Minimizing environmental impacts of hydropower development: transferring lessons from past projects to a proposed strategy for Chile

Peter Goodwin, Klaus Jorde, Claudio Meier and Oscar Parra

ABSTRACT

Large dams have provided extensive benefits during the past 60 years but have also resulted in ecological and social consequences that were unexpected or were deemed to have a lower societal importance than the design benefits. The management of large dams is still a relatively new scientific issue, compared to the timeframe necessary to detect and understand all the consequences occurring at the watershed scale. This paper summarizes the unforeseen or unanticipated environmental consequences of these projects and potential ramifications to the overall project performance. The value of a central knowledge base and the importance of a system-wide monitoring program to assess pre- and post-implementation conditions and adapt operational rules are presented. Knowledge developed in several basins is reviewed in the context of future strategies for Chile. Chile has a strong economy, looming energy crisis and is faced with balancing the long-term value of a renowned natural landscape with unique ecology and the largest salmon aquaculture industry in the world against the prospect of low cost hydropower to drive other sectors of the economy. This paper outlines the hydroinformatics technologies and scientifically based management approaches that can be applied to this complex issue.

Key words | adaptive management, Chile, computer-based modelling, dams, ecohydraulics, ecosystems, environmental hydroinformatics, environmental impacts, hydropower

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INTRODUCTION

Remarkable changes in landscape have occurred over the last 75 years, with the advent of large dams, the development of new dam construction technologies, and an exponential increase in the number of large dams across the globe. Few engineering feats have exerted such a profound influence on the landscape, ecosystems, and people's quality of life. Since the construction of the Hoover Dam in the Colorado River in 1931, the number of large dams (with a height from foundation to crest exceeding 15 m) around the world has increased to more than 40 000, with the largest reaching 300 m in height (ICOLD 1988; McCully 2001). These dams have provided many benefits such as power, irrigation water, flood hazard reduction, navigation, and secure municipal water supplies, all of which have provided economic benefits. Despite these benefits, large dam technology has come under increasing scrutiny during the past decade (IUCN–World Bank 1997; World Commission on Dams 2000). The primary questions that have arisen include:

- Are the benefits predicted during the original design really achieved?
- Is the dam and reservoir system managed in the way that the planners and designers intended?
- Are there consequences from dam construction and operation that were not foreseen by the designers?

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- Are damages to the ecosystem, particularly biodiversity loss, worth the benefits for prevailing societal priorities?
- Are the forced changes to the way of life of indigenous people worth the benefits?
- Are the lessons learned from earlier large dam impacts (from within the region and globally) being systematically included in the design and operation of new projects?

In developed countries, the latter three issues are compounded by the paradigm shift in public perception and values associated with environmental issues, particularly as free-flowing rivers have become very scarce. These changing values are gradually being reflected in laws and policies enacted by government agencies. Few new large dams are likely to be constructed in the "developed" countries partly due to the few remaining suitable locations and due to the prevailing societal priorities. Emphasis is being placed on quantifying the effects of existing dams, and operating or retrofitting them in a way to mitigate adverse impacts (Collier *et al.* 1996).

BALANCING SUSTAINABILITY WITH IMMEDIATE NATIONAL ECONOMIC DEVELOPMENT

The potential for conflict in water management has been well documented (for example, in the US, Reisner 1993; Poff *et al.* 2003). Management approaches to minimize conflict and engage communities such as adaptive management have been discussed extensively in the literature (Peterman & Routledge 1983; Milliman *et al.* 1987; McCubbing & Ward 1997; Ward *et al.* 2003). Furthermore, the need for comprehensive watershed level assessment has become apparent (Independent Scientific Group 1996; Independent Scientific Review Panel 1999; Northwest Power Planning Council 2000). Expenditure for restoration activities to mitigate adverse impacts of large dams runs into the hundreds of millions of dollars per year in the Western States, but this is insufficient to begin to address all the different needs. Despite some success, the effectiveness of these mitigation funds has been questioned, for example by Bash & Ryan (2002) and the GAO Review (2002). An overview of the effectiveness of river restoration in the US is detailed in Palmer *et al.* (2005) and Bernhardt *et al.* (2005).

In developing countries, where abundant locations for potential large dams still exist, the emphasis should be on understanding the river systems and the full societal context as a part of attempting to design construction projects. This strategy would avoid many of the negative consequences experienced elsewhere, instead of repeating the mistakes from the past. This repetition is sometimes justified through "cost effectiveness" of short-term benefits without regard to the sustainability of the operation. These issues are explored through the regional case of Southern Chile. Chile and Southern Argentina have some of the most pristine river systems in the world with high levels of endemism. Often, very little is known about the hydrology and ecology of these systems, but they are also some of the rivers undergoing the most rapid change due to human activities. For example most of the hydropower potential in Chile is based in the south (Regions VII–XII) and preliminary proposals to develop some of these basins are already being prepared.

Adaptive management (Walters 1986) could be a mechanism for achieving watershed development together with preservation and protection of its ecosystems without burdening future generations with massive mitigation or restoration costs as experienced by Europe and North America. Conversely, Chile could assist more developed regions by developing an understanding of the degree of control it is possible to impose on rates of change within ecosystems at the opposite end of the development spectrum.

The structure and functioning of river ecosystems, particularly in the Northern Hemisphere and partly also in Africa and Australia, have been well investigated (e.g. Allan 1995; Petts & Calow 1996). However, by comparison scant attention has been paid so far to the ecological and geomorphic features of rivers from ecoregions west of the Andes which feature steep slopes, short river lengths, especially of the lower river sectors, volcanic influences, large seasonability in flows and sediment loads (Restrepo & Kjerfve 2000), well-marked transitions from rhithral to potamal conditions and highly dynamic behavior (e.g. Magaritz *et al.* 1989; Ruiz & Berra 1994; Focardi *et al.* 1996). Limited work has been done on the plankton ecology, taxonomy and distribution of aquatic biota

(Campos *et al.* 1993, Parra *et al.* 1993; Valdovinos *et al.* 1993), sediment characterization (Cisternas 1993), hydrology and water quality (González *et al.* 1999).

One of the most significant watersheds in Chile is the Biobío (Figure 1). Little is known about the ecological and subsequent socioeconomic effects of the unrestricted use of water from Laja Lake, Laja River and Biobío River on the functions of the river ecosystem. It can be assumed that on a spatio-temporal scale, the man-made fluctuations of water inflow into the Laja and Biobío Rivers from the hydroelectric power stations as well as the seasonal river water withdrawals for irrigation are the main factors affecting the rivers' ecology. These fluctuations often lead to extreme environmental conditions (e.g. short-term water level fluctuations) with a strong perturbation pulse and disturbance regime (Junk *et al.* 1989; Townsend & Riley 1999).

