a shared vision	Quantify relationships or identify the causal relationships among process or variables	Entire community
Alternative scenario (Wollenberg et al. 2000, Nemarundwe et al. 2003)	Imagines and describes several possible future outcomes (negative or positive) based on current trends or uncertainties	Quantify relationships	Entire community
Spidergram (Lynam 1999, 2001)	Represents causal or categorical relationships among variables related to a central question	Represent feedback or dynamic relationships	Individual or group setting; useful in discourse-based valuation to develop consensus
Venn diagram (Pretty et al. 1995)	Represents social relationships and power differences between stakeholders	Represent causal relationships	Individual or group setting
Who Counts Matrix (Colfer et al. 1999b)	Gives priority to stakeholders whose well-being is closely linked to forest management, using dimensions to assess these links	Provide specific definitions of terms and indicators to assess dimensions	Individual or group setting
Multicriteria Decision Analysis, (Belton, 1990)	Develops alternatives, criteria, and weights for evaluation. Documents entire decision process.	Quantify or represent causal relations.	Sets forth alternatives, decision criteria, and weights for decision choice.

Conceptual Ecological Models

Conceptual Ecological Models (CEMs) provide a visual framework or graphical representation (Figure 2) of the proposed relationships among major factors affecting the system being evaluated. The CEM identifies major management actions or natural system inputs, system processes, system responses, and major resources of concern that likely would be affected by changes in the system. CEMs are also used to identify competing hypotheses and research questions to be addressed by management, monitoring and research. Workshop participants are encouraged to provide their perceptions of "how the system works" as a precursor to building hypotheses that can be tested if the group decides to apply adaptive management as a process for determining what the real, rather than hypothetical, relationships are among the system components, management actions, and natural drivers.

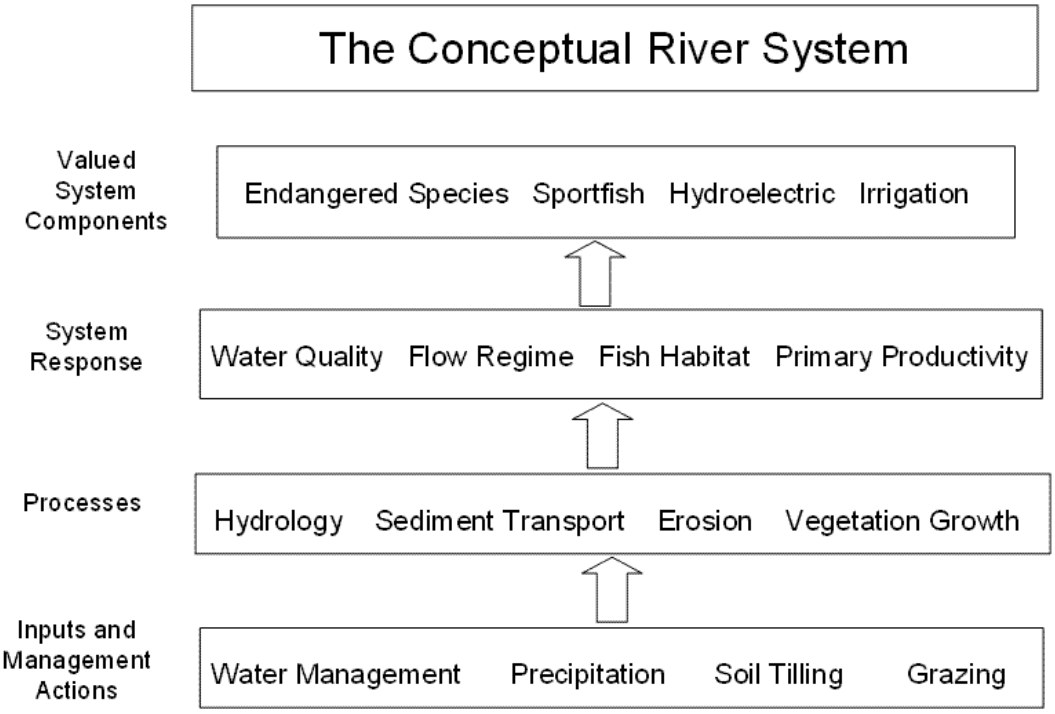

Figure 2. A conceptualized river system illustrating inputs and management actions, system processes, system responses, and valued system components.

