RIVER RESEARCH AND APPLICATIONS

River Res. Applic. **20**: 865–882 (2004)

Published online 7 July 2004 in Wiley InterScience
(www.interscience.wiley.com). DOI: 10.1002/rra.788

GREEN HYDROPOWER: A NEW ASSESSMENT PROCEDURE FOR RIVER MANAGEMENT

CHRISTINE BRATRICH,[a]* BERNHARD TRUFFER,[a] KLAUS JORDE,[b,†] JOCHEN MARKARD,[a] WERNER MEIER,[a] ARMIN PETER,[a] MATTHIAS SCHNEIDER[c] and BERNHARD WEHRLI[a]

[a] *Limnological Research Center, Swiss Federal Institute for Environmental Science and Technology (EAWAG) and Swiss Federal Institute of Technology (ETH), CH-6047 Kastanienbaum, Switzerland*

[b] *Institute of Hydraulic Engineering, University of Stuttgart, Pfaffenwaldring 61, D-70550 Stuttgart, Germany*

[c] *SJE Schneider & Jorde Ecological Engineering, Viereichenweg 12, 70569 Stuttgart, Germany*

ABSTRACT

Hydropower is the most important renewable electricity source worldwide. It shows clear advantages for the global CO_2 balance but creates serious ecological impacts on a local scale. As a consequence, concern for the conservation of natural river ecosystems is growing within society and more people are willing to pay extra for so-called 'green electricity'. The definition of 'green', however, is not straightforward and customers cannot directly examine the quality of electricity products. Therefore, credible certification of high ecological standards is essential for successful green electricity marketing.

In this paper we introduce a new assessment procedure for evaluating environmentally compatible hydropower production. This so-called '*Green Hydro*' concept was developed in the context of a multidisciplinary case study on a 400 MW hydropower scheme in the Southern Alps of Switzerland. The concept guarantees both general standards for different schemes operating in different types of watersheds and flexibility for local particularities. We developed an environmental management matrix that considers basic criteria and eco-investments and covers five environmental areas of concern (i.e. hydrological character, connectivity, morphology, landscape, and biological communities). The ecological perspective is complemented by five management domains (i.e. instream flow regimes, hydropeaking, reservoir and bedload management, and power plant structures). Applying assessment and modelling tools for the *Green Hydro* procedure showed that dynamic habitat models allowed quantification of the effects of different instream flow regulations at morphologically distinct sites. In this case, morphological restoration could be more beneficial than increasing the minimum flow.

The first experience with the *Green Hydro* certification is encouraging. So far, 13 facilities have successfully passed the certification procedure. They produce a total of 186 GWh green electricity per year, which is sufficient for the supply of almost 40 000 households in Switzerland.

KEY WORDS: green electricity; hydropower; eco-labelling; river management; environmental impact assessment; certification; hydraulic modelling

INTRODUCTION

At the beginning of the 21st century, global electricity generation reached more than 15 000 TWh per year, about 60% more than in the early 1970s (IEA, 2002). Over 20% of this production is based on hydropower (IEA, 2001). The global installed hydropower capacity exceeds other renewable sources, such as wind-based, geothermal, or photovolatic production, by one to three orders of magnitude (IEA, 2001, 2002). Although greenhouse gas emissions from decomposing organic material can be substantial in reservoirs with large surface areas (St. Louis *et al.*, 2000), these problems are usually marginal in deep high-alpine storage reservoirs. According to life cycle assessments hydropower schemes in temperate regions produce an equivalent of about 3–4 t CO_2, 10 kg SO_x, and 10 kg NO_x per GWh (Frischknecht *et al.*, 1994; Kaltschmitt and Wiese, 1997). These CO_2 emissions are orders of magnitude lower compared to the CO_2 released by oil- or coal-fired thermal power plants (850 and 990 t CO_2/GWh,

* Correspondence to: Christine Bratrich, Limnological Research Center, Swiss Federal Institute for Environmental Science and Technology, CH-6047 Kastanienbaum, Switzerland. E-mail: bratrich@eawag.ch

† Present address: Ecohydraulics Research Group, University of Idaho—Boise, 800 Park Blvd, Boise, ID 83712, USA.

Received 1 April 2003
Revised 18 July 2003
Accepted 23 July 2003

respectively). Hydropower also compares favourably with nuclear power plants, because decommissioning is simpler and no hazardous waste is generated. In addition, many hydropower schemes serve not only for power generation but also for flood management, irrigation, or drinking water supply.

These advantages, however, are often counterbalanced by massive social conflicts and degradation of aquatic ecosystems. Since the middle of the last century the number of large dams (>15 m high) has increased rapidly. By the end of the 20th century, over 45 000 large dams in over 140 countries were completed (WCD, 2000). During the 1990s, an estimated sum of US$32–46 billion was spent annually on large dams, four-fifths of it in developing countries (WCD, 2000). Globally, the official number of displaced people ranged from 40 to 80 millions, whereas independent sources estimate that the actual number was much higher (WCD, 2000).

Almost 500 000 km^2 of land are inundated worldwide by reservoirs, and extensive habitat fragmentation caused by large dam projects affects nearly 60% of the major river basins worldwide (Gleick, 1998; Johnson *et al.*, 2001). Modifications of flow regimes, migration barriers, trapped nutrients or sediments, and dried-up floodplains caused dramatic ecological conditions in many of the affected river ecosystems (Friedl and Wüest, 2002; Pringle, 2001). Meanwhile, 37 out of the 55 major European rivers are strongly impacted by dams and other engineering schemes and only five can be considered as almost pristine (Hygum, 2001). Switzerland has the highest hydropower production rate per area in the world and about 60% of the inland electricity generation originates from this source (Truffer *et al.*, 2001).

As a consequence of massive social conflicts and ecological degradation the image of the hydropower industry has been damaged over the last two decades (McCully, 1996). Nonetheless, two driving forces reshaped the political arena recently: (1) the World Commission of Dams (WCD) proposed guidelines for new dam projects in developing countries (WCD, 2000); (2) the deregulation of electricity markets offered new opportunities for ecological upgrading of hydropower plants in industrialized countries.

As a key issue the WCD recommended that an individual assessment is needed to evaluate new construction options and non-dam options should be preferred whenever possible (WCD, 2000). In addition environmental, social and economic aspects should be considered equally and all stakeholders should be involved in the decision-making processes. Taking into account that these principles were accepted by non-governmental organizations (NGOs), the dam construction industry, the World Bank, and by private investors (WCD, 2000), the consensus report of the WCD represents a landmark achievement in international policy. The future success of this approach, however, will depend, among other factors, on the availability of efficient ecological assessment tools. Even though the WCD addresses problems with existing dams, the influence of the report remains vague for those countries with large installed hydropower capacities operating on long-term licences.

