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# Modeling the costs and benefits of dam construction from a multidisciplinary perspective

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ABSTRACT

Although the benefits of dam construction are numerous, particularly in the context of climate change and growing global demand for electricity, recent experience has shown that many dams have serious negative environmental, human, and political consequences. Despite an extensive literature documenting the benefits and costs of dams from a single disciplinary perspective, few studies have simultaneously evaluated the distribution of biophysical, socio-economic, and geopolitical implications of dams. To meet the simultaneous demands for water, energy, and environmental protection well into the future, a broader view of dams is needed. We thus propose a new tool for evaluating the relative costs and benefits of dam construction based on multi-objective planning techniques.

The Integrative Dam Assessment Modeling (IDAM) tool is designed to integrate biophysical, socio-economic, and geopolitical perspectives into a single cost/benefit analysis of dam construction. Each of 27 different impacts of dam construction is evaluated both objectively (e.g., flood protection, as measured by RYI years) and subjectively (i.e., the valuation of said flood protection) by a team of decision-makers. By providing a visual representation of the various costs and benefits associated with two or more dams, the IDAM tool allows decision-makers to evaluate alternatives and to articulate priorities associated with a dam project, making the decision process about dams more informed and more transparent. For all of these reasons, we believe that the IDAM tool represents an important evolutionary step in dam evaluation.



## 1. Introduction

Dams have contributed to human development by providing reliable sources of drinking water and irrigation, hydropower, recreation, navigation, income, and other important benefits (World Commission on Dams (WCD), 2000). Further, in the presence of climate change, dams may play an increasingly important role in protecting water resources. For example, areas affected by severe drought and those subject to high vulnerability from flooding due to heavy precipitation will likely increase in coming decades (Intergovernmental Panel on Climate Change, 2007), the negative consequences of which may be ameliorated by dams. Similarly, increased melting of snow packs resulting from climate change may lead to renewed interest in dams as a means of protecting drinking water supplies. Thus, although the National Environmental Protection Act of 1969, the Endangered Species Act of 1973, and the burgeoning national debt have led to a decrease in the number of new dams, the next generation may witness a renewed intensity in large dam development in the U.S. Moreover, new dams continue to be planned and constructed in many developing countries.

The checkered history of large dams offers considerable insight into the risks associated with renewed interest in dam construction. For example, the adverse effects of dams on ecosystems, hydrology, and water quality (e.g., Petts, 1984; Poff et al., 1997; Poff and Hart, 2002; Ward and Stanford, 1979) often disrupt existing cultural and economic institutions (Cernea, 1999; Goldsmith and Hildyard, 1986) and impact relationships between the dam community and communities both up- and downstream, which may include people in other political jurisdictions (Giordano et al., 2005). Dams also have displaced up to 80 million people worldwide (WCD, 2000), resulting in increased landlessness and unemployment as well as social disarticulation (Cernea, 1999). Risks associated with large dams also go beyond the immediate ecological and

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social impacts; for example, 46 large dams catastrophically failed between 1860 and 1995, eight of which resulted in the deaths of at least 1000 people (McCully, 2001).

Analogously, concerns regarding the safety and passage barrier presented by older dams and culverts have contributed to a surge in dam removal (Doyle et al., 2008; Hart et al., 2002) despite the outstanding uncertainties regarding this emerging practices (Doyle et al., 2003; Pizzuto, 2002; Riggsbee et al., 2007; Walter and Merritts, 2008). Similarly, dam removal may have negative consequences for electricity generation, tax revenues, recreation opportunities, and housing values (Acharya and Lewis, 2001; Bohlen et al., 2007; Wyrick et al., in this issue). Dam removal also has political implications as disparate constituencies organize in support of or opposition to dam removal (Graf, 2003). Finally, as in dam construction scenarios, decisions about dam removal are often made under asymmetric information (Born et al., 1998), leading to dissention in affected communities.

The 1992 United Nations Conference on Environment and Development identified biophysics, socio-economics, and geopolitics as the primary areas of concern for environmental and social sustainability in development (United Nations Committee on Economic Development, 1993). As noted above, the impact of dam construction may be felt across each of these areas (Bocking, 1998). For example, relocation efforts associated with dam building often lead to higher population densities and thus to greater struggles over land access (Webber and McDonald, 2004). Similarly, higher levels of siltation and evapotranspiration associated with new dam construction (Phadke, 1999) may exacerbate water and land conflicts among affected river populations (WCD, 2000).

The renewed interest in large dams and the uncertainty surrounding dam removal provide opportunities for improved understanding of the interaction between environmental and social systems. However, despite an extensive literature documenting the benefits and costs of dams, few studies have systematically evaluated the effects of dams from multiple disciplinary perspectives (Whitelaw and MacMullan, 2002, but see WCD, 2000), and important synergistic relationships between biophysics, socio-economics, and geopolitics are not well understood as a result. In this paper, we develop an interdisciplinary approach to evaluate dams in affected communities. Specifically, we propose a new Integrative Dam Assessment Modeling (IDAM) tool for evaluating the relative costs and benefits of dam construction while accounting for biophysical, socio-economic, and geopolitical effects.

The conceptual foundation for this tool is based on existing approaches in multi-objective planning, including amoeba diagrams (ten Brink, 1991; Wall and Marzall, 2006), radar charts (Connell and Wall, 2004), sustainability polygons (Steiner et al., 2000), and wellness appraisal index graphs (Dever, 1991) for illustrating environmental, economic, and human health assessments (Sadler et al., 2000). By further developing these concepts to incorporate analysis of costs and benefits and by adapting the indicators to the context of dam building, we have developed this tool as a unique and potentially valuable instrument for informing dam siting and design, increasing the transparency of decision-making, encouraging public participation in the process, and documenting the process for selecting among various sites and designs in dam development.

In this paper, we introduce the IDAM tool, a conceptual model that explicitly calls for a variety of disciplinary perspectives in evaluating the positive and negative implications of dam construction and removal. This tool also overtly acknowledges both objective and subjective valuations for a transparent consensus-building evaluation of dams. After explaining the mechanics of the tool, we offer an illustrative example of how two alterative dam construction projects would be evaluated using this tool. Next, we provide context for the use of the tool by discussing its generalizability to different settings. We then compare the IDAM tool with other interdisciplinary approaches, commenting on the advantages and disadvantages of each, and we conclude by reflecting on the practical applications of the tool.

## 2. The integrative dam assessment modeling tool

The Integrative Dam Assessment Modeling (IDAM) tool is designed to combine the three themes identified by the 1992 United Nations Conference on Environment and Development into two circle diagrams, one measuring the costs associated with proposed dam development and the other measuring the benefits. Each of the two diagrams consists of 27 individual "impacts," or effects of dam construction, nine of which represent the biophysical theme, nine of which represent the socio-economic theme, and nine of which represent the geopolitical theme (Fig. 1). The same impacts appear on both the cost and benefit circles, and each impact comprises an equal portion ($13^1/_3$ °) of the circle diagram.