Hypotheses and Resource Impact (X-Y) Graphs

An initial step in the development of priority hypotheses is accomplished by describing broad relationships among functional components of each CEM. These broad hypotheses are further refined by the development of specific hypotheses based on the relationship among functional components of the system as illustrated in x-y graphs. The x-y graphs (Figure 3) illustrate the key relationships

upon which hypotheses are based. They allow workshop participants to identify and discover differences among the resource relationships and among their perceptions of what these relationships are. In this way competing hypotheses can be generated.

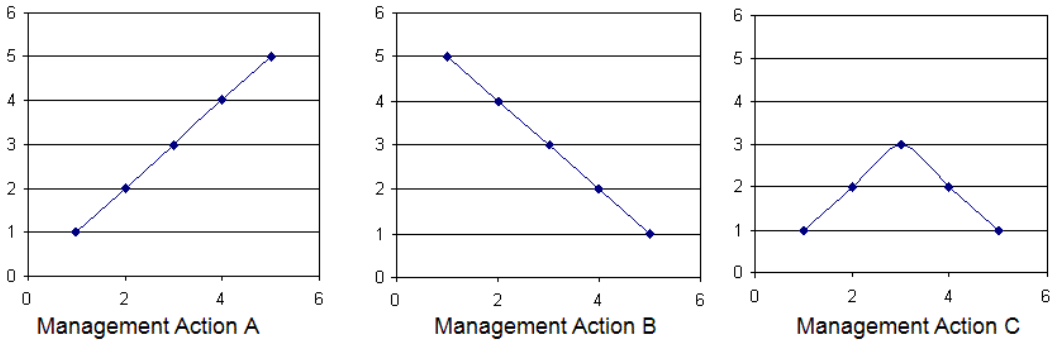

Figure 3. Hypothetical responses of a resource to three management actions.

Geographic Information Systems

Adaptive management practitioners have identified a wide variety of knowledge-building and facilitation tools to improve the likelihood of success in undertaking the process. "Adaptive management [is a decision process that] promotes flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood. Careful monitoring of these outcomes both advances scientific understanding and helps adjust policies of operations as part of an interactive learning process" (Williams, et al. 2007). As a decision process, adaptive management clearly depends upon spatial data, spatial data management, and spatial data processing. Geographic information systems (GIS) provide the technology for these tasks.

Most adaptive management processes start or should start with an accurate representation of the landscape called a map, which the basic component of geographic information technology. Stakeholder participation in the creation of base geographic data layers or themes gives them confidence in the map or maps being used in an adaptive management process. Adaptive management objectives can often be explicitly represented spatially. For instance, "At the end of a specific river restoration effort, the basin should look like this." "This" might be represented by a map. Uncertainties can be modeled using GIS technology, as well as the relationships amongst resources and management impacts. Monitoring efforts are greatly facilitated using GIS. Data can be gathered pre and post treatment to examine trends. Management actions can be adjusted accordingly. What-if scenarios can be tested with stakeholders present to see and discuss what the outcomes of various courses of action will be. In all these ways, GIS technology can materially assist the adaptive management process.

Adaptive management policy formation requires the convergence of science, the social and political economy, and the law. A scientific finding, for instance, that irrigation must be suspended to support an endangered fish, may not be supported in the social and economic sphere. A legal mandate, if not instituted in a rational way, can be devastating for the ecosystem or the local economy. If stakeholders are at the table as the GIS application is developed at key points in the adaptive management process, they can visualize the system in a way that they may not have been able to before and they can participate in the decision process. It may be, for example, that if mandated habitat is re-established or expanded in one place, agricultural development can proceed in another. As Berry (1993) notes, stakeholders with the dynamic map in front of them can participate in the ongoing discussions and the analysis. "If I develop a wetland over here, will you let me increase the density of recreational development over there?" What will happen to the river system if these mine tailings are actually removed? Is the outcome worth the expense? These types of adaptive management discussions can be greatly facilitated in a GIS environment.