Here, the liberalization of electricity markets could support new approaches to minimize negative environmental impacts of the existing facilities. A compilation of data (Holt, 1997; Markard, 1997; Bird *et al.*, 2002; Greenprices, 2001) shows that the number of green electricity products involving solar power, wind, biomass and hydropower increased significantly during the last decade (Figure 1). Competitive markets allow environmentally concerned consumers to 'vote with their pocketbooks' (Raphals, 2001). Recent studies on market potentials concluded that

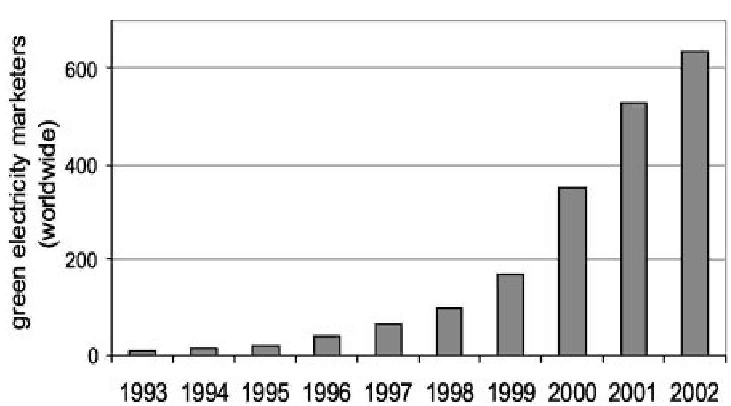

Figure 1. The worldwide number of green electricity marketers

about 20% of private households and customers in the service industry are willing to pay a surcharge of approximately 20% for green electricity (Truffer *et al.*, 2002b; Wüstenhagen, 2000). The definition of green electricity, however, is not straightforward and customers cannot directly examine the quality of the electricity production process. Therefore, credible certification or eco-labelling is essential for successful green electricity marketing (Raphals, 2001). Popular labelling concepts for hydropower use 'limits on the installed capacity' or the 'age of a power plant' as certification criteria. Some even accept hydropower 'generally as green', regardless of the ecological impact of the production process (Markard *et al.*, 2001). Such standards are definitely insufficient. Green hydropower should be labelled only on the basis of sound ecological criteria aiming to improve the ecological condition of the impacted river system. In addition, the certification of green hydropower should *not* subsidize new facilities but should be linked to money invested for restoration activities.

Surprisingly, none of the former labelling procedures considers this simple basic approach. The initial hypothesis of our project on green hydropower can therefore be stated as follows: if a credible certification procedure was addressing the mitigation of ecological degradation, then green hydropower marketing could directly contribute to improving the ecological performance of the most important renewable electricity source (Truffer *et al.*, 2003).

The present paper concentrates on the scientific objectives of the project and is organized around the following three questions. (1) How should an assessment scheme for green hydropower be designed to allow both general comparison among different facilities and individual flexibility for locally adapted restoration measures? (2) What are optimal scientific criteria and tools to assess local environmental impacts of hydropower production? (3) What are the opportunities and challenges of a *Green Hydro* certification for hydropower companies and river ecosystems?

METHODS

To meet the project goals we used three methodological approaches. (1) The relevant literature from river ecology and environmental economics was reviewed to define an appropriate assessment framework and to select ecological criteria for green hydropower. (2) Specific assessment tools were developed within a multidisciplinary case study on a characteristic hydropower scheme in the Swiss Alps. (3) Expert groups and stakeholder panels were established to generalize the results of the case study and make them applicable to other hydropower production settings.

Combining two perspectives in the literature

The assessment of the environmental impact of hydropower facilities usually takes either a management or an ecological perspective, with the two approaches often viewed as alternatives. Typically, techniques like life cycle or risk assessment concentrate on the *management of the power plant* and its resulting impact on the environment. Ecological assessment programmes, by contrast, evaluate the *condition of ecosystems*, generally without investigating the causes of negative effects. They apply a wide variety of methods to measure the ecological integrity of river systems but a detailed analysis of the hydropower scheme and its different management options is usually lacking. Both approaches—purely management- and purely ecological-driven methods—have limitations to establish an eco-label. Therefore, we combined the two perspectives to develop the *Green Hydro* procedure.

We based the conceptual framework for the certification on methods used for improvement analysis in industrial ecology, for risk management, life cycle assessment, and resource management (Graedel and Allenby, 1995; The World Bank, 1993; Wenger *et al.*, 2000). Procedural input came also from environmental impact assessment techniques and from standardized environmental management systems like the ISO 14001 or EMAS certifications (Cheremisinoff and Bendavid-Val, 2001; Edwards, 2001; Schaltegger and Sturm, 1995).

To create broad reliability for consumers, we selected two ecological assessment principles as relevant for a *Green Hydro* certification. The first principle focuses on abiotic driving forces like morphology, hydrology or hydraulics, assuming healthy biological communities result from intact habitat conditions (bottom-up approach: Kondolf, 1998; Muhar and Jungwirth, 1998; Naiman *et al.*, 1992). The second principle concentrates on species or communities and assumes that biological analyses can serve as integrative assessment tools. According to this

top-down approach temporal and spatial information about the integrity of an ecosystem can be indicated by biosurveys even when an environmental impact occurred a long time ago or far away from the local investigation sites (Karr and Chu, 1999).

In practice, bottom-up concepts characterize, for example, the 'River Habitat Survey' (morphology: Raven *et al.*, 1998) or the 'Range of Variation Approach' (hydrology: Richter *et al.*, 1997). Multivariate or multimetric procedures use aquatic species as indicators (e.g. DeShon, 1995; Hawkins *et al.*, 2000; Norris and Hawkins, 2000; Wright, 1995), whereas some assessment schemes apply both elements, e.g. the British SERCON (Boon *et al.*, 1997), the Austrian ÖNORM (Chovanec *et al.*, 2000), or the Swiss Stufen Modul Konzept (Bundi *et al.*, 2000).

Case study

Practical advice for hydropower owners on how to improve the ecological condition of their schemes needs standardized assessment tools. To select a set of appropriate tools, we performed a three-year case study in the catchment of the Brenno River (Canton Ticino, southern Switzerland; Figure 2). Here, the hydropower scheme owned and operated by the Officine Idroelettriche de Blenio company (OFIBLE) uses a head of more than 1500 m and a catchment area of 400 km^2 to generate 900 GWh electricity annually on average (Meier, 2002). Operating three production units the installed capacity reaches almost 400 MW. Water is collected in more than 20 intakes on the Brenno and its tributaries. The water is transported from the village Olivone via the Malvaglia reservoir to the Biasca plant near the Ticino River (Figure 2). The main stretch of the Brenno is strongly influenced by the hydropower scheme. Nevertheless, it represents a typical case for alpine hydropower use in Switzerland.