High water and peak flows have varied with far-reaching effects on the physiochemical and biological state

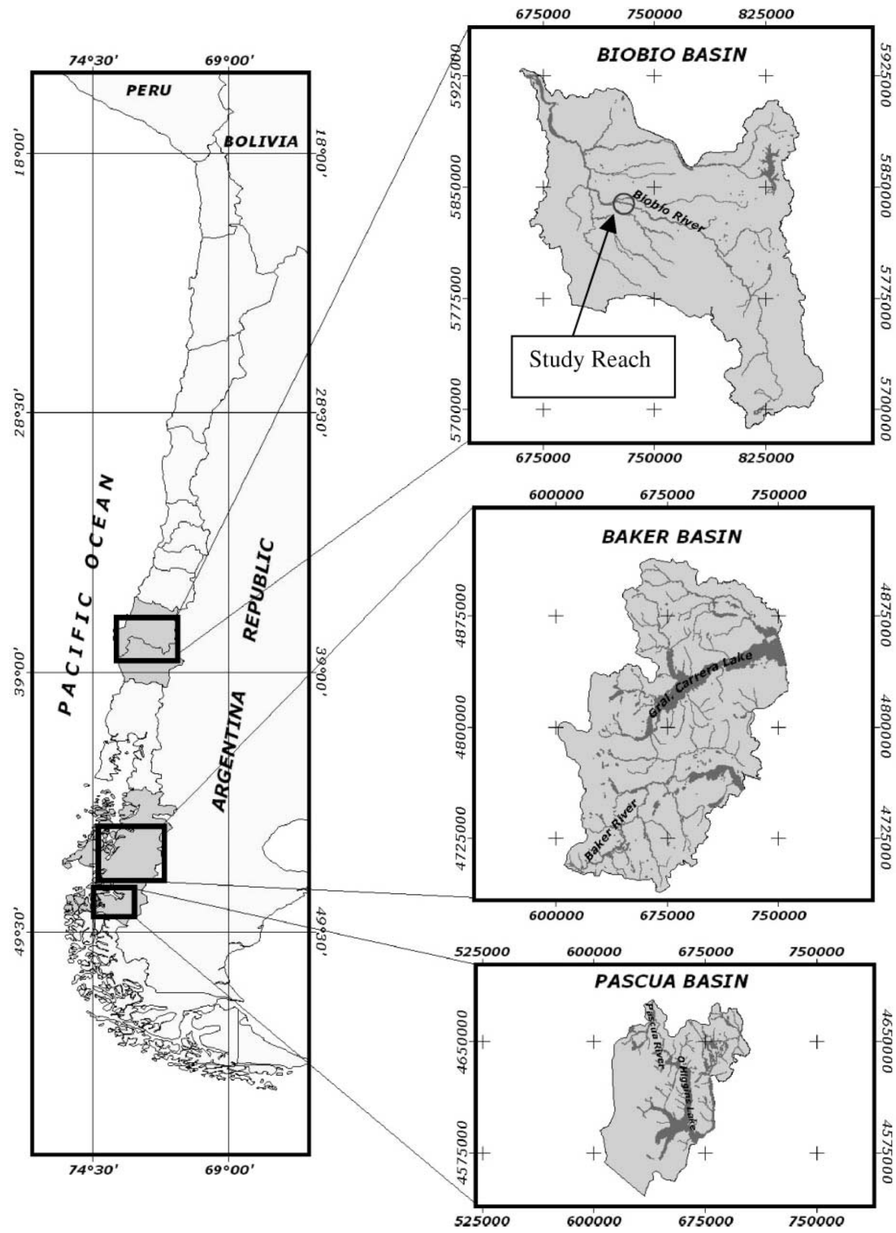

Figure 1 | The primary watersheds in Chile with hydropower potential – Biobio, Baker and Pascua.

and processes within the rivers. Due to the inclusion of flood plains and terrestrial areas, the fraction of allochthonous material entering the system increases (Rice *et al.* 1990; Eisma 1993). Low water levels are also a strong perturbation pulse on river ecosystems. The decline of water volume and wetted area, together with the concomitant changes, e.g. temperature, light, changing chemical characteristics, turbulence and flow pattern, decrease in volume-related ecological capabilities (for example, conversions of substances, self-cleansing ability) and ecological stability due to municipal, industrial and agricultural discharges (e.g. Aass & Kraabøl 1999; Bernado & Alves 1999; Karrasch *et al.* 2001, 2006), profoundly affect the ecology of the system but have not been adequately quantified in the Biobío and other systems in Chile.

The creation of reservoirs and the withdrawals within the course of a river all have dramatic consequences for the ecology of the river and generate a complex web of impacts, affecting the chemical, physical, biological, and human components of the environment (Petts 1984). The disruption of a horizontally oriented lotic system by a vertically structured impoundment, cancels out the diversity-enhancing effects of increasing physical and morphological heterogeneity along the river (Tramer & Rogers 1973). One important feature of reservoirs is the ability to trap and decompose particulate organic matter leading to ecological changes within the canal downstream such as an increase in photosynthetic production due to reduced turbidity. However, reservoirs can also export large numbers of living and moribund plankton organisms, replacing sedimented particulate organic matter (Petts 1984) or may even surpass by far the suspended organic matter compared to the upstream reach of the river (Spence & Hynes 1971), proving that reservoirs possess individual spectrums of biogeochemical behavior.

The limnological features of a solitary reservoir compared to consecutive reservoirs are quite different and have a far-reaching impact on the whole river system (Straskraba 1990). The first reservoir of the reservoir chain is fed by a free river, whereas the subsequent reservoirs mainly receive water which has been physiochemically and biologically processed by the upstream reservoir. The ecological consequences of alternating lotic and lentic ecosystems have yet to be thoroughly investigated.

The fluxes of matter and energy within the aquatic system are mediated by microbes, and their metabolic diversity and activities play a leading role in various biochemical cycles (e.g. Cole *et al.* 1988; Sherr & Sherr 2000), as well as enabling most ecological capabilities such as the degradation of organic carbon, nitrogen and phosphorus compounds (microbial self-cleaning power), the elimination or fixation of nitrogen, and the detoxification of harmful substances. Although the damming of rivers has occurred on a large scale, the far-reaching socio-economic consequences for the microbial conversion of substances, the mediation of material and energy fluxes, the degradation of organic matter and self-purification processes within reservoirs and reservoir series have not yet been well investigated and understood.