What follows is a set of case studies that illustrate the power of this technology for facilitating the adaptive management process. This is followed by a discussion of the analytic and modeling capabilities of GIS for adaptive management support, a list of studies undertaken by Reclamation GIS personnel, and a discussion of the collaborative capabilities of GIS.

Green Spring and Worthington Valleys

Decisions are made amongst tradeoffs. McHarg (1967) wrote the following about the Green Spring and Worthington Valleys of Baltimore County, MD:

- The area is beautiful and vulnerable;
- Development is inevitable and must be accommodated;
- Uncontrolled growth is inevitably destructive;
- Development must conform to regional goals;
- Observance of conservation principles can avert destruction and ensure enhancement;
- The area can absorb all prospective growth without despoliation;
- Planned growth is more desirable than uncontrolled growth, and more profitable;
- Public and private powers can be joined in partnership in a process to realize the plan. (p. 82).

The rational approach to resource management, illustrated in these statements, is to maximize social benefit and minimize ecological cost, which is in itself also a social cost. In his plan study for the urbanization of the Green Spring and Worthington Valleys, McHarg replaced old development criteria with new ones.

With regard to the introduction of new roads, the old criteria consisted of the following: economic cost/benefit analyses, safety, time savings, operating costs,

engineering costs, land and building purchase costs, administrative costs, construction costs, operation and maintenance costs. Others included traffic generation and volume, design speed, capacity, pavements and structures. The new planning criteria included:

(a) increase the facility, convenience, pleasure, and safety of traffic movement,
(b) safeguard and enhance land, water, air, and biotic resources,
(c) contribute to public and private objectives of urban renewal, metropolitan and regional development, industry, commerce, residence, recreation, public health, conservation, and beautification, and
(d) contribute to the public and private objectives of urban renewal, metropolitan and regional development, industry, commerce, residence, recreation, public health, conservation, and beautification.

Such criteria include the orthodoxies of route selection, but place them in a larger context of social responsibility.

More specific highway development criteria included the following:

- < 2% slope
- Avoid surface water
- Good internal soil drainage
- Strong bedrock foundation
- Good soil foundation
- Soils resistant to erosion
- Low land values
- Areas not prone to flooding
- Absence of historic sites
- Areas of low scenic value

Having developed a set of development cost criteria, the next step was to map each area with weights on each value, color the maps so that the higher the cost or value, the darker the color. For example, a valuable archeological site on a cliff would receive a very dark color and would be unsuitable for development. The next task was to lay the maps on top of one another, examine areas with the lightest colors for development, and then choose a route with the least value and cost which would also connect the points of origin and destination.

For other types of land use in the overall area, specific ground rules for development were formed. Urban development was prohibited in the valleys to preserve the pasturelands. Permitted uses in the valley included agriculture, large estates, open space, parks, and the like. Development was prohibited over aquifers, in 50 year flood plains, in areas unsuitable for septic systems, within 200 feet of natural water courses, at dam sites and in impoundment areas, on valley walls, and in certain forested areas. Higher densities of development were allowed on un-forested plateaus, lower in forested plateau areas, and very low on

forested valley walls. The highest levels of development were allowed in and around existing urban aggregations.

Using these and other planning principles, all of the projected growth was accommodated, developers realized higher profits than they were projected to take away with unplanned growth, and the natural environment was preserved.

McHarg's (1967) work in the Green Spring and Worthington Valleys predated geographic information systems (GIS), but he has been called the father of GIS. As noted, he worked with map transparencies that contained soils on one layer, topography on another, forests on another, water resources on another, and so on. From overlay analyses of these transparencies were developed suitability maps for various types of land use, including transportation corridors, open space, mining, agriculture, low density urban, high density urban, etc. Today, such analyses can readily be performed with geographic information systems and electronic maps called layers, not hardcopy transparencies. By analyzing various tradeoffs, sustainable use of the natural environment is possible using geographic information system technology.