Almost 20 research projects were performed in the case study. The research was organized along four lines of activity: (1) instream flow regulations; (2) floodplain management; (3) market and policy analysis; and (4) criteria development (Truffer *et al.*, 2002a). Several subprojects tested and adapted analytical methods to evaluate the ecological impact of hydropower production in alpine river systems. Special emphasis was put on developing modelling tools to predict the effects of different management options on the ecological quality of river systems.

Generalizing the outcomes of the case study

Obviously, not all information needed to evaluate different types of hydropower production can be obtained from a single case study. Furthermore, to be accepted by hydropower owners an eco-label should offer an attractive return on investment and must therefore gain support of all relevant stakeholder groups. To generalize information and to increase acceptance we used parts of the 'cooperative discourse model' which relies on expert panels and participatory stakeholder involvement (Renn, 1999). In a two-day workshop the literature-based set of assessment criteria was peer-reviewed by an international expert panel composed of specialists in river management, river ecology, geomorphology, and civil engineering. This expert panel also suggested additional criteria to ensure the adaptation of the procedure to different river types and hydropower plants. Subsequently, the proposed set of green criteria was authorized by the Swiss Association for Environmentally Sound Electricity (VUE), an independent organization which is supported by Swiss hydropower companies, electricity suppliers, environmental NGOs, and consumer NGOs. To facilitate stakeholders' input regular meetings with federal agencies, private consultants, and hydropower companies have been organized right from the beginning of the project (Truffer *et al.*, 2003). The stakeholders helped to verify the overall perspective of the project, e.g. by reviewing environmental goals, green criteria, and assessment tools developed from literature surveys and case study results. Finally, all information was condensed in a comprehensive handbook for green hydropower production (Bratrich and Truffer, 2001).

RESULTS

Four steps towards the certification of green hydropower

As a result of the literature review we adopted a four-step approach for the *Green Hydro* certification procedure (Figure 3). First, the hydropower scheme wishing to be certified is asked to analyse its ecological performance and to estimate the costs for further studies necessary. This *screening* allows a 'go or no-go' decision (step 1).

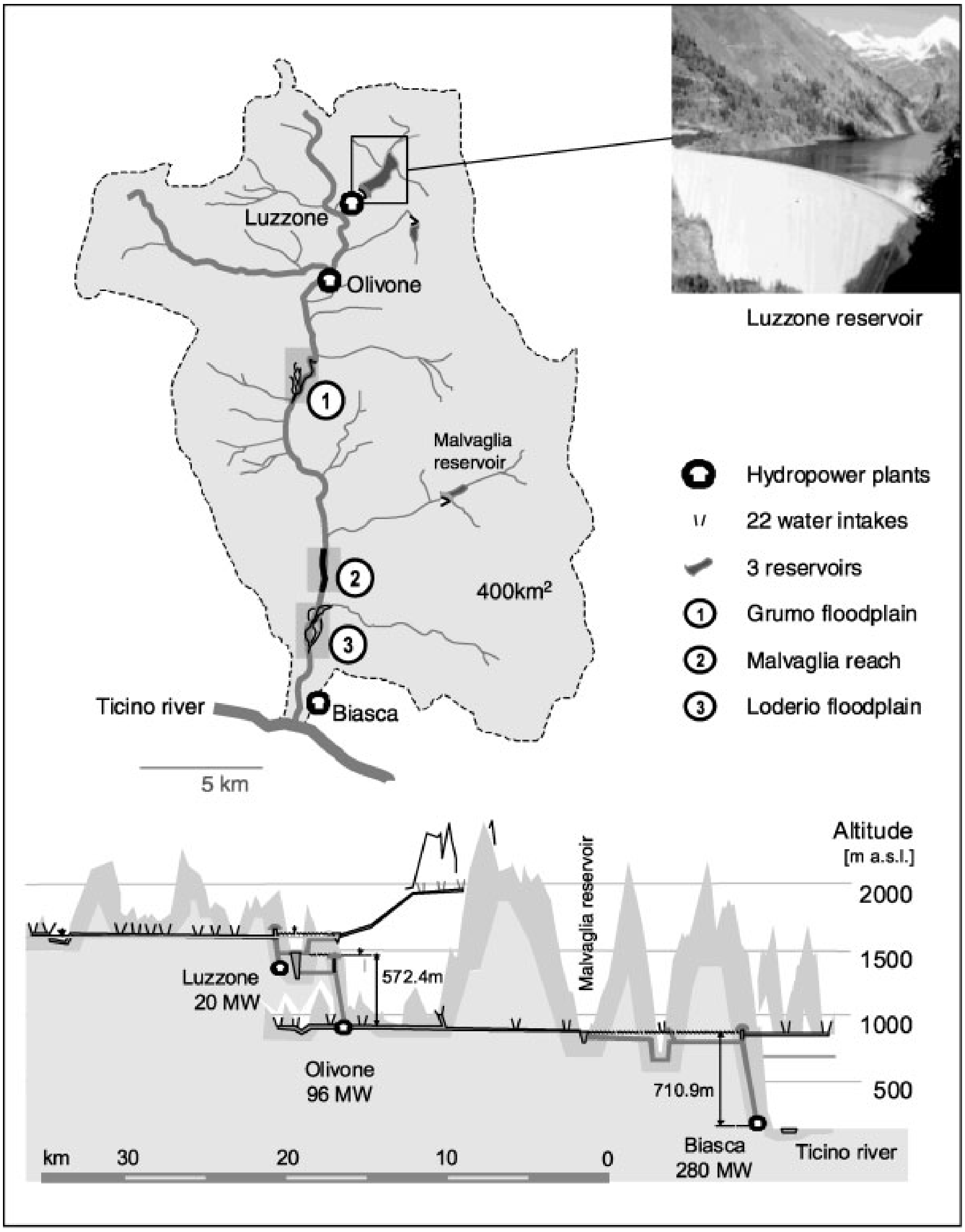

Figure 2. Map of the Brenno catchment in southern Switzerland showing the location of hydropower reservoirs, water intakes, and the main power plants. The location of the three main test sites for the case study are indicated with circles

It delivers information about serious environmental impacts and upgrading measures needed for a certification. If the company expects economic incentives and decides therefore to embark on the labelling procedure, then it has to take step 2 and develop a *management programme* based on two components: *basic requirements* and *eco-investments*.