Sociopolitical and socio-economical concern for river systems has emerged mainly due to pollution problems, although nowadays there is growing social interest in ecosystem sustainability, on the one hand jeopardized but on the other hand favoured by increasing demand, e.g. hydropower and irrigation for a rapidly growing population, especially in newly industrialized countries. Although concepts of sustainable river management and restoration have been published in large numbers for rivers in Europe, Australia and North America, for example Boon *et al.* (1992), Harper & Ferguson (1995), Naiman & Bilby (1998), Nienhuis *et al.* (1998), and Brizga & Finlayson (2000), they are not available in many regions facing intense development such as Patagonia in Chile.

UNFORESEEN ENVIRONMENTAL ISSUES

To understand the flexibility that is required within a management program, some unanticipated responses of large dam projects need to be reviewed. The benefits of large dams in the early stages were relatively easy to quantify. Hydropower, irrigation and flood storage were analyzed primarily based on a mass balance approach related to timing and delivery of water. Any downside of these projects, if acknowledged at all, was approached from the perspective that every problem had an engineering ‘fix’.

Research during the past three decades is just beginning to reveal the true complexities and linkages of watershed ecosystems, and how rivers are affected by dams and impoundments. Fluvial ecology and geomorphology came of age in the 1970s and many consider that the discipline of regulated river ecology started at the *First International Symposium on Regulated Streams* (Ward & Stanford 1979). Before that, the few papers dealing with dam impacts were mostly concerned with specific issues such as anadromous salmonid migration or water quality. Ackermann *et al.* (1973) and Baxter (1977) provide a compilation of papers and a review of the earlier literature on environmental effects of dams, more focused on the changes caused within the reservoir itself, while Petts (1984) can be considered the first comprehensive textbook on environmental management of impounded rivers.

Environmental effects of dams can be classified by subject themes and/or environmental components: examples include impacts on hydrology, morphology, fish, phytobenthos and also within a hierarchical framework of causality (barrier effects or multiple order impacts), which improves understanding of the complex interactions between factors and scales (Petts 1984). Acknowledging this extensive body of work, the approach adopted here is based on scale and location, and thus considers downstream, upstream, basin-wide, and coastal, as well as global impacts.

DOWNSTREAM IMPACTS

The effects of dams on the flow regime and sediment transport, with the concomitant downstream geomorphic changes have been recognized and anticipated for several decades (see, for example, Simons & Senturk 1977). Typical possible responses include reduction in channel bed slope downstream of the dam, encroachment of riparian vegetation, decreases in the channel's conveyance capacity, changes in channel pattern or style (for example, from braided to meandering), and degradation of the river bed.

A less obvious effect is that the decrease in large flooding events can result in a loss of biodiversity. The landforms in a river corridor, and the vegetation able to colonize them, if any, which together provide habitats for aquatic and riparian species, are not fixed in space and time, but change continuously due to their interaction with the river. This shifting habitat mosaic, created by flooding disturbances, is a fundamental component of a healthy river ecosystem (Stanford *et al.* 2005). If the rate of physical change within the river corridor is decreased, the river system becomes more homogeneous, as the existing vegetation stands mature and fewer species dominate. The replacement of the original, changing, heterogeneous habitat mosaic by a uniform corridor results in a loss of ecosystem diversity and resilience, because different aquatic and riparian species require a diversity of habitats, with different species and uneven stages of growth.

The ecological impacts of dams show some striking generalities worldwide (Petts 1984; Stanford *et al.* 1996; Wirth 1997; Schmidt *et al.* 1998):

1. *Habitat diversity is substantially reduced*. Flow and sediment régimes are drastically affected, so that the fluvial dynamics that create heterogeneous channel and floodplain habitat patches are altered. The longitudinal connectivity is interrupted by the dam barrier. Seasonal flow variability is reduced, but daily discharges can be highly variable. The natural temperature regime is lost because of hypolimnetic releases. Dewatering severs the longitudinal dimension and can cause high mortality of aquatic organisms through stranding. The lack of flooding allows vegetation to encroach upon the channel and the riparian zone then becomes less diverse.
2. *Native diversity decreases while exotic species proliferate*. The altered hydrologic, sediment, and temperature regimes do not provide adequate environmental conditions for most native species. Conversely, the homogenization of habitats allows exotics to compete better. For example, some desert fish species are adapted to extreme flow and temperature regimes. They fare well where no exotic species could survive, but if a dam regulates flow conditions, then the non-natives can invade and out-compete the native species, driving them to extinction.
3. *Water quality is altered downstream of the dam*. Alterations to the temperature regime and increases in the fine organic material are often anticipated during project design but the severity of the problem was frequently underestimated (d'Anglejan 1994).

It must be noted that in some cases, productivity can be enhanced by the changes, for example when a highly variable flow regime is regulated into a constant discharge year-round. In this case, a handful of species can reach large population numbers, but this is always matched by a decrease in diversity, due to the extirpation of many other, rarer species, that depended on the temporal variability of the flows, and the associated spatial variability of the habitat, for their survival.

UPSTREAM EFFECTS

Sedimentation issues are not confined solely to the reservoir and downstream reaches. The backwater reach can extend many miles upstream of the reservoir. The depositional environment immediately following implementation is confined to the delta region at the head of the reservoir. As this delta builds up, additional sediment is deposited in the upstream reach of the river due to the backwater effect. The aggradation in the reach in turn raises the local water surface elevations, creating additional backwater and deposition even further upstream. This feedback mechanism allows the depositional environment to propagate much further upstream than the initial hydraulic backwater curve might suggest. Upstream effects include effects to the benthic communities due to deposition as well as the obvious barriers to fish migration corridors. Conversely, the effects of the backwater due to dams is the potential drowning of natural migratory barriers within a basin, promoting the spread of some fish species beyond their pre-project domains. For example, the Itaipú reservoir inundated Guayara Falls (Brazil/Paraguay) and eliminated a natural barrier which had prevented fish from the Upper Paraná spreading through the lower watershed. Conversely, in other parts of the world, dams are being used to protect native headwater species from harmful exotics. In Colorado, dams are used to isolate native greenback cutthroat trout from mixing with the larger, more aggressive, introduced brook trout (Pringle 1997). However, reservoirs can pose risks to headwater streams if facultative river species move up through a watershed, displacing local populations. Such an example occurred above the 200 m deep Dworshak Reservoir (Idaho, USA), where redside shiners (*Richardsonius balteatus*), although native to the system, developed very large populations of robust individuals in nearshore waters of the reservoir that were far more abundant than the original river populations. Adults would subsequently travel far upstream for spawning, competing with the native cutthroat trout populations (Falter *et al.* 1979).