For planning and adaptive management purposes, GIS can facilitate mapping, geo-referencing, and overlay procedures. It can expedite the testing of what-if scenarios. It helps to capture and incorporate public input. Draft and final maps can be readily produced. Natural resource management in any setting, including land use planning, conservation management, agriculture, etc. must be undertaken hueristically and holistically. Development can proceed in a sustainable manner. GIS can facilitate the accomplishment of these tasks.

Potomac River Basin

McHarg's (1967) problem in case of the Potomac River Basin was to find the highest and best uses of all the land in the Potomac River basin – from the Appalachian Plateau to the Valle Ridges to the Great Valley to the Blue Ridge to the Piedmont and Fall Belt to the Coastal Plane-- but in every case also identify the maximum conjunction of these uses. The approach was to inventory the climate, geology, hydrology, soils, plant communities, animal communities, topography, and mineral resources. Each region, shown above, had its own profile. From these, intrinsic suitabilities for development could be built up and mapped.

Agriculture was deemed to find favorable soil, climate, slope, and drainage conditions in the Great Valley, the Piedmont, and occasionally in the Ridge and Valley Province. The Coastal Plain soils were deemed infertile, but could grow vegetables with fertilization.

Forestry needed to be located within 25 miles of a pulp mill, on a 5th order stream or higher, and on slopes of less than 25 per cent. Recreational opportunities were

found at unique historic, geologic, environmental, and physiographic areas; fishing waters various prized species; fossil sites; caves, waterfalls, tidewaters, and swamps. Urbanization was restricted to slopes 5% or less, located out of 50 year floodplains, avoided aquifer recharge zones, was sited away from fog zones, and avoided prime agricultural lands. Cities must also have adequate water supply to develop or expand.

In addition to having intrinsic suitabilities, land uses in the Potomac basin had varying levels of compatibility with each other. Each human land use generated its own positive or negative consequences in terms of soil, flooding, or drought control, stream sedimentation, water pollution, or air pollution. Reservoirs, for example, were incompatible with quarry and coal operations, but were fully compatible with vacation settlements, softwood and hardwood forestry, and various freshwater recreational opportunities.

Again, by coupling basin land use planning with intrinsic suitabilities, compatibility with other land uses, and by paying attention to the consequences of each use for soils, flooding, sedimentation, air pollution, and the like, planning could occur in a rational manner.

Once again, McHarg's (1967) work predated geographic information system technology, but the overlay capabilities of GIS today allow basin-wide analyses like these to proceed quickly and rationally.

Like McHarg's (1967) decision processes, adaptive management decisions often develop end-state solutions that seek to provide for development in an ecologically sound and sustainable manner. These end states are mappable and the development of the end-states based upon the native genius of the place can proceed in a rational manner using GIS techniques. Various trade-offs can be tested and modeled for economic soundness and ecological sustainability.

Water Quality: The Wippany River, New Jersey

Similar principles can be used for watershed management efforts. For instance, the state of New Jersey has taken a state-wide approach to dealing with the problem of water quality using GIS technology. The unit of analysis is the watershed, i.e. areas that drain into a common body of water. In an article prepared for the Environmental Systems Research Institute publication Managing Natural Resources with GIS, the New Jersey Department of Environmental Protection focused on the Whippany River watershed (Lang 1998).

The problem was that pollution from one jurisdiction was finding its way to other jurisdictions. Water samples were collected from the Whippany River near Morristown, New Jersey, an urban area. This watershed receives pollution from sewage plants, factories, farms, and storm runoff. Measurements were taken on concentration of organics, nutrients, metals, temperature, dissolved oxygen, and pH. In addition, selected samples of mayflies, stone flies, and caddis flies were

taken, all of which are sensitive to water pollution. Collection site locations were taken using GPS.

A base map of the watershed's streams and lakes was created. Supporting data themes were added such as topography, roads, soils, wetlands, and open space. The locations of potential polluters were also added. The GIS analyst performed queries to determine the proximity of known sites of contamination such as landfills, factories, farms, etc.