The *basic requirements* are defined as a general ecological standard for all green hydropower producers. They allow a supra-regional comparable certification of different power plants, regardless of their age, size or how they are built or operated. Covering 45 scientifically defined criteria, the *basic requirements* are organized in a so-called *environmental management matrix* (for details see below and Figure 4). In this assessment stage scientific input

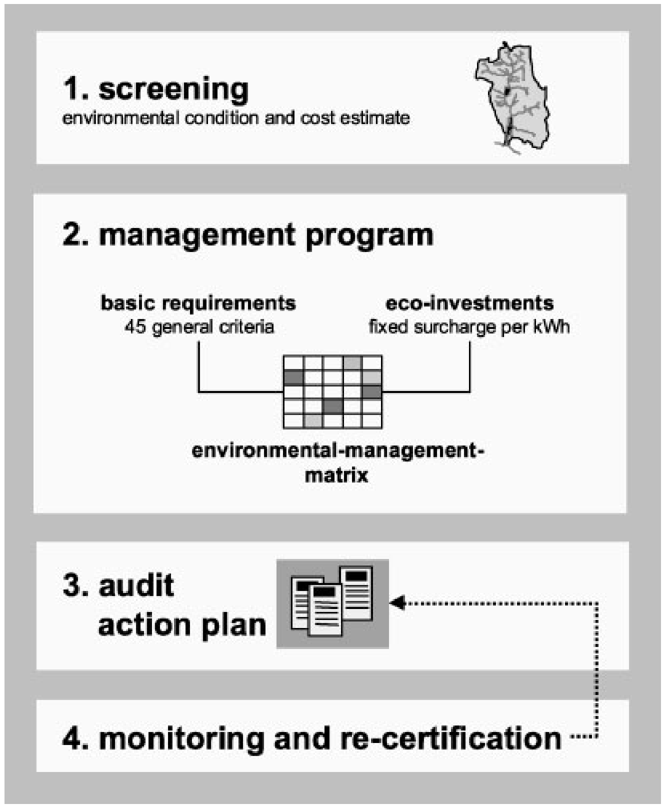

Figure 3. The step-wise assessment approach for the *Green Hydro* certification

from hydrologists, river ecologists, geomorphologists etc. is crucial, since the plant operators have to prove that the basic requirements are met.

In addition, a flexible instrument is intended to support an individual upgrading process of the hydropower schemes in their distinct catchment sites. This instrument is implemented in the certification process as so-called *eco-investments*. It is defined as a fixed mark-up on every kilowatt-hour sold as green hydropower. On an annual basis, this surcharge must be re-invested in the river system in the form of river restoration measures. Currently, the eco-investments provide additional money for restoration activities at a rate of 0.01 Swiss franc per kWh (about €0.006/kWh). The utilization of the eco-investments needs to be based on a catchment analysis. All measures should be specifically adapted to the demands of the individual river system. To guarantee the best local adaptation, they need to be prioritized by round-table decisions with local stakeholders and agencies.

As soon as a hydropower scheme meets both the basic requirements and a defined set of priorities for eco-investment activities, the management concept will be reviewed in a formalized *audit action plan*. This step 3 comprises an independent inspection of the facility and the river. It requires documentation prepared by an accredited company and by independent expert auditors. Once the scheme has been positively inspected, the eco-label can be granted. It is then up to the owner of the facility to use the eco-label as a marketing instrument to achieve higher prices for this electricity. Regular *monitoring* of success (step 4) will provide the basis for a *re-certification* after five years (Figure 3).

The environmental management matrix

The literature analysis allowed us to choose an assessment framework mainly based on the driving force concept but supplemented with a few indicator species such as fish and benthic organisms. Selecting specific criteria for green hydropower involves estimating the direct impact of power generation on the river ecosystem and its riverine

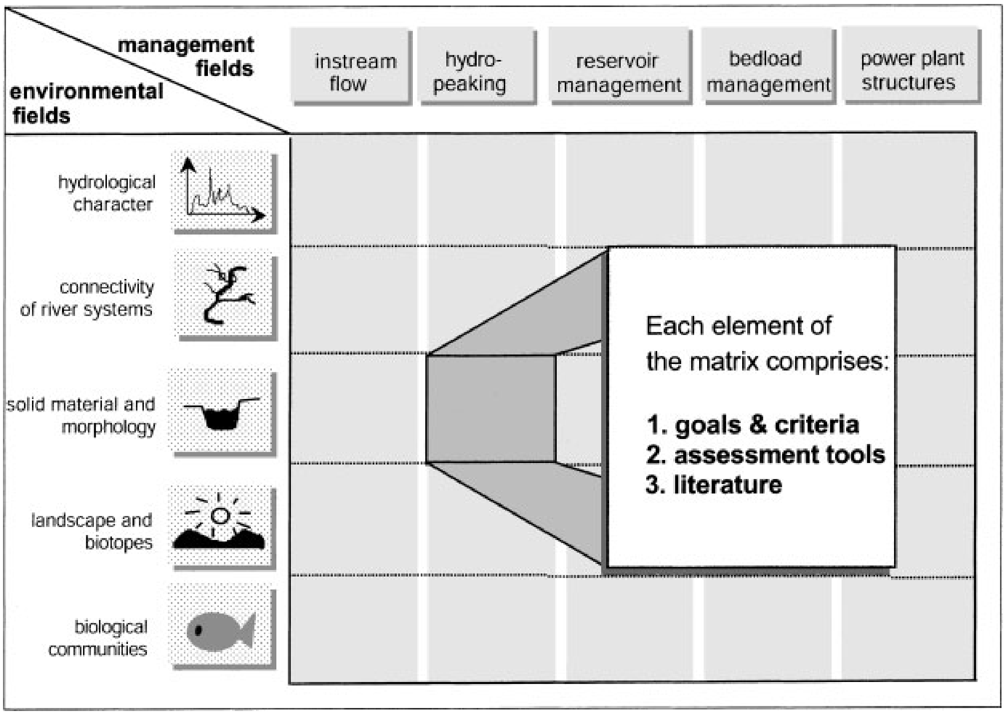

Figure 4. The *environmental management matrix* combines the perspectives of ecological river assessment techniques with know-how of hydropower management. Each matrix component contains the general goals, assessment criteria, and references in an annotated bibliography. The goals are outlined in Table I

landscapes. By combining ecological impacts and management options, the criteria of the basic requirements were structured in a so-called *environmental management matrix* (Figure 4). Within the matrix five *management fields* describe operational issues related to hydropower generation. These should be organized in order to allow the power plant to be run in a more ecologically optimized manner. Requirements were defined for the following management fields: (1) instream flow regulations; (2) hydropeaking regulations; (3) reservoir management; (4) bedload management; and (5) design of power plant structures (Figure 4, Table I). In addition, five *environmental fields* were selected to cover the most important aspects for ensuring the ecological integrity of a river ecosystem. They comprise the following areas: (1) hydrological character; (2) connectivity of river systems; (3) solid materials regime and morphology; (4) landscape features and biotopes; and (5) biological communities (Figure 4, Table I).

Specific goals and a set of mostly qualitative criteria are formulated for every component within the matrix. These are designed to be universally applicable to all types of power plants in different types of watersheds. Additionally, annotated bibliographical references and suggested assessment tools for deriving quantitative management advice are available to assist the application in practice and ensure its quality. Table I summarizes most of these goals in the form of a short overview. More details are given by Bratrich and Truffer (2001).