Another key issue related to large dams is rooted in conservation biology theory. If the fluvial system is stressed too far by the implementation of large dams, the ecosystem may not be able to recover from major natural perturbations such as droughts, fire, tributary ‘blow-outs’, or episodic flood events. If there are insufficient stronghold watersheds with robust populations remaining in the system, then these types of natural disturbance could extirpate some species (Rieman *et al.* 2000).

BASIN-WIDE EFFECTS

Alteration to the nutrient balance is not solely restricted to downstream reaches. Recent research (Bilby *et al.* 1996; Cederholm *et al.* 1999; Soto *et al.* 2006) has demonstrated the role of Pacific salmon and other anadromous salmonids in transporting marine nutrients across ecosystem boundaries, from oceans to headwaters. Fish behavior is also influenced by changes in the hydrologic regime, for example by creating shifts in physical cues that affect the timing of the migration.

COASTAL ZONE EFFECTS

Most regulated rivers diminish or alter the timing of freshwater outflow to bays, estuaries and coastal wetlands with resulting negative impacts (Rozengurt & Haydock 1993). One well-documented example of additional stresses created by dams and water diversions pushing an ecosystem toward collapse has been documented in San Francisco Bay (Nichols *et al.* 1986; Williams 1989). In the extreme drought of 1977, release of water flows controlled by upstream reservoirs dropped to 100 m^3/s from the customary dry season discharges of 400 m^3/s. This reduction in freshwater inflow contributed to a drop in phytoplankton biomass to less than 20% of normal, with zooplankton also significantly reduced. These conditions resulted in striped bass, one of the key indicator species of the health of the ecosystem, being reduced to the lowest recorded levels.

SENSITIVITY IN COST–BENEFIT ANALYSES

Traditionally, reservoirs have been designed for optimizing the cost–benefit ratio of the project and various methodologies appeared extensively in the literature through the 1970s and 1980s (see, for example, Loucks *et al.* 1981). This approach represents a logical and defensible approach to the engineering and economic aspects of the project. These computations were undertaken from the best available flow records, sedimentation predictions, reduction in flood damages, power generation, irrigation deliveries and municipal usage.

However, out of necessity many projects were designed with incomplete or short record data. Very few of these analyses consider a sensitivity analysis that was then verified periodically following implementation.

CHANGING SOCIETAL VALUES DURING THE DESIGN LIFE

A large dam is a massive structure that is not a static fixture in the landscape, but is also capable of dramatically altering the landscape during its design life (McCully 2001). The physical and ecological changes are described above. However, given the long design life of these structures it is probable that the political and societal values may change. As an example, many of the first large dams in the Western USA were developed to break the society out of an economic depression. The creation of jobs, cheap power and delivery of irrigation water fueled the economic recovery. During the past two decades, societal values have shifted toward environmental preservation and enhancement, which is reflected in legislation such as the Clean Water Act and Endangered Species Act (ESA). Many countries do not currently have such strong legislation to balance extractable resources, environmental values and quality of life for people living in the impacted regions – but global perspectives are changing. These changing societal values and implementation of laws can exert considerable restraints on operations of large dams.

ADVANCING TECHNOLOGIES FOR MANAGEMENT ACCOUNTABILITY

A major issue surrounding large dam projects is the question of management accountability and whether the routine operation is linked back to the original project objectives, mitigation requirements and project performance. Another variation on the difficulties in managing the reservoir is that the responsible entity may represent only narrow interests. For example, urban water users, industry and agriculture may exert disproportionate influence compared with flood management or the benefit to the individual farmer or small communities.

Recent advances in technology can play a significant role in improving management and engaging communities through simulation-based engineering to assist decision-making. Improved sensor technologies and computer models facilitate real-time forecasting. For example, the use of NEXRAD, snow pack telemetry and satellite imagery can be used to gage the flood risk and provide flood warnings with greater lead times. Integration of aerial or satellite imagery, geographical information systems and hydrodynamic/water quality models allow complex issues to be evaluated and different interested parties to pose “what-if” scenarios. The emergence of internet based technologies allows agencies and local communities access to meteorological, hydrological data, predictions and feedback on current conditions, forecasts and summaries of past management decisions as well as being able to participate remotely (Mynett 2002). This technology of course assumes that there is the ability to represent all interests fairly in the decision-making structure and all interested parties have ready access to the technology. However, the rapid development of the internet facilitates dissemination and cyber-collaboratories host communication on complex natural resource projects.

FLEXIBILITY IN OPERATIONAL RULES

One of the most publicized re-operation studies in recent years has been the artificial flooding program at the Glen Canyon Dam in the Grand Canyon, USA (Wirth 1997; Schmidt *et al.* 1998). The installation of the dam has had numerous downstream effects such as beach erosion, changes in the vegetative characteristics along the channel and native fish species have either disappeared or been pushed to the brink of extinction. This bold initiative was to create an artificial flood to restore some of the physical characteristics of the channel, in the expectation that vegetation recovery would follow. Although this is a continuing experiment, this type of strategy shows great promise to minimize and halt progressive ecological damage in the downstream reaches of large dams. In fact, the issue of Environmental Flows is receiving considerable attention in the ecohydraulics community around the world.

Barriers to developing revised operational rules through adaptive management or reservoir re-operation studies are frequently encountered in multi-objective reservoirs. Institutional difficulties may be encountered due to the missions of different agencies, contractual limitations established in the planning phase of the project when little was known about the true performance of the project and legal issues such as water rights or the liability associated with flooding.

This list of unforeseen problems, selected from an extensive literature, would suggest the value of developing a comprehensive checklist of experiences encountered in large projects around the world, as well as establishing protocols for assessing trends, anticipating rates of change and implementing adaptive management strategies. Furthermore, the scope of the monitoring should include assessment of the entire system despite the challenges of scale and complex and non-linear relationships between river hydrology, morphology, ecology and socio-political factors.

EXAMPLES OF THE DIFFICULTIES IN IMPLEMENTING SUSTAINABLE BASIN MANAGEMENT – THE CASE OF PATAGONIA IN CHILE

The hydropower development within Chile is currently primarily within the Biobío river basin which has a drainage basin of 24 260 km^2 and a mean annual flow of 960 m^3/s (the second largest in Chile after the Baker), and is considered to be the most important hydrologic system in Chile, in terms of water use. It is also one of the most disturbed large rivers in Latin America due to flow regulation for hydropower generation, water withdrawal for irrigation, the disposal of industrial and urban effluents and other anthropogenic impacts whose cumulative ecological effects have not been evaluated. The river is also an important source for drinking water, is used for many industrial processes including pulp and paper mills, refineries and steel production but also has an important role for recreation and culture (Parra 1996; Parra & Meier 2003).