The water quality data were compared to standards set by state and Federal agencies to keep water clean enough for fish to live in and humans to swim in. Biological data were analyzed to see if samples were composed mostly of pollution tolerant species such as midges and worms.

Proximity analysis was conducted to determine the spatial relation between contaminated sites and rivers and streams. Stream impairment ratings, i.e. the health hazard a water body posed to fish and humans, were generated for locations in the watershed. Severely polluted segments were mapped and forwarded to scientists, who put together models of water quality and conducted what-if scenario analyses as to how the river's chemistry might change if new chemicals were added or old ones were removed.

Maps were used identify potential polluters. Inspectors were sent out to monitor sites for possible mitigation. Monitoring locations were sited using GIS to test whether water quality was improving. GIS maps were used at public meetings to generate discussion of issues among stakeholders as to the present and future actions that must be taken to promote water quality.

In summary, GIS in this case was used to (a. identify pollution health-hazard hot-spots, (b. determine their proximity to known polluters (and by implication, discover new polluters), (c. develop a composite map of water quality throughout the basin, (d. monitor water quality conditions over time to determine improvement or deterioration, and (e. generate living maps for public meetings where discussions of future actions were ongoing. The implications for adaptive management are clear. The problem must be identified and mapped, along with potential causes. Prevailing conditions must be monitored for change under various policy scenarios. Outcomes must become part of a living map. These can be discussed in a public setting and the outcomes of policy changes can be modeled.

Endangered Species

Lang (1998) presented a case study of endangered fish species in the Columbia Basin. The Forest Service must balance the needs for timber, fishing, recreation, and other interests in the lands and waters it manages with the need to maintain healthy plant, animal, and fish populations, recover threatened and endangered species, and produce wildlife for sport and commercial use.

Cut-throat and steel-head trout, and sock-eye, Chinook, and coho salmon are dwindling over a large part of the West. The Forest Service, together with other state, Federal, and Native American tribal governments are working together on restoration programs. These take into account the entire life-cycles of each fish species.

Stream data-- width, depth, water temperature, quality, amount of wood in the stream, and the current and past distributions of fish are being collected. Other habitat, land use, and land cover variables for the entire Columbia River Basin have also been inventoried.

Data on land ownership have been captured (restoration projects may or may not be undertaken on private lands).

The Forest Service has identified current fish populations, and using GIS, identified streams that could be links to these viable populations. They, then, reselected for those suitable for the particular species in question– such as coho. Relevant variables included water temperature, woody debris causing back-waters, and large pools. Composite suitability maps have been prepared to show candidate stream segments for the endangered fish and identify stretches where restoration actions can be taken. Thus, GIS can be used to monitor:

- Current species distributions and health
- Changes in these distributions
- Areas where restoration is possible
- The success of restoration and conservation programs
- The results of various state, federal, and private agencies' efforts to conserve, restore, or make use of fish and other natural resources.

Obviously, adaptive management processes for fish restoration would also benefit from maps of current fish distributions, variation and change in distributions over time and space, composite maps showing candidate areas for restoration activities, successful monitoring activities, and the capability of mapping results of various policy alternatives.

GIS Analytic Techniques

Natural resource applications of GIS are concerned with the spatial distribution of resources. There are multitudes of tools that GIS can use to assist in the management of natural resources including water. The list below highlights some of the most important of these (see Berry, 1993, Berry 1996):