Specifically adapted assessment tools

The evaluation of whether a specific power plant meets the basic criteria (Table I) requires a series of scientific investigations. A major part of the *Green Hydro* project was devoted to implementing and testing scientific assessment tools targeted to different elements of the management matrix. The case study in the Brenno valley (Figure 2) offered a scientific playground to test different assessment tools in the complex setting of a large hydropower scheme. The following section is organized along the five environmental fields of the environmental management matrix (hydrologic character, connectivity, solid materials regime and morphology, landscape and biotopes and biological communities; Table I).

Table I. The *environmental management matrix* with basic goals for a *Green Hydro* certification (for criteria and more details see Bratrich and Truffer, 2001)

Management field environmental field	Instream flow regulations	Hydropeaking regulations	Reservoir management (storage reservoirs)[a]	Bedload management (run-of-the-river)[b]	Design of power plant structures
Hydrological character	. . . follows the seasonal changes and the variability of natural discharge patterns.	. . . is slowed down sufficiently to allow aquatic organisms to migrate to safer areas, . . . minimizes critical temperature effects.	. . . assures the timing of reservoir flushing only during high discharge.	. . . requires minimum flow regimes in diverted river reaches which enable sediment transport, bank erosion and deposition as in the natural case.	. . . involves control systems to prevent abrupt release of high water flows, . . . includes technical measures to meet minimum flow regimes at any time.
Connectivity of river systems	. . . ensures interconnection with groundwater and lateral tributaries and allows fish migration.	. . . avoids stranding of aquatic organisms outside the main channel.	. . . allows fish to pass with the headwaters, if they are stocked with a natural fish population.	. . . ensures that lateral stream inlets retain a functional connectivity.	. . . ensures unimpeded up- and downstream migration, preferably by creating bypass channels, (technical aids need a record of functionality).
Solid materials regime and morphology	. . . preserves natural structure of the riverbed and maintains solid transport.	—	. . . avoids excessive silting or erosion in the tailwaters during flushing.	. . . allows for a necessary influx of bedload into tailwaters to prevent the erosion of the riverbed and to develop a typical morphology.	. . . optimizes the weir design for bedload transport in order to maintain an equilibrium bedload level in the tailwaters.
Landscape features and biotopes	. . . maintains hydraulic characters and preserves inventoried floodplains.	. . . preserves the specific landscape features of the river and allows safe recreational activities.	. . . preserves habitats requiring conservation, . . . pays special attention to requirements of migratory birds.	. . . permits an adequate influx of bedload into the tailwater for maintaining a typical riverine landscape.	. . . avoids any new buildings in protected areas . . . optimizes bypass channels as substitute habitats for rheophilic organisms.
Biological communities	. . . preserves natural biodiversity and sustains the reproduction of native fish species, . . . ensures that temperature regime and dilution capacity remain close to natural level.	. . . minimizes long-term damage to biodiversity, . . . maintains the age class distribution of native fish populations, . . . prevents irreversible drift of organisms and . . . preserves the diversity of habitats.	. . . schedules flushing outside critical seasons for the reproduction of important fish species, . . . ensures that rare and endangered species are not disappearing due to reservoir flushing.	. . . ensures that typical riverine habitats are forming.	. . . protects wildlife from harmful contact with installations and machines.

[a] Additional basic requirements in the column ‘reservoir management’ are also given for run-of-the-river plants and sand traps, see Bratrich and Truffer (2001) for details.
[b] Additional basic requirements in ‘bedload management’ cover also storage plants, see Bratrich and Truffer (2001).

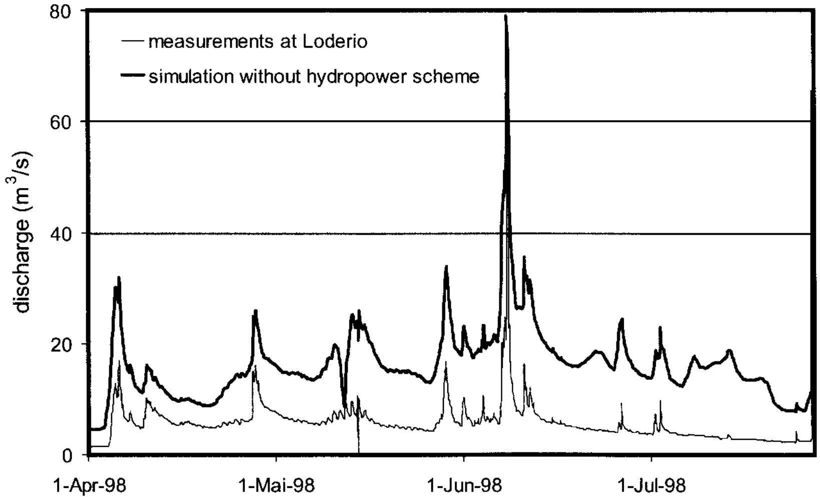

Figure 5. Discharge of the Brenno River at the Loderio gauging station compared with a simulation without hydropower scheme (after Meier, 2002)

Analysing changes in the hydrological character

The diversion of water in the Brenno has been monitored at the gauging station in Loderio (Figure 2). The largest dam (Luzzone) and the power plants started operating in 1961, leaving an average annual discharge of 4.7 $m^3 s^{-1}$ in the Brenno in Loderio, compared to 17.6 $m^3 s^{-1}$ before dam construction (Meier, 2002).

Such average values tell only part of the story. The seasonality of discharge and the frequency and magnitude of flood events are major driving forces for the aquatic and riparian ecosystems (Resh *et al.*, 1988; Richter *et al.*, 1996). The AQUASIM package, a one-dimensional hydrodynamic model (Reichert, 1994), was used in the Brenno case study to evaluate the effects of water diversions in this complex hydropower scheme. It offers a module for the hydrodynamic simulation of river reaches and the option to combine those into a river network, which allowed quantification of the effect of water diversion on parameters like discharge patterns and the temperature regime at different critical points in the Brenno river system (Meier *et al.*, in press). Figure 5 illustrates a typical result. The plot compares the measured discharge under minimum flow conditions with a modelled curve for a natural situation without any water intakes. The Brenno hydropower scheme changes the hydrological character significantly. Most of the runoff from snowmelt during summer remains stored in the reservoirs. Both frequency and amplitude of high discharge events in the range of 20 to 100 $m^3 s^{-1}$ are diminished. Only extreme events such as a major flood in June 1987 with 515 $m^3 s^{-1}$ develop their full power to modify the floodplain morphology because they exceed the capacity of the intakes by far.