The impacts included in the model were informed by an extensive review of the existing literature, including evaluations of environmental effects (e.g., Bunn and Arthington, 2002; Goldsmith and Hildyard, 1986; McAllister et al., 2000; Rosenberg et al., 2000; WCD, 2000), social effects (e.g., Bartolome et al., 2000; Égré and Senécal, 2003; Lerer and Scudder, 1999; Sadler et al., 2000; Scudder, 1997), and the geopolitics (e.g., Bakker, 1999; McCully, 2001; Ribeiro, 1994; Scudder, 2005; Waterbury, 1979) of large dams. Groups of experts with experience in evaluating dam impacts (including the authors) then gathered for semi-structured discussions on the specific indicators to be included using the Delphi Technique (Gordon and Helmer, 1964).[1] This method enables interdisciplinary dialog to develop consensus on the key components for analysis and provides process techniques to resolve differences as they arise.[2] The biophysical impacts identified through this process are water retention time; natural value; downstream tributaries; biodiversity' distance of river left dry downstream of the dam; $CO_2$ equivalent to coal; flood protection; site stability; and reservoir surface (see Table 1 for more detail). The socio-economic impacts of primary concern are social change; cultural change; non-agricultural economic activity; health; agricultural economic activity; displacement; hydropower and infrastructure; housing values; and transportation (see Table 2 for more detail). The geopolitical indicators include downstream riparian population; downstream irrigation; political boundaries; existing dams; agreements and institutions; political participation; historical stability/tensions; domestic governance; and socio-economic impacts for non-constituents (see Table 3 for more detail).

Within the context of the IDAM tool, each of these 27 impacts includes both an objective evaluation of the magnitude of the effect of dam construction (called a "metric") and a subjective evaluation of its biophysical, socio-economic, or geopolitical effect (called a "valuation"). That is, each impact is broken into five sub-sections (each representing $2^2/_3$ ° of the circle) that classify the objective magnitude of the effect on a six-point scale (Likert, 1932), ranging from 0 for "no impact" to 5 for "extreme impact"; Table 4 provides three detailed examples. These categories are normalized so the model may be used in evaluating the costs and benefits of small dams such as those in New Jersey (Wyrick et al., in this issue) and

[1] These discussions were held as part of the International Symposium on the Modeling of Dams in Washington on April 11–13th, 2007 and the symposium on Damming the Nu: Evaluating Hydropower on China's Angry River in Maine on October 6–7, 2007.

[2] Linstone and Turoff (1975) and Rowe and Wright (1999) provide thorough summaries of the strengths and weaknesses of the Delphi Technique and Meedham and de Loë (1990) describe its applicability to water resources planning.

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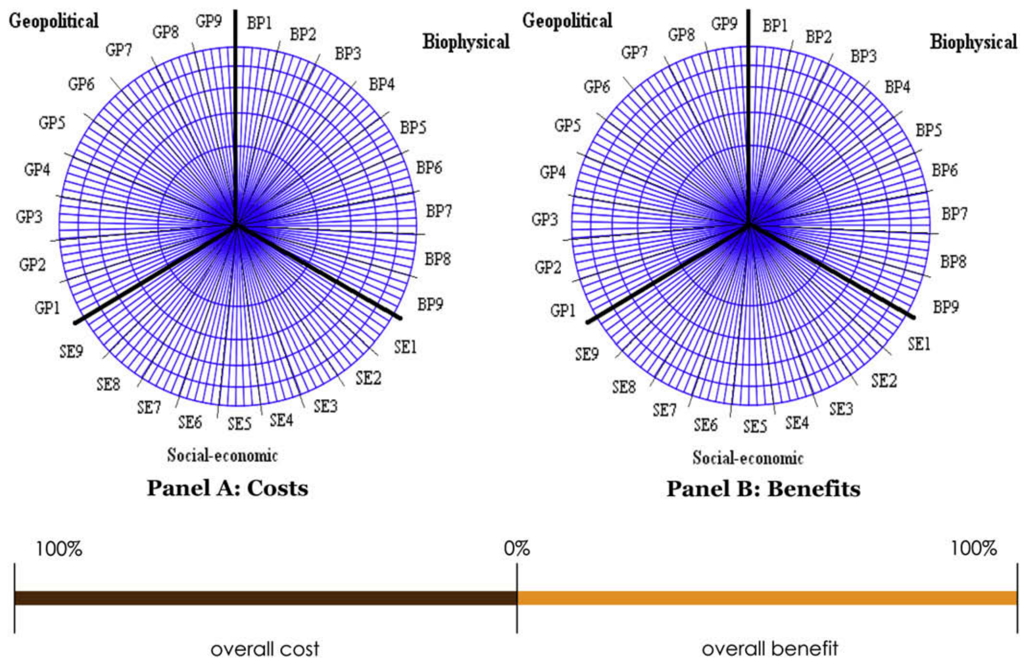


**Fig. 1.** IDAM tool. The sum of the shaded area for a completed IDAM characterizes the aggregated costs and benefits. The proportion of the costs and benefits is displayed on the scale below. The scale runs from 0 to 100 on both the costs and benefits.

Maine (Bohlen and Lewis, in this issue) as well as massive hydropower development projects such as those in China (McNally et al., in this issue; Tullos, in this issue), Lesotho (Tilt et al., in this issue), and the American West (Burke et al., in this issue). Given this objective impact of a proposed dam, decision-makers are asked to evaluate the benefits and costs associated with the objective impact of proposed dams on the following scale: “none,” “very small,” “small,” “moderate,” “large,” or “very large.”[3]

The objective metric of the costs and benefits of dam construction is measured along the circumference of the IDAM circle and the subjective valuation of this outcome is measured along the radius. Given these data, the IDAM figure is shaded to provide a visual comparison of the magnitude of the effects and the decision-makers’ valuation thereof (see Fig. 2 for a detailed account of this process for a single indicator, and note that an impact without shading does not imply a lack of data, but rather no objective impact, no subjective cost or benefit, or both). The IDAM tool thus provides an opportunity for heuristic decision-making.[4]

In an ideal setting, the decision-making team will include experts who are trained to assess the impacts of dams through the various disciplinary frameworks as well as stakeholders with local knowledge and experience. We anticipate that this process will involve negotiation and consensus-building through a process similar to the Delphi Technique, thereby improving the transparency of the decision-making process.

[3] It is important to acknowledge that while some effects of dam construction on human and natural systems can be felt immediately, others are dynamic and cumulative, becoming apparent over many years. Decision-makers should thus keep the “life cycle” of a given dam project in mind when assigning objective metrics and subjective valuations (Sadler et al., 2000).

[4] As currently implemented, the IDAM tool assigns an equal area of the decision circle to each impact. We believe that such an approach accommodates weighting through the subjective valuation of each impact, although it may nevertheless be worth experimenting with a model which allows for a more flexibility in weighting impacts.