The Biobío basin is one of the main agricultural areas in the country with over 220 000 ha of land irrigated. Total withdrawal basinwide is approximately 250 m^3/s during the dry season. Large sectors of the basin have been planted with exotic pine and eucalyptus which has resulted in a reduction of base-flows and require significant summer water diversions to irrigate agricultural areas. The forestry and pulp industry produces 1.4 million tonnes of cellulose per year (this figure will double by the end of 2006) through three pulp mills and three pulp/paper plants, which add treated and untreated discharges to the Biobío River. Domestic wastewaters from a population of about 1.0 million people are discharged to the river and its tributaries, with about 80–85% receiving some level of treatment.

The total flow diverted for drinking water is insignificant in terms of quantity, but the quality affects over 700 000 people in the lower basin. The water quality concerns are most severe in the low-flow season, when streamflow at the mouth of the river, in the city of Concepción, can be as low as 120 m^3/s and upstream urban and industrial discharges can be detected in the lower reaches (Parra 1996; Parra & Meier 2003). Water quality problems are also compounded by the daily flow fluctuations introduced by the Pangue dam. Eight hydropower plants are located within the Biobío basin, with a total installed capacity of 2480 MW, and two smaller plants (32 and 60 MW) are under construction. With 53% of the installed hydropower capacity of 4700 MW, the Biobío basin is by far the most important contributor to Chile's electrical grid (total capacity of 8300 MW).

Pangue and Ralco Dams

The Pangue and Ralco dam complex (the latter fits the definition of a major dam) were completed in the Upper Biobío River in 1996 and 2004, respectively. Considerable controversy surrounded the construction of these mega-projects, mostly regarding the social effects on the local Pehuenche people, but also with respect to their environmental impacts.

The Pangue dam is 115 m tall and impounds a 5.1 km^2 reservoir with a primary purpose of load following regulation. The powerplant has 450 MW of installed capacity, generated by two Francis turbines with a nominal flow of 250 m^3/s each. Ralco is a 155 m tall dam, located upstream of Pangue reservoir, forming a 34.7 km^2 impoundment, with a volume of $1200 \times 10^6\, m^3$, of which $800 \times 10^6\, m^3$ are for regulation. The powerhouse is located about 7 km downstream of the dam, resulting in a total head for the project of 175 m, generating 692 MW at the design discharge of 368 m^3/s. It also has two large, equally-sized Francis turbines. An extra 32 MW are generated at the dam site with the mandated 27.1 m^3/s minimum instream flow. In 1992, the Universidad de Concepción was asked by Chile's House of Representatives and the Courts to comment on the Environmental Impact Assessment (EIA) for Pangue dam.

Meier (1992, 1993, 1995) found the Pangue EIA conclusions to be inadequate. Only potential impacts in the impoundment area were evaluated and the Biobío river downstream of the dam was not considered as an impacted area. No design or operational alternatives to hydropeaking were considered. Impacts were evaluated for long term average hydrological conditions instead of evaluating ranges of scenarios. No cumulative effects were evaluated despite being the first in a proposed series of five dams. The report was based on limited (except for hydrological) data, and many issues, such as the downstream routing of flow fluctuations, their effects on fluvial and riparian communities, on water quality, on irrigation diversions, fish migration patterns, and reservoir effects on turbidity and temperature, were not considered.

The only mitigation that was carried out was reforestation, in order to replace the native forests that were inundated. Additional study needs and possible mitigation measures were also discussed in Meier (1993) and included fish passage, operating Pangue as a run-of-the-river plant, reducing flow fluctuations, and recommending an alternative design, based on unequally-sized turbines, that would allow for generation with low summer flows, without the need for hydropeaking. Multiple-depth intakes were also proposed to facilitate selective withdrawal for developing some control over the temperature of releases or for sediment pass through.

LEGAL AND PLANNING FRAMEWORK

The implementation of the Pangue project occurred before Chile enacted environmental laws (the utility had acted on its own initiative when submitting the EIA), and faced with potential energy rationing there was little political will to impede additional energy production.

Things were different for Ralco, as legislation mandating EIAs had been enacted in Chile. Nonetheless, because of the nascent environmental programs regarding environmental impacts of dams, little was mandated in terms of environmental studies, mitigation, and monitoring. The only major difference with respect to Pangue was that a constant minimum instream flow was mandated in the dewatered reach between the dam and the powerhouse tailrace. The value was determined to be 10% of the mean annual flow at the site or 27.1 m^3/s. Other critical elements, including flow fluctuations downstream of the powerhouse, fish migrations, water quality changes and temperature regime, received only cursory attention.

However, the emerging environmental protection programs are following a steep learning curve and the official Environmental Resolution for Ralco Project prescribed a monitoring program to cover the impacts of both Ralco and Pangue dams. The problem is that the monitoring programs for large dams do not consider adequate temporal and spatial scales to understand river processes. For example, only three or four surveyed cross-sections are monitored regularly over a downstream reach of more than a hundred kilometers. This sparse data is inadequate for quantifying the relative contributions of different causal effects – many of which may have not be induced by the Ralco–Pangue complex.

When utilities initiate the environmental permitting process for a new hydropower development, they propose to the authorities which variables should be studied, as well as the sampling locations and frequency. Without formal baseline surveys of the river basins, the impact area and issues addressed are fixed *a priori.* Thus, potentially important impacts described above, such as the effects of sediment and organic matter retention on the coastal zone, the ecological changes caused by the longitudinal discontinuity, the changes in fish population genetics introduced by the barrier, and the morphological and ecological impacts of short-term flow fluctuations, are eliminated from analysis from the initiation of the process.

Environmentally-sensitive sustainable projects in Chile are hindered by the "old approach" for planning the development of large hydropower projects (Oud & Muir 1997): an anticipated future demand for power needs to be covered in the "least-cost" manner. Alternative technical solutions are developed, the "least-cost" option is selected, and then – in theory at least – the environmental and social impacts of the chosen "technically and economically optimal" design and operation are mitigated. The "least-cost" is obtained from the perspective of the private utility with large discount rates and social and environmental costs as externalized except for those requiring mitigation as mandated by the public agencies. In this way, it is very difficult, if not impossible, to obtain environmentally-friendly projects, as exemplified with the turbine design and operation for the Pangue dam. Moreover, as has been shown in the USA, mitigating impacts *a posteriori* through retrofitting dams or conducting restoration can be a very expensive proposition.