Tracing lateral connectivity

The observation that the frequency of medium-sized flood events decreased since 1961 sparked a debate among local NGOs and the regional administration about whether protected floodplain forests were in danger due to drier conditions. Residence times and sources of groundwater were determined by the ^{3}H-^{3}He transient tracer method (Holocher *et al.*, 2001). Water ages were determined in different observation wells in the floodplain over one seasonal cycle. Surprisingly, old groundwater with an age of around six years was found during autumn and winter, when the water table was low, while in spring and early summer the groundwater levels increased towards the surface and the water ages decreased significantly (Figure 6). The chemical composition of the different samples suggested that lateral inflow from the slopes was mainly responsible for the groundwater recharge in the floodplain forest during summer. With the Brenno acting as drainage for groundwater flow, increasing the constant minimum flow regime would therefore not significantly improve the conditions of the riparian vegetation.

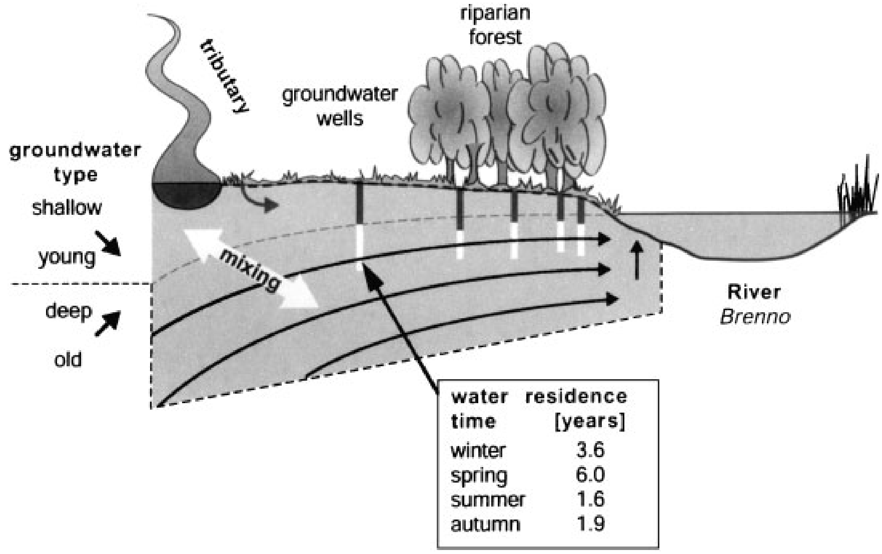

Figure 6. River–groundwater interactions at the Grumo floodplain. The Brenno River acts as principal groundwater source, ^{3}H–^{3}He transient tracer dating provided evidence for the exfiltration of groundwater several years old from lateral hill slopes into the minimum flow reach of the Brenno (modified after Holocher *et al.*, 2001)

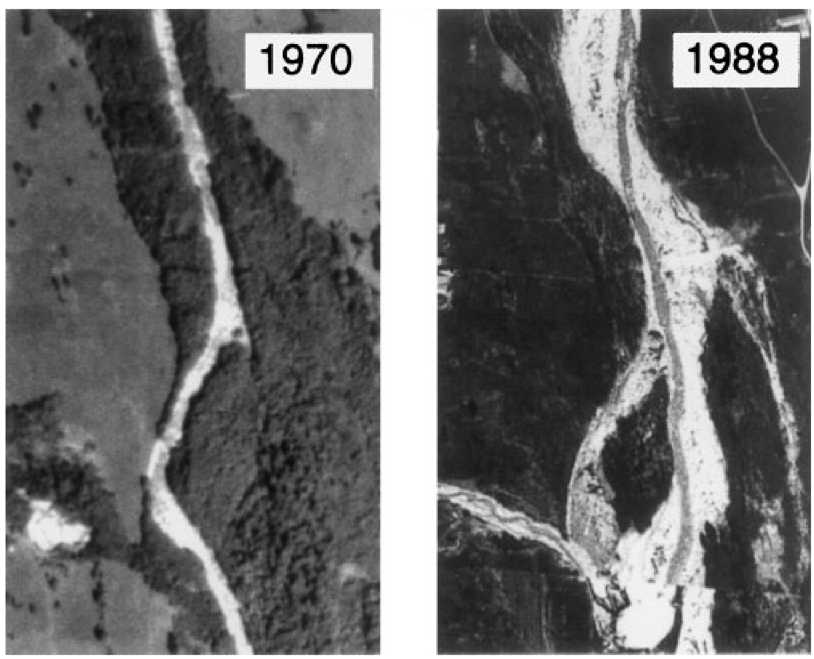

Figure 7. Aerial photographs at the Grumo site before and after the catastrophic flood event of 1987

Restoring morphological dynamics

Long-term morphological changes in the structure of floodplains are best quantified by the comparison of historical and recent aerial photographs or other remote sensing techniques. The two photographs in Figure 7 compare the situation of the Brenno near the village of Grumo before and after the largest flood event on record in July 1987 with a peak discharge of 515 $m^3 s^{-1}$ (Truffer *et al.*, 2002a). This one flood event deposited about twenty times the

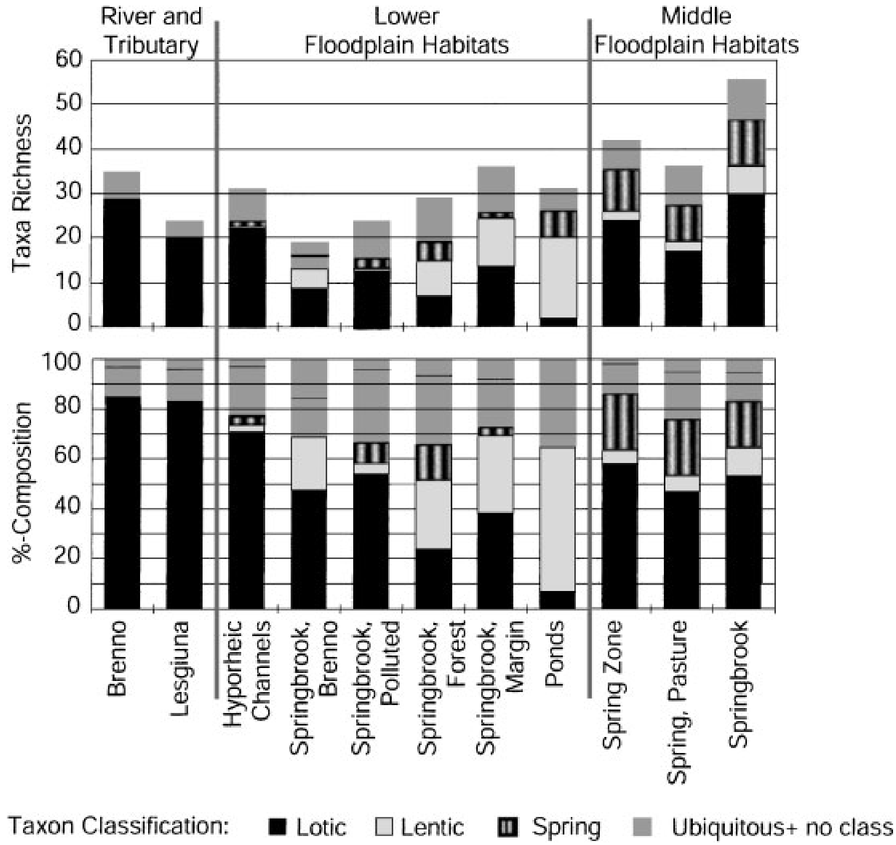

Figure 8. The comparison of taxa richness and composition in the lower Loderio floodplain and the Grumo floodplain in the middle reach of the Brenno River (based on data by Brunke, 2002)