## 3. Illustrative example – low vs. high-impact dams

In what follows, we offer two hypothetical examples of how dam construction projects may be evaluated using the IDAM tool, one for a relatively high-impact dam site and one for a low-impact dam site.

**Table 1**
Biophysical impacts.

| Label | Impact | Description | Metric |
|---|---|---|---|
| BP1 | Water retention time | Time water is stored in reservoir as indicator of ecological impact | Time |
| BP2 | Natural value | Potential gain or loss associated with dam activity | UNESCO “natural” selection criteria |
| BP3 | Downstream tributaries | Number of tributaries for supplying sediment and organic material, buffering hydrology, and providing habitat | Number |
| BP4 | Biodiversity | Threatened/endangered plants and animals | % of known species that are threatened or endangered |
| BP5 | Distance of river left dry downstream of dam | In scenarios where flow is diverted for irrigation | Length |
| BP6 | $CO_2$ equivalent to coal | Benefit of producing hydropower as opposed to coal as alternative energy source | Pounds per MW |
| BP7 | Flood protection | The magnitude of flooding event captured by the dam in Return Year Interval (RYI) | RYI year |
| BP8 | Site stability | Presence of geologic hazards, e.g. landslides, site stability, distance to faults, and reservoir-induced seismicity | None to very large |
| BP9 | Reservoir surface | Surface area of reservoir at full storage | Area |

**Table 2**
Socio-economic impacts.

| Label | Impact | Description | Metric |
|---|---|---|---|
| SE1 | Social cohesion | Change in social networks and perceived social cohesion | Buckner scale |
| SE2 | Cultural change | Sites of cultural significance | Number |
| SE3 | Non-agricultural economic activity | Aggregate change in total income, less government transfers | Dollars |
| SE4 | Health | Frequency and severity of contamination | Days per year |
| SE5 | Agricultural economic activity | Aggregate change in total income, less government transfers | Dollars |
| SE6 | Displacement | Relocation costs associated with changing water levels | Dollars |
| SE7 | Hydropower/ infrastructure | Value of hydropower consumed locally or sold | Dollars |
| SE8 | Housing values | Hedonic value of recreation and landscape | Dollars |
| SE9 | Transportation | Value of change in economic activity | Dollars |

### 3.1. High-impact dam site

This hypothetical new dam site is located on the main stem of a large river in the Unites States, with the primary objective of providing a reliable source of irrigation water and a secondary objective of producing hydropower. It is a wide (820 m) and relatively short (21 m) structure, blocking passage for three species of endangered salmon as listed under the Endangered Species Act (ESA) to an 88 km spawning habitat and leaving 18 km dry downstream during very dry years.

Because of the generally low slope of the river valley, the reservoir will have a high surface area and will inundate two Native American reservation communities comprising nearly 1000 people in total. Archaeological digs have recently discovered artifacts of a community dating back to 2200 years within the inundated area, and sites of spiritual importance will be submerged. The residents of the affected communities will be relocated outside of the valley to a reservation in the dry grassland 200 km away. Water is not immediately accessible at the relocation site, but the U.S. government has agreed to dig wells for the displaced communities. However, no agreements have yet been signed between the communities and the federal government because the residents are concerned that the wells will be insufficient to meet their water needs. Employment opportunities will exist at the new reservation in the form of a newly constructed casino. Educational programs will be developed at the new site for the relocated residents.

The benefits and costs of this high-impact dam are described in the IDAM circles presented in Fig. 3. Note that the objective metrics and subjective valuations have been estimated for this hypothetical dam for illustrative purposes (see Table 5 for detail); for a true IDAM evaluation, a decision-making team must provide the data for metrics and valuations. In addition, recall that an impact without shading implies that there is no objective impact and/or that the subjective valuation associated with that impact is zero. Subtracting the total cost (Panel B) from the total benefit (Panel A) in the IDAM tool indicates a net cost of 10 units as follows: net cost of 58 units to biophysical impacts; net benefit of 23 units to socio-economic indicators; and net benefit of 25 units to geopolitical indicators. This outcome is compared to the net benefit (or cost) of a low-impact dam built on a tributary of the dam below.

### 3.2. Low-impact dam site

This hypothetical new dam site is located on a steeper tributary to the main stem river proposed above, with similar objectives of developing irrigation resources and producing hydropower. This structure would be narrower (120 m) and taller (47 m) than the dam on the main stem of the river, with a small, but deep reservoir with 23 km$^2$ in surface area. The low surface area of the reservoir blocks only 21 km of spawning habitat for two ESA-listed salmon. This facility generates a similar amount of electricity (23 MW per year), but the electricity will need to be transmitted farther to the transfer facility. Furthermore, the structure will only store enough water for irrigating only 423 ha of farmland for corn production. There are numerous downstream tributaries that regularly supply sediment and runoff to the main stem. However, because all of the flow is diverted, the river will be left dry most years 6 km down to the next tributary. By storing and diverting all of the flood water in this river, this facility offers the benefit of downstream flood protection. The value of this protection is quite limited, however, because the habitat between the dam and the main stem is industrial forest that was harvested just prior to construction. As such, no communities will be displaced and no cultural or anthropological artifacts will be inundated.

The benefits and costs of this low-impact dam are described in the IDAM circles presented in Fig. 4. Subtracting the total cost (Panel B) from the total benefit (Panel A) in the IDAM tool indicates a net benefit of 10 units as follows: net cost of 24 units to biophysical impacts; net benefit of 19 units to socio-economic indicators; and net benefit of 15 units to geopolitical indicators. Although the benefits of dam building at the high-impact site are significantly larger than the benefits of building at the low-impact site, the costs of dam building are also disproportionately larger in the former case. Indeed, the IDAM tool indicates that the net benefit to dam construction in the tributary of the river outweighs that of dam construction in the main stem.

## 4. Applicability and generalizability of the IDAM tool

WCD (2000) calls for social, environmental, and technical monitoring and assessment for proposed dam projects. Further, the "Five Key Decision Points" described in the WCD report propose that decisions about dams should be rooted in careful discussions of needs assessment, selecting alternatives and investigative studies, project preparation, project implementation, and project operation.