The obvious solution to this planning problem is to adopt what Oud & Muir (1997) call the "*new planning procedure for large dams*" which involves all stakeholders and takes into account technical, economic, financial, environmental, social, institutional, political and risk factors as early as possible in the planning stage to ensure broad acceptance of a project. Interested parties jointly formulate a limited number of alternative plans to cover the future power demand. These alternatives should consider potential social and environmental impacts, and include demand-side measures (e.g. energy conservation) as well as the no-project option. Studies are then carried out to identify the consequences of the different alternatives. A consensus among stakeholders on what is the "best" project, i.e. that with the maximum acceptance or the least regret (IUCN–World Bank 1997). This approach requires both independent and unbiased experts to carry out the studies and the monitoring, as well as facilitators, in order to reach consensus. New environmental sensors and simulation tools being developed within the hydroinformatics and ecohydraulics communities can be essential in assessing the best project and then evaluating the project performance to ensure expectations are met.

Oud & Muir (1997) aptly describe the planning process works in Chile, when they write "In developing countries, however, decisions on development options have generally been taken in isolation by governments and utilities, together with the international funding agencies, following the previously mentioned least-cost approach."

In the last two decades, Chile has experienced strong economic growth, which has been mostly supported by natural resources, where water has played an important role. Water resources development has occurred in a piecemeal way, driven by short-term and local interests. This problem is compounded by the complex water rights law (Bauer 2004) and the fact that at the national level private water rights prevail over all surface waters except in Regions XI and XII. Sustainable management of water resources to ensure the most efficient use of water, whilst protecting fisheries and the broader ecosystem, requires both private and public sectors collaborate to establish basin-wide organization dealing with water resources planning and management. There is consensus that the Chilean economy will not be able to keep growing at past rates if the current water management problem is not addressed.

Chile now faces a new energy crisis with the strong economy and the addition of new mining projects into the Central Interconnected System (electricity grid) expected to generate a mean annual increase in demand for the period 2008–2017 of 6.8%, therefore doubling the current demand during the next 10 years. Attention is inevitably focusing on Patagonia due to its hydropower potential 8000 + MW that could meet the needs of the southern part of the continent. However, these sites are contained within the unique and fragile ecosystem of Patagonia. There is currently no comprehensive overall national energy plan and power generation, transmission and distribution are within the private sector. There are no incentives for energy conservation; indeed, the framework fosters consumption. Currently, only 20 MW are generated for local use but the Pascua and Baker Rivers (Figure 1) maintain relatively stable flows of approximately 600 and 900 m^3/s, respectively. The need to evaluate Patagonian ecosystems in their current condition (pristine or very low human intervention) and to develop the sensor networks and predictive models is an urgent task.

DEVELOPMENTS IN MEASUREMENT TECHNIQUES AND SIMULATION MODELING

Part of these shortcomings can be explained by the lack of data or information on which to base decisions. However, the development of new technologies is allowing data to be collected in a cost-effective manner at unprecedented temporal and spatial scales. Although these technologies cannot directly generate detailed data on historic conditions, they can provide a very detailed picture of existing conditions. In the US, these new sensors can be classified as physical, chemical and biological sensors (Arzberger *et al.* 2005). The emergence of nanotechnologies allows not only miniaturization and reduced power requirement of measurement equipment, but also offers potential for rapid impact detection while refresh cycles allow sampling at unprecedented spatial densities and temporal scales. At larger scales the application of satellite technologies or airborne detectors such as green LIDAR offer unprecedented accuracy in detecting shifts in vegetation cover, topography and channel bathymetry surveyed remotely (Mynett 2003). These factors taken together pose opportunities for data driven models that complement and have the potential of vastly improving predictive capabilities (Beck 2006). Examples of advances in interdisciplinary approaches are aquatic habitat simulation models. These models have been widely used since the early 1980s to assess instream flow requirements downstream of reservoirs or diversion schemes that change the hydrological regime or reduce discharges (Leclerc *et al.* 2003). Most of the applications have been focusing on fish species, but models to assess benthic habitats or floodplain vegetation habitats have also been developed and applied in a few cases (Jorde 1996). In general, these integrated modeling tools consist of two major components: a numerical hydrodynamic model, and a habitat suitability model. The habitat suitability model can be anything from a very simple univariate preference function (e.g. Bovee 1982; Jorde 1996), to more complex models that use, for example, multivariate logistic regression (Guay *et al.* 2000), fuzzy logic (Schneider & Jorde 2003) or neural networks (Brosse & Lek 2000) to describe the multidimensional physical niches that are suitable for certain fish species and life stages. Fairly complex models have been developed and applied to describe the potential for the development of certain types of floodplain vegetation based on a suite of spatially distributed physical processes (Burke 2006). Predominantly, aquatic habitat simulation models have been used to address fish habitat alterations.

In the past a number of cross sections were usually surveyed and used as "representative" for a reach of river but it has now become more common to survey river reach bathymetry from boats (sonars combined with DGPS) or through remote sensing technologies (e.g. water penetrating LiDAR) and develop 2D hydrodynamic models (Baptist *et al.* 2006). By combining the suite of physical parameters at a "location", e.g. a cell of a computational grid, with the habitat suitability criteria mentioned above, the habitat quality of that location can be determined. Visualization of those results in a spatially distributed manner yields "habitat maps". Figure 2 shows an example of habitat quality for juvenile *Trichomycterus areolatus* in one arm of a braided reach of the Biobio River at a flow of 50 m^3/s. The models are run for different situations depending on the scale and issue to be addressed. The visualization of habitat alterations over a year's time span and how habitat quality and distribution has been altered by reservoir operation and changed hydrological regimes is a powerful tool to demonstrate this type of environmental effect. In a next step, habitat quality as shown in Figure 2 is usually integrated over the reach considered (Figure 3), and a so-called "Weighted Usable Area" (Bovee 1982) or "Habitat Suitability Index" (Jorde 1996) is calculated (Figure 4). This number contains information on how averaged habitat quality in a river reach changes as a function of flow, or time, and how it is altered by an upstream reservoir or a diversion. Figure 4 shows discharges and habitat quality for *Trichomycterus areolatus* adult (TA-A), and juveniles (TA-J). The corresponding time periods between the top (pre-dam situation) and bottom (post-dam situation) diagrams in Figure 4 show the influence of Ralco and Pangue dams on flows and aquatic habitat quality for one of the native species living in the Biobio River. The gradual increase in habitat quality as flows decrease in the natural situation has been replaced by very strong fluctuations in available habitat. It is not clear yet what this means to the fish and further studies are on the way (Garcia-Lancaster 2006).