average yearly bedload. The riverbed was completely restructured and its width doubled to 50–100 m. In the time following such a catastrophic flood the river remains confined most of the time to the narrower and deeper parts of the riverbed. Erosion processes intensify in these areas, the riverbed incises and the banks become recolonized by riparian forest. The situation of 1970 in Figure 7 reflects an endpoint of this process. Substantial floods in the order of 150–200 $m^3 s^{-1}$ are required to widen such eroded river channels thus triggering morphological changes. In the Brenno valley they occur only on decadal time scales. The hydropower scheme, however, diminishes neither their frequency nor their magnitude, because of the limited capacity of the water intakes. Bedload management is therefore not a major issue in this specific case.

Mapping critical habitats and biodiversity hotspots

A management plan for preserving valuable landscape features and biotopes should be based on habitat maps and biodiversity analyses. Such a comparative analysis based on the benthic fauna was performed in two floodplain sections of the Brenno (Brunke, 2002; Truffer *et al.*, 2002a). Figure 8 compares the taxa richness and the percentage composition with lotic, lentic, spring and ubiquitous taxa among the Brenno, its tributary, and two flood plains. Two-thirds of all 110 taxa were found exclusively in floodplain habitats but not in the Brenno or the tributary (Brunke, 2002; Truffer *et al.*, 2002a). The floodplains near Grumo (middle course) and near Loderio (lower part of the Brenno) are nature preserves according to Swiss law (Figure 2). They require special attention, because the instream flow regime might affect their ecosystem functions. The Grumo site has steeper slopes, an incised riverbed, and its groundwater flow is mainly towards the Brenno. Several springs are found at the slopes representing stable habitats for specialized taxa. As a consequence the taxa richness in these spring habitats is high. The wider Loderio floodplain is 1.2 km long and has a rich diversity of aquatic habitats, which are regularly flooded

during high-flow periods. Therefore, the river morphology is more dynamic and many structural features are of a transient nature. As a consequence, alpha diversity in these younger habitats is lower compared to the Grumo habitats, but beta and gamma diversity is higher (Brunke, 2002; Truffer *et al.*, 2002a). This analysis identifies the priorities to protect the springbrook habitats as biodiversity hotspots at the Grumo site and to secure the dynamic morphology in the lower part of the Brenno River. Such analyses provides basic guidelines for deciding at which sites an environmental management concept for a hydropower plant should be targeted, but the procedure is less effective in comparing different management options.

Using habitat models in decision-making

Aquatic habitat modelling is effective for comparing the ecological benefit of different river management options (Gibbins and Acornley, 2000; Hardy, 1998; Parasiewicz and Dunbar, 2001). In the Brenno case study habitat qualities for fish and macrozoobenthos were analysed with the simulation model CASIMIR (Jorde and Bratrich, 1997; Schneider *et al.*, 2002) which uses fuzzy models for the simulation of fish preferences (Schneider, 2001). Table II compares two river reaches in the lower Brenno sections, the Loderio floodplain (discussed above) and the Malvaglia reach (Figure 2). The latter consists of a 3.1 km long channelled river reach. Longitudinal dykes prevent overflows into the floodplain that is used for agriculture and settlements. Two aerial photographs compare the two sites in Plate 1. Habitat use and fish population characteristics were determined by electro-fishing at both sites (Table II). Population estimation was carried out in September 1998, and habitat use studies mainly in autumn 1999. The natural Loderio floodplain provides habitat for 11 fish species with a total fish biomass of 99 kg ha^{-1}. Natural reproduction was verified for nine species. By contrast, the river channel near Malvaglia harboured only five fish species (four of them with natural reproduction) and a total stock of 41 kg fish ha^{-1}. This population analysis indicates that the habitat quality is mainly limited by morphological constraints (Malvaglia reach) and not by hydrologic deficits of the minimum flow regime. The discharge dynamics shown in Figure 5 is sufficient to allow

Table II. Analysis of fish habitat and fish population in the lower Brenno valley (dominant species are underlined)

Parameter	Malvaglia reach (channelled)	Loderio floodplain (near natural morphology, regularly flooded)
Fish species present in order of decreasing abundance	<u>1. bullhead</u> (*Cottus gobio*) <u>2. brown trout</u> (*Salmo trutta fario*) 3. lake resident brown trout (*Salmo trutta lacustris*) 4. Italian barbel (*Barbus plebejus*) 5. grayling (*Thymallus thymallus*)	<u>1. brown trout</u> (*Salmo trutta fario*) <u>2. soufie</u> (*Leuciscus souffia*), <u>3. bullhead</u> (*Cottus gobio*) <u>4. grayling</u> (*Thymallus thymallus*) 5. chub (*Leuciscus cephalus*), 6. Italian barbel (*Barbus plebejus*) 7. dog barbel (*Barbus meridionalis*) 8. lake resident brown trout (*Salmo trutta lacustris*) 9. minnow (*Phoxinus phoxinus*) 10. rainbow trout (*Oncorhynchus mykiss*) 11. eel (*Anguilla anguilla*)
Natural reproduction	four species brown trout, lake resident brown trout, bullhead and Italian barbel	nine species brown trout, soufie, lake resident brown trout, bullhead, grayling, chub, Italian barbel, dog barbel and minnow
Habitat description	uniform channel, levees cut off the transfer of floodwater between the river channel and floodplain	riffles, pools, woody debris, island, gravel bars, lateral channels, temporarily isolated pools (TIPs)
Habitat use by fish	main channel only	<u>grayling</u>: main channel, lateral channel, avoidance TIPs <u>soufie</u>: young fish in TIPs, adult fish in pools and well structured zones close to the bank, lateral channels <u>brown trout</u>: avoidance of TIPs, use of lateral and main channels <u>bullhead</u>: use of main channel only