**Table 3**
Geopolitical impacts.

| Label | Impact | Description | Metric |
|---|---|---|---|
| GP1 | Downstream riparian population | People in downstream communities potentially affected by upstream dams | Number |
| GP2 | Downstream irrigation | Downstream irrigated area potentially affected by upstream dams | Area |
| GP3 | Political boundaries | Number of national and sub-national political boundaries crossed by waterway | Number |
| GP4 | Existing dams | Regulatory/storage capacity of existing dams on waterway | Capacity |
| GP5 | Agreements/institutions | Number of inter-governmental institutions devoted to management of shared waterway | Number |
| GP6 | Political participation | Plurality of decision-making processes in country where dam will be sited | Democracy index |
| GP7 | Historical stability/tensions | Degree of interstate and intra-state stability versus tension among riparian countries | Internal Basins at Risk (BAR) Scale |
| GP8 | Domestic governance | "Durability" of state government, including its ability to anticipate and, where necessary, appropriately respond to domestic challenges | International Basins at Risk (BAR) Scale |
| GP9 | Socio-economic impacts for non-constituents | Estimate of the magnitude of impacts for non-constituents (e.g. downstream communities in other riparian countries) | Low–high |

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**Table 4**
Example metrics for objective measurement of dam impacts. The objective metrics associated with each of the 27 indicators in the IDAM tool are evaluated on a 6-point scale in which 0 indicates no effect and 5 indicates a very large effect. In the interest of space, three detailed examples (one each from the biophysical, socio-economic, and geopolitical perspective) are provided; as noted in the text, these metrics should be adapted to local circumstances.

| | |
|---|---|
| *BP7: Flood protection, relative to historical record for the same river* | |
| 0 | None |
| 1 | Flood protection for only small storms (1–10 RYI) |
| 2 | Flood protection for modest events (10–25 RYI) |
| 3 | Flood protection for large but regular events (25–100 RYI) |
| 4 | Flood protection for large and irregular events (100–1000 RYI) |
| 5 | Flood protection for events >1000 RYI |
| *SE1: Resettlement cost, as a share of watershed GDP* | |
| 0 | No displacement |
| 1 | Less than 0.5% of total watershed GDP |
| 2 | 0.5–1.5% of total watershed GDP |
| 3 | 1.5–3.0% of total watershed GDP |
| 4 | 3.0–5.0% of total watershed GDP |
| 5 | Greater than 5.0% of total watershed GDP |
| *GP4: Capacity of existing dams to regulate annual flow* | |
| 0 | No existing dams on the main trunk of the river |
| 1 | Existing dams have capacity to regulate <10% of mean annual flow |
| 2 | Existing dams have capacity to regulate <20% of mean annual flow |
| 3 | Existing dams have capacity to regulate <30% of mean annual flow |
| 4 | Existing dams have capacity to regulate <40% of mean annual flow |
| 5 | Existing dams have capacity to regulate >40% of mean annual flow |

The proposed IDAM tool may therefore be useful in operationalizing these recommendations, offering a systematic and transparent approach for evaluating dam siting to meet the development and sustainability needs of affected communities.

The IDAM tool is comprehensive in its evaluation of dam construction from multiple disciplinary perspectives. Moreover, because simple steps may be taken to adapt the model to local conditions (such as adjusting or changing specific indicators included the tool) and because it explicitly incorporates both objective metrics and subjective valuations of dam impacts, the tool is extremely flexible. By providing a visual representation of the various costs and benefits associated with two or more dams, the tool also allows decision-makers to evaluate alternatives and to articulate priorities associated with a dam project, making the decision process about dams more informed and transparent. For all of these reasons, we believe that the IDAM tool represents an important evolutionary step in dam evaluation.

Thus, the IDAM tool is currently being used to evaluate dam removal in Oregon, where the need to better understand the integrated biophysical, socio-economic, and geopolitical advantages and disadvantages of dam removal is great (Bowman, 2002). Specifically, impacts identified in Tables 1–3 were adapted based on current literature of dam removal (e.g., Graf, 2003), replacing contextually inappropriate impacts (e.g., "distance of river left dry downstream of dam") with more appropriate alternatives (e.g., "predicted distance of downstream sediment deposition") while retaining those that remained relevant (e.g., "biodiversity"). We then solicited feedback on the proposed impacts during facilitated meetings with stakeholders, including representatives of federal agencies, experts on environmental monitoring, and local landowners. We are now applying the IDAM tool to document and analyze decision-making and environmental outcomes associated with two economically, politically, and environmentally dissimilar small dam removals. The results will include an evaluation of the indicators for use in decision-making about dam removals beyond these two case studies.

## 5. Other interdisciplinary approaches to modeling dams

Other approaches exist for performing interdisciplinary assessments on "coupled human–environment systems" (Global Land Project, 2005; Turner et al., 2003). For example, economic approaches such as hedonic analysis and contingent valuation have been used to value the impact of dam construction and removal on water quality and fish biodiversity (e.g., Bohlen and Lewis, in this issue). Similarly, micro- and macroeconomic factors have been included in biophysical simulation models (e.g., Benstead et al., 1999; Costanza and Ruth, 1998; Haberl et al., 2006; Simonovic and Fahmy, 1999). However, using economics to value socio-cultural and ecological indicators is a source of debate due to difficulties in accounting for variability in interpretation and positions on metrics and values (McCauley, 2006; Sullivan, 2001).

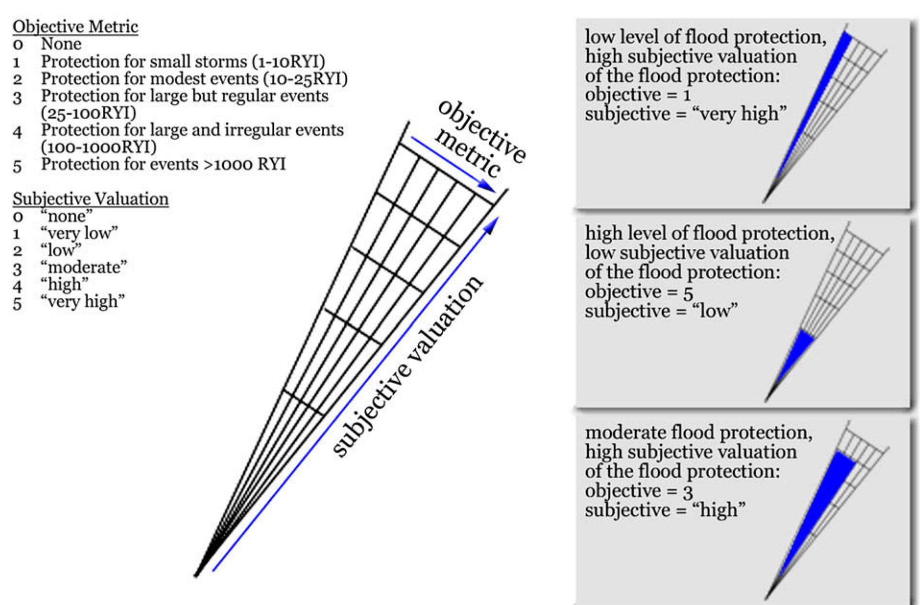


**Fig. 2.** Sample evaluation of the benefits of flood protection. Experts characterize the benefits of dam construction according to an objective metric. In the case of flood protection, this metric describes protection relative to the historical record for the same river. Decision-makers assign a subjective valuation to these quantified benefits based on a scale ranging from "none" to "very high." The IDAM figure is then shaded in order to provide a visual representation of both the objective metric and the subjective valuation.