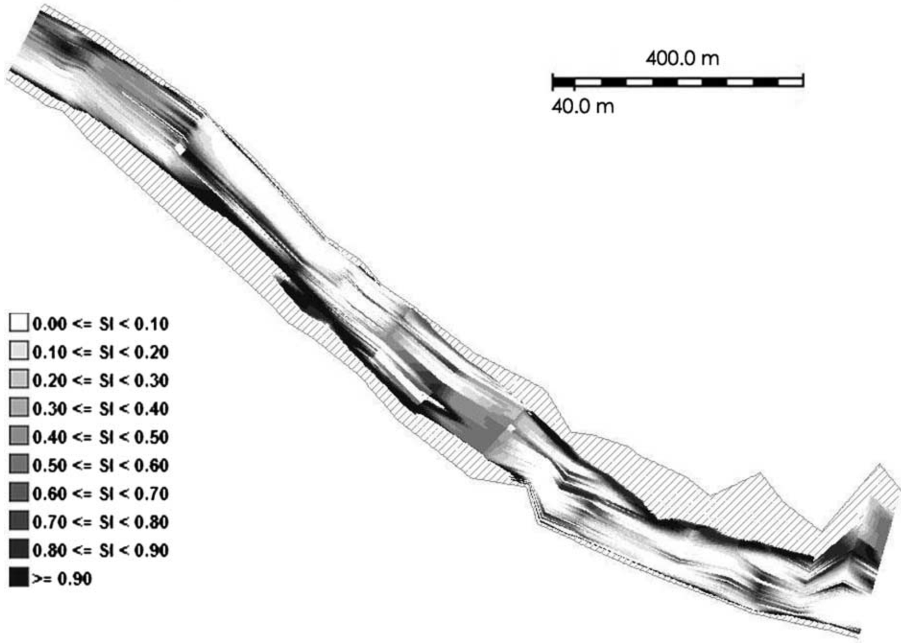

Figure 2 | Habitat map for *Trichomycterus areolatus* for one arm of a braided reach of the Rio Biobio in Chile, approximately 15 km upstream of Negrete, as part of a study to address ecological effects caused by the operation of the upstream Pangue and Ralco dams and reservoirs (Garcia-Lancaster 2006).

If such models are combined with general or individual based growth models for species they can even be used to predict how biomass or fish communities and abundance respond to alterations (Gouraud *et al.* 2004). Usually it requires many years of consistent fish data collection to develop, calibrate and validate such models. An additional problem is that many additional variables must be included such as water quality, food availability, inter- and intraspecies competition, in- and out-migration, effects of episodic events such as fire, landslides and major floods.

For Chilean rivers the first problem that had to be addressed was to fill some of the knowledge gaps regarding fish species native to Chilean rivers. Native Chilean fish species are relatively small and are not considered economically significant. Therefore, up to now little consideration was given to their fate following dam construction and reservoir operation. Also, nonnative salmonids have been widely introduced into Chilean rivers and estuaries for commercial fish production and angling tourism. However, along with the growing pressure on Chile's unutilized hydropower potential, fish scientists and ecologists have started looking at native fish species from a conservation perspective. For the Biobio and Laja Rivers, the fish inventory has been assessed and habitat requirements have been developed for some of these species (Campos *et al.* 1993; Garcia-Lancester 2006, Habit *et al.* 2006). Very little quantitative knowledge was previously available about what kind of physical habitat these fish use. Since the traditional models require large amounts of fish observations, which are difficult or impossible to collect, a combination of expert knowledge and empirical data was used to develop the habitat requirements based on fuzzy logic. The simulation model CASiMiR (Jorde 1997; Schneider 2001) uses fuzzy rules and fuzzy sets to describe the types of habitats that fish species prefer. CASiMiR was used to simulate habitat quality for a number of fish species and life stages in a braided reach of the Biobio River halfway between the headwaters and the mouth, approximately 15 km upstream of Negrete, which is considered representative for the braided part of the Biobio. Modeling was done to compare the pristine hydrologic situation with the one affected by the upstream Pangue and Ralco dams and reservoirs. Modeling results show that, under natural flow regimes, the habitat availability and suitability increases during the summer for Chilean native freshwater fish in the Biobío River, as the discharge decreases (December to

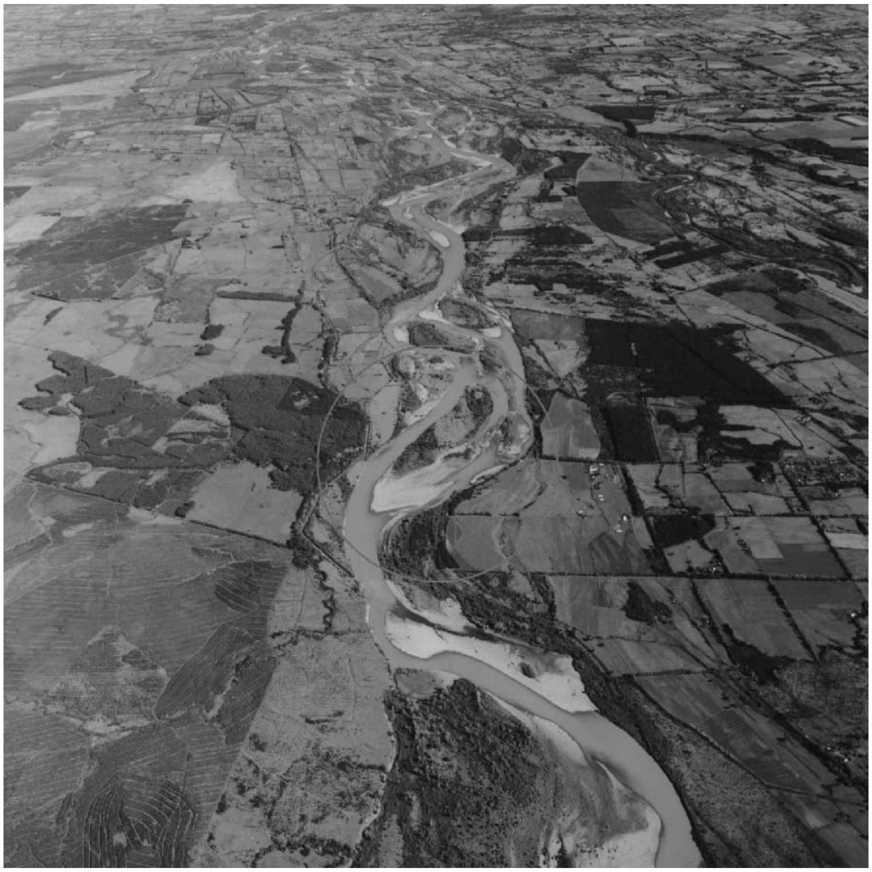

Figure 3 | The study reach on the Biobio. The circle corresponds to the study reach in Figure 1.