- Basic and advance mathematical operations: addition, subtraction, multiplication, division, along with trigonometric, power, and root functions.
- Descriptive statistics: mean, median, mode, variance, deviance, frequency, diversity, deviation, count.
- Comparative statistics: cross-tabs, t-tests, chi-square, F-tests, etc.
- Distance measures: simple distance, least cost distance (effort, time, cost), proximity, narrowness, buffering.
- Neighborhood characterization: surface configuration (slope, aspect, grade, curvature), roving windows summaries (summarizing values within a specified vicinity along with associated descriptive statistics), interpolation (computing predicted values for each map location), diversity, interspersion, deviation.
- Distributional analysis. Clustering or evenly spaced (lattice) patterns can indicate that some underlying process accounts for the spatial distribution, while a random distribution may not.
- Visual exposure: viewshed delineation (all locations 'within sight' of a place, exposure density (determines how often each location is 'within sight' of a linear or areal entity
- Spatial correlations or associations. For instance, it can detect the relation of fauna to vegetation to soils to parent materials. Is there a connection between a particular endangered bird species distribution and the distribution of an exotic plant? Spatial correlation can provide quantitative evidence.
- Surface generation based on autocorrelation: topography, pollution concentrations, temperature surfaces, etc.
- Shape characterization: convexity and concavity, complexity, integrity, contiguity, inter-feature distance, regularity and irregularity. Some animals and plants require habitat of various shapes, extents, and regularity in order to thrive.
- Homogeneity and heterogeneity. Is a landscape composed of homogeneous elements or is it characterized by a high degree varied elements? Knowledge of this could help identify, for instance, encroachment of new species.
- Segregation and integration. Are certain species sub-populations separated from one another or are they found together on a regular basis?
- Connectivity: tests if places are accessible by some means with one another or are they islands. For instance, endangered species in different locations need access to one another for continued propagation.

For the purposes of adaptive management, GIS provides an extensive set of tools for measuring initial, intermediate, and ongoing conditions in a dynamic, rigorous analytical environment. Is water quality improving? Where and by how much? Are endangered species and their habitat truly recovering in a measurable way? Everywhere, or only in certain regions? Are there spatial variations in the patterns of recovery? Are there areas that appear to be lagging behind? Are there

encroachments of other species? If so, are there spatial associations that might explain why? For instance, has an eradicated invasive species in the restoration area left behind soil residues that prevent successful reintroduction of the endangered species? Or do recent measurements of temperature and precipitation indicate possible climate change? Adaptive management is a dynamic process and GIS, which is a map as numbers, is equally dynamic. This dynamism allows for monitoring with an ease and rigor that could not have been managed just a few years ago.

GIS Modeling Capabilities

One of the requirements of adaptive management is predictive modeling. GIS has many capabilities for doing this. The purposes of modeling are:

- To improve management of resources and the micro and macro ecosystems in which they exist
- Ecosystem protection, especially of genetic diversity
- Ecosystem restoration
- Forecast changes in the ecosystem

A model is a formal expression of the essential elements of some problem in either physical or mathematical terms. It is a symbolic representation of real-world structures and/or processes. Variables in a model are of two types, (a. external variables, which represent elements external to the model that influence the ecosystem, for example, precipitation or pollution or social and economic factors and (b. state variables: major structural elements of the system being modeled. Mathematical expressions are used to describe relationships among variables. Parameters represent characteristics not expected to change with respect to the temporal or spatial dimensions of the model, e.g., the water infiltration rate in a particular type of rock.

Models have the following characteristics:

- They simplify the systems they represent
- They generally do not attempt to model the entire system, but some very limited questions related to it
- They operate at some space and time scale and may not necessarily be translated from one scale to another.
    - E.g. A model of a river running through a basin would not be appropriate for water moving through a particular soil type on a certain slope.
    - E.g. Models representing climatic processes during an ice age at 100,000 year intervals have a different temporal resolution than those forecasting tomorrow's weather.

- Models can be verified to test if they give a reasonable representation of the structural and functional relationships of a real system and system externalities. Such tests look at the internal logic of the model, examine the correctness of the mathematical expressions, and ask if the scale is appropriate.

Models must be validated. Validation is an objective test of a model results. Do the model results conform with independent experimental data? Models are transparent, i.e. they are designed to address a particular problem and they make explicit assumptions about natural processes and their related scales.