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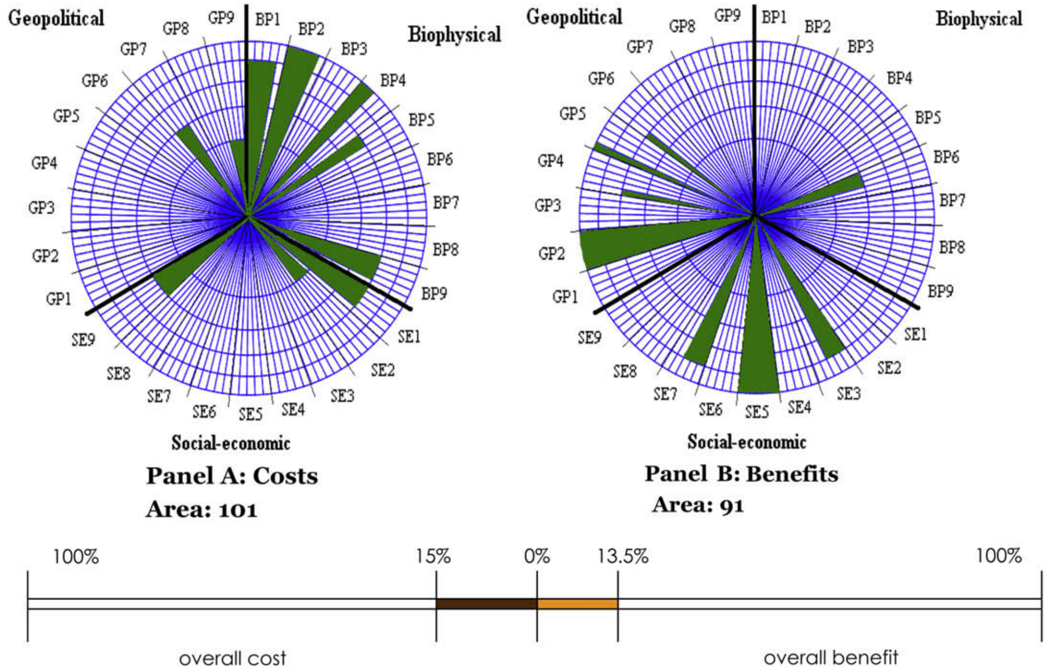


**Fig. 3.** Illustrative example, high-impact dam. A dam on the main stem of a large river would block passage for salmon and sometimes leave downstream reaches dry. However, it would also produce a modest amount of electricity and irrigate and for corn production. The reservoir would displace 1000 Native Americans, and compensation is still under negotiation. Although important heritage sites would be lost, economic opportunities exist at the relocation site. See Table 5 for objective metrics and subjective valuations of these impacts.

**Table 5**
Illustrative example: high- versus low-impact dams. A decision-making team comprised of experts and stakeholders will participate in a consensus-building process such as the Delphi Technique to identify and evaluate the objective and subjective costs and benefits of dam construction at different sites. Based on the information provided in the illustrative example, a decision-making team might arrive at the following objective metrics and subjective valuations. These values were used in constructing Figs. 3 and 4.

| Key | Impact | High-impact dams | | | | Low-impact dam | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Benefits | | Costs | | Benefits | | Costs | |
| | | Obj. metric | Subj. valuation | Obj. metric | Subj. valuation | Obj. metric | Subj. valuation | Obj. metric | Subj. valuation |
| *Biophysical (BP) impacts* | | | | | | | | | |
| BP1 | Water retention | 0 | 0 | 4 | 4 | 0 | 0 | 2 | 4 |
| BP2 | Natural value | 0 | 0 | 4 | 5 | 0 | 0 | 3 | 5 |
| BP3 | Downstream tributaries | 0 | 4 | 3 | 0 | 3 | 4 | 0 | 0 |
| BP4 | Species of concern | 0 | 0 | 2 | 5 | 0 | 0 | 1 | 5 |
| BP5 | Dry river | 0 | 0 | 2 | 3 | 0 | 0 | 3 | 3 |
| BP6 | $CO_2$ equivalent to coal | 3 | 2 | 0 | 0 | 2 | 2 | 0 | 0 |
| BP7 | Flood protection | 2 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| BP8 | Site stability | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BP9 | Reservoir surface | 0 | 0 | 4 | 3 | 0 | 0 | 1 | 3 |
| *Socio-economic (SE) impacts* | | | | | | | | | |
| SE1 | Social cohesion | 0 | 2 | 4 | 3 | 0 | 2 | 0 | 3 |
| SE2 | Cultural change | 0 | 0 | 4 | 1 | 0 | 0 | 0 | 1 |
| SE3 | Non-agr. economic activity | 3 | 4 | 4 | 0 | 0 | 4 | 0 | 0 |
| SE4 | Health | 5 | 0 | 0 | 4 | 3 | 0 | 0 | 4 |
| SE5 | Ag. economic activity | 5 | 5 | 0 | 0 | 3 | 5 | 0 | 0 |
| SE6 | Displacement | 3 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| SE7 | Hydropower/infrastructure | 3 | 4 | 0 | 5 | 1 | 4 | 0 | 5 |
| SE8 | Housing values | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 |
| SE9 | Transportation | 0 | 3 | 5 | 2 | 0 | 3 | 0 | 2 |
| *Geopolitical (GP) impacts* | | | | | | | | | |
| GP1 | Downstream riparian pop. | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 |
| GP2 | Downstream irrigation | 5 | 5 | 0 | 0 | 3 | 5 | 0 | 0 |
| GP3 | Political boundaries | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| GP4 | Existing dams | 1 | 3 | 0 | 0 | 0 | 3 | 0 | 0 |
| GP5 | Agreements/institutions | 1 | 5 | 4 | 0 | 0 | 5 | 0 | 0 |
| GP6 | Political participation | 1 | 3 | 3 | 0 | 0 | 3 | 0 | 0 |
| GP7 | Historical stability/tensions | 0 | 0 | 3 | 2 | 0 | 0 | 0 | 2 |
| GP8 | Domestic governance | 0 | 1 | 4 | 0 | 0 | 1 | 0 | 0 |
| GP9 | Socio-economic impacts for non-constituents | 0 | 0 | 5 | 1 | 0 | 0 | 0 | 1 |