March, Figure 4). Under regulated conditions with Pangue Reservoir alone (2002–3), the habitat availability fluctuates with the hydrograph under the flow regime controlled by dam operation. Every hydropeaking event lowers the habitat availability and suitability for all fish species and restricts dramatically the habitat for benthic species. Additional changes were determined during 2004–2005 after the Ralco reservoir was filled and the dam started operation. The modeling results could be used to ecologically optimize the operation of the Ralco and Pangue reservoirs. Ralco is upstream from Pangue and has an annual storage capacity, whereas Pangue has only weekly storage capacity but could be used to minimize hydropeaking pulses caused by Ralco. The way the system is operated now, this is not the case.

In general, habitat simulation models give valuable quantitative information on how the physical habitat quality may change due to natural or anthropogenic changes in river bed morphology or the hydrological regime. But this is only a small component of the more complex spatiotemporal puzzle of the processes that drive the shifting habitat mosaic of riverine floodplain ecosystems. For a complete ecological assessment, results from habitat simulation models must be embedded in a larger scale assessment of hydrological regime alterations that influence all fluvial processes. Since comparably little is understood of the ecology of these fishes, especially the ones endemic only to one catchment, it is very essential to assess carefully what damage should be expected from any kind of activities that influences their habitat.

Integrated aquatic habitat studies are a perfect example where hydroinformatics and ecohydraulics are combined. Hydroinformatics provides the data collection and data analysis as well as computer-based modeling techniques

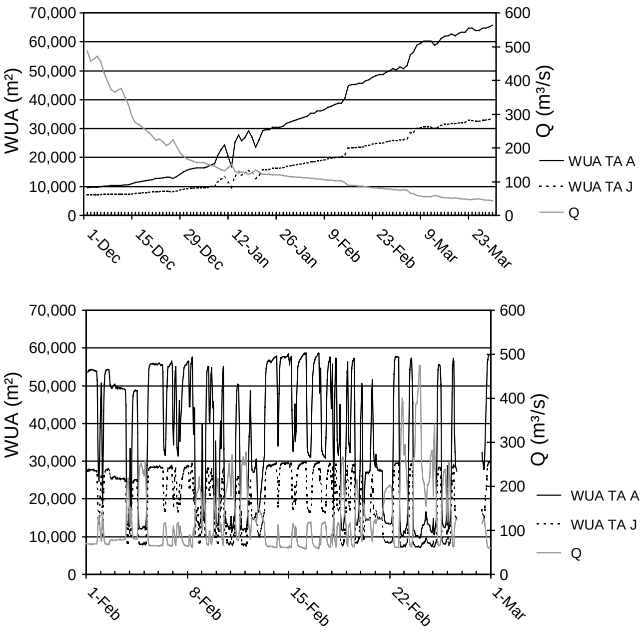

Figure 4 | The difference in discharge and habitat quality for *Trichomycterus areolatus* as Weighted Usable Area, WUA, in a comparison between pre- (top) and post-dam (bottom) conditions for similar periods of time (Garcia-Lancester 2006).

required, while ecohydraulics provides the interdisciplinary understanding of the interaction among biota and physical processes and the conceptual methods to describe these interactions and dependencies. The question is how these emerging technologies and modeling approaches can best be embedded into managing rapidly developing regions such as Patagonia in Chile – particularly in view of the lessons learned in other parts of the world.

ESTABLISHING PERFORMANCE CRITERIA AND EFFECTIVENESS MONITORING

The importance of monitoring after implementation of a dam has been stressed by Collier *et al.* (1996). Management of dams and rivers must take into account the dynamic nature of a regulated river. Adaptive management procedures should be developed to track these changes through time and to anticipate the need for refinements of the dam operation. As dam operations are modified, the downstream effects are to be tracked and integrated back into the dam's management plan. This adaptive management strategy can of course be extended to include upstream and regional effects.

CONCLUSIONS

River basins are immensely complex and much has been learned about ecosystem functions as well as benefits and losses due to river regulation. In so-called developed countries, considerable emphasis and investment is presently being placed on restoration of the natural functioning of river systems. Managing large river systems in Chile, such as the Biobío, presents particularly challenging problems because these ecosystems are poorly understood and are increasingly threatened from multiple anthropogenic stressors. Therefore, it is essential for the conservation and protection of these ecosystems to develop and implement management approaches and technologies to build the knowledge base and fully understand long-term consequences. Southern Chile is endowed with one of the most spectacular landscapes that draws tourists from across the globe and the clean natural waters have resulted in the least contaminated and largest salmon fishery industry in the world. The looming energy shortage in Chile threatens its vibrant economy and poses the challenge of how to develop sections of the region to facilitate economic growth without jeopardizing the quality of life or biodiversity. Chile has an advanced telecommunications industry and evolving cyberinfrastructure which will provide a platform for hydroinformatics and ecohydraulics technologies to guide policy makers in a sustainable future. A key to developing sustainable management strategies will be the implementation of new sensor technologies and the conversion of this data into knowledge, which is at the heart of the hydroinformatics and ecohydraulics disciplines.

Particular concern is focused on proposed large dams in Patagonia and the transfer of experiences from the Biobio and other regions to guide the location and design of new dams, while applying conservation theory to establish which areas should be protected. Despite the acknowledged severe potential impacts of large dams, there is no universally accepted methodology for monitoring the downstream, reservoir or upstream ecological responses of river systems (Ligon *et al.* 1995). Further, there appears to be no systematic monitoring and reporting of the benefits or impacts accrued by large dams. This monitoring could justify the original investment, develop knowledge that could be used in other projects and adapt operational rules to minimize adverse impacts while maximizing benefits. This systematic assessment of project performance should include:

- Clear performance criteria of the design objectives and sustainability of biological diversity.
- Implementation of a planning process that includes local communities and special interest groups
- Independent monitoring for performance assessment
- Processing of basic data to knowledge, or development of information that allows management actions to be taken.
- Validation of design assumptions.
- Documentation of any unforeseen consequences.
- Flexibility in operation rules to account for changing physical or socio-economic conditions.
- Application of adaptive management or direct feedback from monitoring to refinement of operational procedures.
- Accountability for dam operation and maintenance.
- Feasible decommissioning or refurbishment strategies developed prior to project implementation.
- Application of technologies to minimize public safety risks (Kuo & Yen 1999).
- Licensing of hydropower facilities with periodic review and license renewal.

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