There are many types of GIS models (see Morain 1999, Mitchell 1999):

- Descriptive: Only attempt to reproduce the behavior of a system without getting at underlying processes. For example, a logistic growth curve offers no insight about underlying population dynamics in terms of natural increase or migration
- Explanatory: Attempt to explain a process by including appropriate structural and functional elements such as growth rate and carrying capacity.
- Static: Represent a particular phenomenon at a point in time, for example, GIS overlay map algebra analysis for a specific objective such as siting a facility.
- Dynamic: Models that include temporal change as an important component, e.g.. flood modeling
- Deterministic: Contain no random variables. Initial conditions are always the same in each run.
- Stochastic: Contain random variables, which potentially take on new values at each run. Random levels of precipitation and ground saturation could be introduced to a flood model.
- Analytic and Simulation: Model changes in functions of one or more variables resulting from a small change in the variables. Analytic models can be represented by a single equation. Simulation traces the behavior of a system through time, step by step using the solution of more than one model.

Some models are spatially explicit. From the natural resources perspective, spatially explicit models are of special interest. Resources exist in, are constrained by and change in space. This raises the question of the portability of models. For a particular type of simulation, are the variables always the same and their interrelations always the same in all locations? The probability that a specific undeveloped area will be urbanized at any point in time depends upon the factors and processes listed above (and others, e.g. planning goals), many of which are also changing through time.

GIS modeling, then, offers one of the things adaptive management most requires, namely the dynamic, spatial representation of the natural system be it an alpine forest, a steppe, or a river basin. By modeling the salient processes of the system, it allows for testing various interventions. What happens if we re-introduce an extinct species? What happens if we stop clear-cutting in the basin? What happens if we allow a paper mill in the system? Will the effects be wide spread or localized and manageable? Such questions can be answered in a rigorous manner with good data stewardship practices and GIS.

Downloadable GIS Data for Water Resources Adaptive Management

An abundance of GIS data relevant to water management is available for immediate download from sources such as the EPA, the USGS, the NRCS, FEMA, and the Census Bureau. The list below is a partial catalog of cost-free, downloadable, data:

- Water Flow
- Water Level in Wells
- Water Quality
- Aquifers
- Water Use
- Water Discharges
- Toxic Releases
- Hazardous Waste
- Superfund Sites
- Digital Elevation Model
- Digital Raster Graphic Topography Sheets
- Soils
- HUCs: Basin Boundaries
- Orthophoto Quads
- National Agricultural Imagery Program Photography
- National Land Cover Dataset
- Annual and Monthly Precipitation
- Annual and Monthly Temp
- Census of Agriculture
- Census Data
- FEMA Establishment Data

These and other spatial data from local sources can be readily combined by a GIS analyst for water resource management projects. In doing so, an overall view of the entire water system can be readily produced for the first adaptive management meeting. Then, as time goes on, other data can be collected and added.

Water Resource Studies in Reclamation's Technical Service Center

The Remote Sensing and Geographic Information unit at the Bureau of Reclamation's Technical Service Center has conducted numerous water resource management studies over the years in support of Reclamation's mission of delivering water in an economically sound and environmentally responsible manner. Here is a short list of the kinds of studies the group has performed over the years:

- Water quality: chlorophyll-A, turbidity, temperature
- Habitat mapping and trend analysis
- Flow to fish habitat relations
- Snow cover and accumulation
- Irrigated lands and water spreading
- Habitat loss and gain
- Endangered species and endangered species habitat
- Non-native and invasive species of plants and animals
- Canal weed mapping
- Land management evaluations for areas adjacent to reservoirs
- Land suitability for irrigation
- Island erosion
- Wetland change
- Land cover trend analyses
- Sediment transport and channel characterization
- Environmental justice
- Dam safety population at risk and economic impact studies
- Limnological studies
- Environmental impact studies
- Fish egg imaging
- Inventory and monitoring efforts
- Flood modeling and mapping
- Crop mapping and consumptive use studies

Any and all of these could be used to support various adaptive management studies.

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Appendix — Adaptive Management Experts

The following experts in adaptive management will be utilized as external peer reviewers of the adaptive management workshop manual. They represent a diverse cross-section of expertise in the theory and practice of adaptive management from government, academic, and business environments.

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We also intend to request assistance from adaptive management practitioners within the Bureau of Reclamation. Individuals engaged in the Bay-Delta, Trinity, San Joaquin, Upper Colorado River Recovery Programs, and others will be solicited for input to the manual. They and their stakeholders could serve as very effective focus groups for manual review and training exercises.