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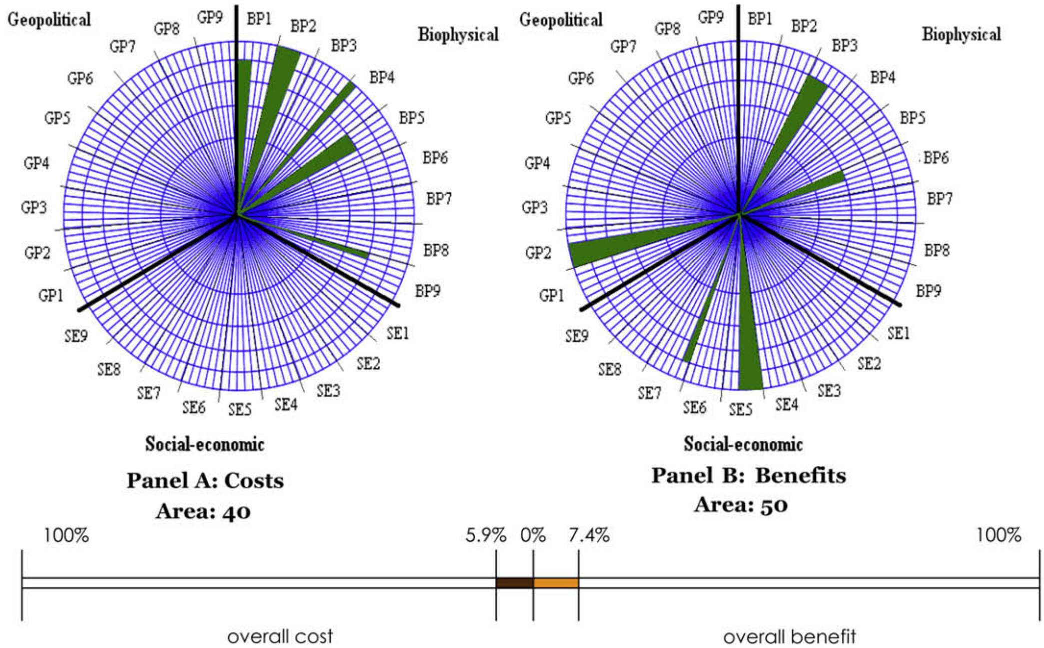


**Fig. 4.** Illustrative example, low-impact dam. This dam is taller and narrower than the high-impact dam, yet it blocks less spawning habitat for salmon and no communities would be displaced by its construction. This dam would provide some flood protection, but only to industrial forest land. The small amount of electricity generated from this facility would be transported farther away, and the dam would irrigate far less land. See Table 5 for objective metrics and subjective valuations of these impacts.

In another approach, Haberl et al. (2006) propose the use of social–ecological metabolism measures drawn from the ecological economics, industrial ecology, and human ecology literatures to integrate biophysical and socio-economic processes through a common currency (e.g., carbon and water). Such analyses combine field data with statistical social data and use historical sources to reconstruct past states of the system, thereby contributing to socio-ecological models that integrate economic and ecological dynamics (Ayres, 2001; Ibernholt, 2002) in river systems such as the Hudson (Ayres and Ayres, 1988; Ayres and Tarr, 1990) and the Rhine (Stigliani et al., 1993). However, this approach is limited in that it requires a rigid spatial scale over which systems are compared, which is difficult to define for socio-economic systems (Liverman and National Research Council (U.S.) Committee on the Human Dimensions of Global Change, 1998).

Finally, agent-based models have also been used to study complex social and environmental systems by attempting to replicate the behavior of individuals and groups. The complex dynamics within and between biophysical and human systems are linked in such models as each disciplinary perspective is treated as an agent that interacts with other agents. One advantage of agent-based models over other types of interdisciplinary models is that they are based on the underlying framework of each discipline, rather than trying to meld disciplines under a single framework and set of assumptions (McConnell et al., 2001). Moreover, by separating policy questions from data, agent-based modeling increases the transparency of decision-making in water resources planning (Simonovic and Fahmy, 1999). However, agent-based models are limited by the requirement to develop deterministic rules by which agents drive system change. Furthermore, agent-based models assume that agents have decision-making autonomy, and this assumption may not be appropriate for large-scale public works projects such as dams.

In light of the availability and limitations of these tools, the IDAM tool offers at least five distinct advantages. First, and perhaps most importantly, the tool renders explicitly the need for decision-makers to simultaneously consider the biophysical, socio-economic, and geopolitical implications of dams. We believe that identifying data needs in this way will help decision-makers to produce comprehensive and empirically valid policy decisions. Second, it combines both objective measurements and subjective valuations of dam building into a single model. Third, neither the model nor the authors of this study arbitrarily assign subjective weights to the various impacts; instead, the importance of each impact is left up to the decision team. We feel this is a vital component in the development and functioning of this model, and one that increases its applicability across different socio-cultural and geographic contexts. Fourth, this work benefits from and contributes to the perspectives of individual disciplines. Similar to agent-based models, this approach does not require disciplines to conform to a single framework for assessing impacts, but it does integrate the various disciplinary perspectives into a single model. Finally, the IDAM tool is visually accessible: costs and benefits of the proposed project are clearly shown in figures, and conclusions regarding dam impacts can be easily drawn by comparing the shaded area of the two circles.

One disadvantage of the IDAM tool is the considerable up-front data requirements for the objective assessments of dam impacts. Still, any thorough evaluation of dams (e.g., environmental and social impact assessments) is based on nearly identical information, yet the IDAM tool makes the data needs clear at the outset. A second potential limitation of the tool is that the 27 individual impacts may not be appropriate to every setting; although we have endeavored to make these categories widely applicable, we expect that some decision-makers may find utility in adapting them to the local context. Third, the value of the IDAM tool depends on a balanced treatment of each disciplinary perspective: if natural scientists or environmentalists comprise a disproportionate share of the decision-making team, for example, the socio-economic and geopolitical costs and benefits of dams may be undervalued, leading to biased evaluations. Finally, the tool requires consensus-building among interested constituencies. Again, we view this as an advantage of the model, although some decision-makers may disagree.

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## 6. Conclusions

With the growing demand for water and energy, a concurrent rise in the need for water storage and hydropower projects may be expected, particularly in developing countries. At the same time, aging hydropower stations are being removed with increasing frequency in developed countries. The literature rooted in biophysiology, socio-economics, and geopolitics may inform decision-makers' decisions about the siting and sizing of new dams and about the costs and benefits of removing existing dams, albeit often from a single disciplinary perspective that may miss other important outcomes associated with dam construction or removal. Unfortunately, past attempts to integrate the biophysical, socio-economic, and geopolitical effects in a coherent way have been stymied by the disparate vocabularies and concepts under which individual disciplines operate.

Nevertheless, this paper and others in this issue (e.g., Tullos et al., in this issue; Wyrick et al., in this issue) have highlighted the importance of assessing the impacts of dams from a multidisciplinary perspective. To facilitate such evaluation, we have introduced the IDAM tool, which allows decision-makers to assign objective metrics and subjective valuations to a range of biophysical, socio-economic and geopolitical effects of dam construction and removal. Properly implemented, this tool encourages consensus-building and affords an opportunity for heuristic decision-making. As such, it will advance our understanding of how dams affect human and ecological systems.

Recognizing that the credibility of a model depends on the validity of underlying assumptions and on stakeholder buy-in, we advocate a careful data collection process to verify the selection of impacts, documented procedures for data quality and control, and a deliberate attempt to include the breadth of stakeholders in the evaluation process. Data needs are likely to involve analysis of primary literature, household surveys, hydrologic and GIS analyses, and public participation activities. While such data collection needs are not trivial, they are no more cumbersome than those associated with well-designed social and environmental impact assessments. Developing stakeholder buy-in is likely to entail demonstration of the IDAM tool, mechanism analysis, and opportunities for public discussion, all of which contribute to the transparency of the decision-making process. Further, while true validation of the IDAM tool is difficult in the absence of a natural experiment, the tool will accommodate sensitivity validation (Schneider, 1997) by allowing researchers to simulate changes in objective metrics and subjective valuations to better understand the effect of each impact on high-priority state variables. Finally, this approach facilitates an evaluation of the relative importance of biophysical, socio-economic, and geopolitical indicators in assessing dam impacts. These techniques can be valuable in evaluating the credibility of the IDAM tool as well as the currently held assumptions regarding the impacts of dam construction and removal.

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## References

Acharya, G., Lewis, L., 2001. Valuing open space and land use chaos in urban watersheds: an hedonic property value analysis. Journal of Real Estate Economics and Finance 22 (2/3), 221–237.

Ayres, R.U., 2001. The minimum complexity of endogeneous growth models: the role of physical resource flows. Energy 26 (9), 817–838.

Ayres, R.U., Ayres, L., 1988. An Historical Reconstruction of Major Pollutant Levels in the Hudson–Raritan basin, 1800–1980. National Oceanic and Atmospheric Administration, Rockville, MD.

Ayres, R.U., Tarr, J.A., 1990. Environmental change in the Hudson River Basin and the Hudson–Raritan Estuary. In: Turner, B.L., Clark, W.C., Kates, R.W., Richards, J.F., Mathews, J.T., Meyer, W.B. (Eds.), The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere Over the Past 300 Years. Cambridge University Press with Clark University, Cambridge, pp. 623–640.

Bakker, K., 1999. The politics of hydropower: developing the Mekong. Political Geography 18 (2), 209–232.

Bartolome, L.J., de Wet, C., Nagaraj, V.K., 2000. Displacement, Resettlement, Rehabilitation, Reparation and Development; Thematic Review I.3. Prepared as an input to the World Commission on Dams. World Commission on Dams, Capetown.

Benstead, J.P., March, J.G., Pringle, C.M., Scatena, F.N., 1999. Effects of a low-head dam and water abstraction on migratory tropical stream biota. Ecological Applications 9 (2), 656–668.

Bocking, S., 1998. Dams & Development. International Development Studies Network. <http://www.idsnet.org/Resources/Dams/Development/DinD.html>.

Bohlen, C., Lewis, L. Using GIS to inform economic analysis on the impacts of hydropower dams. Journal of Environmental Management, in this issue.

Bohlen, C., Lewis, L., Wilson, S., 2007. Dam Removal and Property Values: a Hedonic Analysis. Mimeo. Bates College.

Born, S., Genskow, K., Filbert, T., Hernandez-Mora, N., Keefer, M., White, K., 1998. Socioeconomic and institutional dimensions of dam removals: the Wisconsin experience. Environmental Management 22, 359–370.

Bowman, M., 2002. Exploring Dam Removal: a Decision-Making Guide. American Rivers, Trout Unlimited, Washington DC.

Bunn, S., Arthington, A., 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental Management 30 (4), 492–507.

Burke, M., Klaus, J., Buffington, J. Effects of hydropower operation on river processes downstream of Libby Dam, Kootenai River, U.S.A. and Canada. Journal of Environmental Management, in this issue.

Cernea, M.M., 1999. The Economics of Involuntary Resettlement: Questions and Challenges. World Bank, Washington, DC.

Connell, D.J., Wall, E., 2004. Profiling economic capacity. Journal of Extension 42 (4).

Costanza, R., Ruth, M., 1998. Using dynamic modeling to scope environmental problems and build consensus. Environmental Management 22 (2), 183–195.

Dever, G.E.A., 1991. Community Health Analysis: Global Awareness at the Local Level, second ed. Aspen Publishers, Gaithersburg, MD.

Doyle, M.W., Stanley, E.H., Harbor, J.M., 2003. Channel adjustments following two dam removals in Wisconsin. Water Resource Research 39 (1), 1011.

Doyle, M.W., Stanley, E.H., Havlick, D.G., Kaiser, M.J., Steinbach, G., Graf, W.L., Galloway, G.E., Riggsbee, J.A., 2008. Aging infrastructure and ecosystem restoration. Science 319, 286–287.

Égré, D., Senécal, P., 2003. Social impact assessments of large dams throughout the world: lessons learned over two decades. Impact Assessment & Project Appraisal 21 (3), 215–224.

Giordano, M., Giordano, M., Wolf, A., 2005. International resource conflict and mitigation. Journal of Peace Research 42 (1), 47–65.

Global Land Project, 2005. Science plan and implementation strategy. Report Number 53/IHDP Report Number 19, International Geosphere–Biosphere Programme (IGBP), Stockholm.

Goldsmith, E., Hildyard, N., 1986. The Social and Environmental Effects of Large Dams. Sierra Club Books, San Francisco.

Gordon, T., Helmer, O., 1964. Report on a Long Range Forecasting Study. RAND Corporation, Santa Monica, CA.

Graf, W.L., 2003. Dam removal research. In: Graf, W.L. (Ed.), Dam Removal Research: Science and Decision Making. Heinz Center, Washington, DC.

Haberl, H., Winiwarter, V., Andersson, K., Ayres, R.U., Boone, C., Castillo, A., Cunfer, G., Fischer-Kowalski, M., Freudenburg, W.R., Furman, E., Kaufmann, R., Krausmann, F., Langthaler, E., Lotze-Campen, H., Mirtl, M., Redman, C.L., Reenberg, A., Wardell, A., Warr, B., Zechmeister, H., 2006. From LTER to LTSER: conceptualizing the socioeconomic dimension of long-term socioecological research. Ecology and Society 11 (2), 1–34.

Hart, D.D., Johnson, T.E., Bushaw-Newton, K.L., Horwitz, R.J., Bednarek, A.T., Charles, D.F., Kreeger, D.A., Velinsky, D.J., 2002. Dam removal: challenges and opportunities for ecological research and river restoration. Bioscience 52 (8), 669–681.

Ibernholt, K., 2002. Material flow accounting and economic modeling. In: Ayres, R.U., Ayres, L. (Eds.), A Handbook of Industrial Ecology. Edward Elgar, Northampton, MA, pp. 177–184.

Intergovernmental Panel on Climate Change, 2007. Working Group 2: Impacts, Adaptation, and Vulnerability. <http://www.gtp89.dial.pipex.com/chpt.htm>.

Lerer, L.B., Scudder, T., 1999. Health impacts of large dams. Environmental Impact Assessment Review 19 (2), 113–123.

Likert, R., 1932. A technique for the measurement of attitudes. Archives of Psychology 140, 1–55.

Linstone, H., Turoff, M. (Eds.), 1975. The Delphi Method: Techniques and Applications. Addison-Wesley, New York.

Liverman, D.M., National Research Council (U.S.) Committee on the Human Dimensions of Global Change, 1998. People and Pixels: Linking Remote Sensing and Social Science. National Academy Press, Washington, DC.

Please cite this article in press as: Brown, P.H., Modeling the costs and benefits of dam construction from a multidisciplinary perspective, Journal of Environmental Management (2008), doi:10.1016/j.jenvman.2008.07.025

McAllister, D., Craig, J., Davidson, N., Murray, D., Seddon, M., 2000. Dams, Ecosystem Functions and Environmental Restoration; Thematic Review II.1. Prepared as an input to the World Commission on Dams. World Commission on Dams, Capetown. <http://www.dams.org/docs/kbase/contrib/env245.pdf>.

McCauley, D.J., 2006. Selling out on nature. Nature 443, 27–28.

McConnell, W., Parker, D., Berger, T., Manson, S., 2001. Agent-based Models of Land-use and Land-cover Change. Center for Spatially Integrated Social Science, University of California at Santa Barbara. <http://www.csiss.org/resources/maslucc/ABM-LUCC.pdf>.

McCully, P., 2001. Silenced Rivers: the Ecology and Politics of Large Dams, Enlarged & updated ed. Zed Books, New York.

McNally, A., Magee, D., Wolf, A. Powersheds and sustainability: a geopolitical framework for assessing the impacts of dams. Journal of Environmental Management, in this issue.

Meedham, R., de Loë, R., 1990. The policy Delphi: purpose, structure, and application. The Canadian Geographer 32 (2), 133–143.

Petts, G.E., 1984. Impounded Rivers: Perspectives for Ecological Management. Wiley, Chichester, New York.

Phadke, R., 1999. Dams, Displacement, and Community Reconstruction: an Annotated Bibliography and Reference Guide. Institute of International Studies, University of California at Berkeley. <http://globetrotter.berkeley.edu/EnvirPol/Bib/B01-Phadke.pdf>.

Pizzuto, J., 2002. Effects of dam removal on river form and process. Bioscience 52 (8), 683–692.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime: a paradigm for conservation and restoration of river ecosytems. Bioscience 47 (11), 769–784.

Poff, N.L., Hart, D.D., 2002. How dams vary and why it matters for the emerging science of dam removal. Bioscience 52 (8), 59–68.

Ribeiro, G.L., 1994. Transnational Capitalism and Hydropolitics in Argentina: the Yacyretá High Dam. University Press of Florida, Gainesville.

Riggsbee, J.A., Julian, J.P., Doyle, M.W., Wetzel, R.G., 2007. Suspended sediment, dissolved organic carbon, and dissolved nitrogen export during the dam removal process. Water Resource Research 43 (9), W09414.

Rosenberg, D.M., McCully, P., Pringle, C.M., 2000. Global-scale environmental effects of hydrological alterations: introduction. Bioscience 50 (9), 746–751.

Rowe, G., Wright, G., 1999. The Delphi Technique as a forecasting tool: issues and analysis. International Journal of Forecasting 15 (4), 353–375.

Sadler, B., Verocai, I., Vanclay, F., 2000. Environmental and Social Impact Assessment for Large Dams, Thematic Review V.2. Prepared as an input to the World Commission on Dams. World Commission on Dams, Capetown. <http://www.dams.org/docs/kbase/thematic/tr52main.pdf>.

Schneider, S.H., 1997. Integrated assessment modeling of global climate change: transparent rational tool for policy making or opaque screen hiding value-laden assumptions? Environmental Modeling and Assessment 2 (4), 229–249.

Scudder, T., 1997. Social impacts of large dams. In: Dorcey, A.H.J., International Union for Conservation of Nature and Natural Resources, World Bank Group (Eds.), Large Dams: Learning from the Past. IUCN & World Bank, Gland, Switzerland.

Scudder, T., 2005. The Future of Large Dams: Dealing with Social, Environmental and Political Costs. Earthscan, Sterling, VA.

Simonovic, S.P., Fahmy, H., 1999. A new modeling approach for water resources policy analysis. Water Resources Research 35 (1), 295–304.

Steiner, K., Herweg, K., Dumanski, J., 2000. Practical and cost-effective indicators and procedures for monitoring the impacts of rural development projects on land quality and sustainable land management. Agriculture, Ecosystems & Environment 81 (2), 147–154.

Stigliani, W.M., Anderberg, S., Jaffe, P.R., 1993. Industrial metabolism and long-term risks from accumulated chemicals in the Rhine basin. Industry and Environment 16 (3), 30–35.

Sullivan, K.M., 2001. Discursive practices and competing discourses in the governance of wild North American Pacific Salmon resources. In: Blatter, J., Ingram, H. (Eds.), Reflections on Water: New Approaches to Transboundary Conflicts and Cooperation. MIT Press, Cambridge, MA, pp. 163–188.

ten Brink, B., 1991. The AMEOBA approach as a useful tool for establishing sustainable development. In: Kuik, O., Verbruggen, H. (Eds.), In Search of Indicators of Sustainable Development. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Tilt, B., Braun, Y., He, D. Social impacts of large dam projects: a comparison of international case studies and implications for best practice. Journal of Environmental Management, in this issue.

Tullos, D. Assessing the influence of environmental impact assessments on science and policy: an analysis of the Three Gorges Project. Journal of Environmental Management, in this issue.

Tullos, D., Tilt, B., Liermann, C. Interdisciplinarity of dams and dam removals-measuring benefits and tradeoffs. Journal of Environmental Management, in this issue.

Turner, B.L., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Hovelsrud-Broda, G.K., Kasperson, J.X., Kasperson, R.E., Luers, A., Martello, M.L., Mathiesen, S., Naylor, R., Polsky, C., Pulsipher, A., Schiller, A., Selin, H., Tyler, N., 2003. Illustrating the coupled human–environment system for vulnerability analysis: three case studies. Proceedings of the National Academy of Science of the United States of America 100, 8080–8085.

United Nations Committee on Economic Development, 1993. Agenda 21. United Nations Publications, New York.

Wall, E., Marzall, K., 2006. Adaptive capacity for climate change in Canadian rural communities. Local Environment 11 (4), 373–397.

Walter, R.C., Merritts, D.J., 2008. Natural streams and the legacy of water-powered mills. Science 319, 299–304.

Ward, J.V., Stanford, J.A. (Eds.), 1979. The Ecology of Regulated Streams. Plenum Press, New York.

Waterbury, J., 1979. Hydropolitics of the Nile Valley, first ed. Syracuse University Press, Syracuse, NY.

Webber, M., McDonald, B., 2004. Involuntary resettlement, production, and income: evidence from Xiaolangdi, PRC. World Development 32 (4), 673–690.

Whitelaw, E., MacMullan, E., 2002. A framework for estimating the costs and benefits of dam removal. Bioscience 52 (8), 724–730.

World Commission on Dams, 2000. Dams and Development: a New Framework for Decision-Making. Earthscan, London.

Wyrick, J., Rischman, B., Burke, C., McGee, C., Williams, C. Using hydraulic modeling to assess the socio-economic impacts of small dam removal in southern New Jersey. Journal of Environmental Management, in this issue.

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