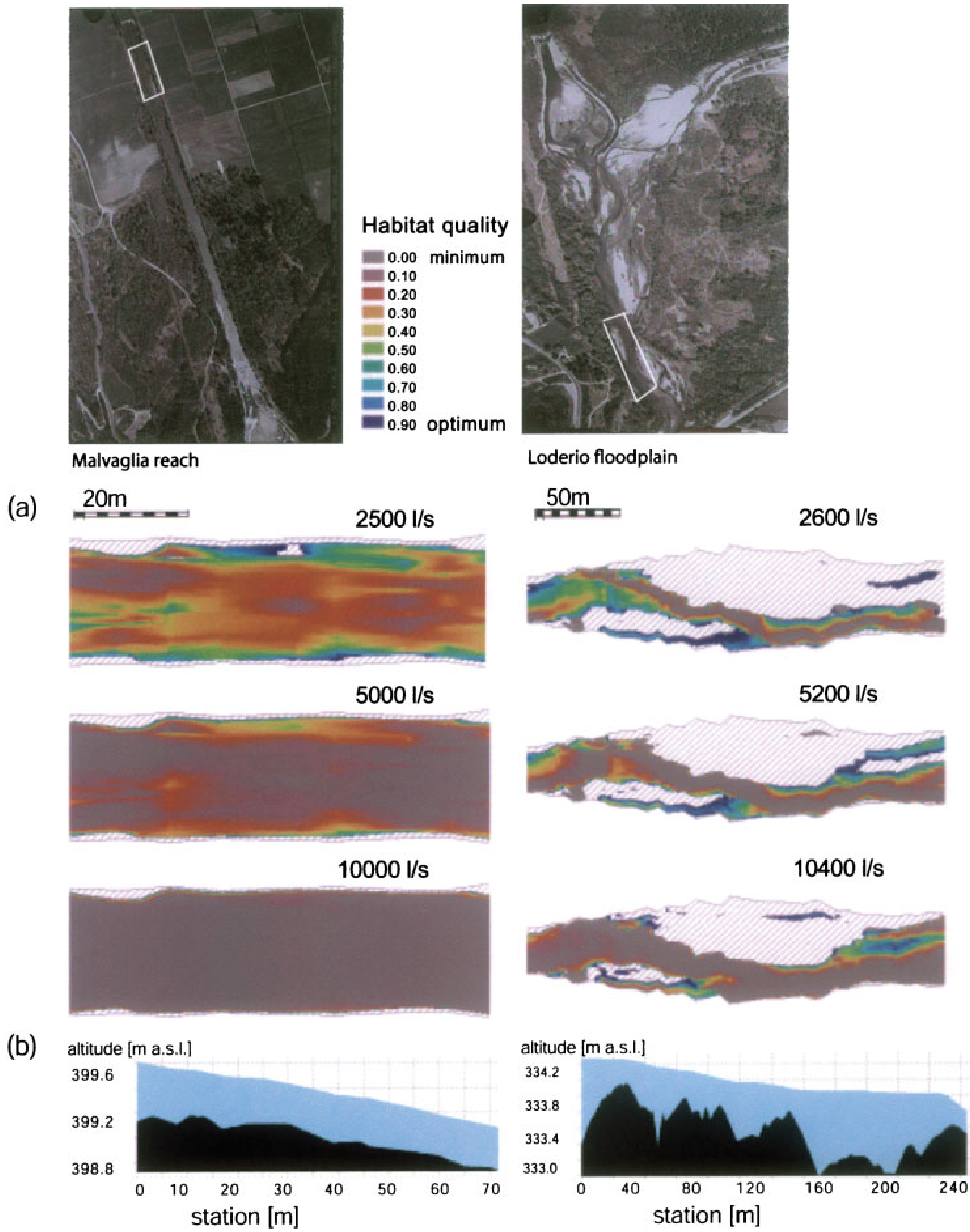

Plate 1. Results form the habitat simulation model CASIMIR in the two different morphological stretches. The habitat quality (a) for brown trout (fry) decreases rapidly with increased discharge in the uniform channel reach. This is due to the small spectrum of water depths (similar for flow velocities), that can be identified in thalweg (b)

natural reproduction of vulnerable fish species such as the soufie (*Leuciscus souffia*), the grayling (*Thymalus thymallus*) or the dog barbel (*Barbus meridionalis*) with special habitat requirements (Table II).

Habitat modelling now allows quantification of the effects of different minimum flow regimes at these two morphologically distinct sites. Plate 1 shows the habitat quality for brown trout (fry) at two different discharge regimes. The comparison shows that restoring the morphology of the channelled Malvaglia stretch is much more effective for improving fish habitats than any constant increase in minimum flow. In this case, a strategy of choice would consider financing river restoration projects as part of the eco-investment measures.

DISCUSSION

We start this discussion with a short evaluation of the *Green Hydro* assessment procedure. Then we address the critical knowledge gaps for the different management fields listed in Table I. In the final section we discuss the first practical experiences with the certification of hydropower schemes.

The Green Hydro procedure

The *stepwise approach* towards certification of a power plant (Figure 3) facilitated overcoming the initial reservations of the hydropower industry against the perceived complexity of the procedure. The initial screening allows concentrating on the relevant basic requirements and provides cost estimates of the certification process. A specifically adapted investigation programme for small hydropower plants helped also to minimize prejudices against the assessment procedure. In addition, the general procedure is designed after familiar environmental management systems (such as environmental impact assessment or ISO 14001 certification) which are already widely accepted in the industry.

In a similar way, the environmental management matrix (Figure 4) helped to build a common perspective among environmental scientists, hydraulic engineers, representatives from NGOs, and power plant managers by targeting specific goals for the relevant environmental topics and management domains. The criteria that represent the basic requirements were developed from scientific objectives and selected for high effectiveness in the framework of hydropower management. The fact that these criteria represent minimum standards to be complemented by additional *eco-investments* was another critical factor in achieving consensus among the different stakeholders.

The mechanism of eco-investments (Figure 3) was especially well received among plant operators, regulators and consumers. It provides flexibility (investments are due only if green electricity is sold), synergy (hydropower plants and regulators are joining forces in some revitalization projects) and transparency (consumers can be informed about the progress in a specific river system). The concept of a fixed surcharge on the green electricity sold turned out to create considerable ecological and economical benefits. Eco-investments provide money for improving the ecological integrity of impacted river systems. They also serve as a strong marketing tool for highlighting ecological benefits of green electricity and to promote integrated restoration concepts (Hart *et al.*, 2002). Within the last two years this mechanism generated about 1 million Swiss franc (€0.6 million) of new investments in restoring river systems affected by hydropower in Switzerland.

Evaluating the assessment tools

The case study in the Brenno valley provided a test site for different assessment tools regarding the five management fields. In the case of instream flow regimes dynamic river models such as AQUASIM (Reichert, 1994) can predict the effects of different discharge scenarios on water temperature and on the concentrations of dissolved and suspended substances. Model results can then be compared to the physiological requirements of target organisms in a river system in order to derive suitable conditions for their reproduction and survival. Hydraulic habitat models such as CASIMIR provide a complementary perspective (Jorde and Bratrich, 1997; Schneider, 2001). They require detailed information on the morphology, water levels and choriotopes of typical river sections. After proper calibration, the models estimate the aquatic habitat quality as a function of discharge. In addition, CASIMIR offers modules for an integrated simulation of the electricity generation of a hydropower plant providing valuable information about the financial consequences of an individual instream flow regulation. Because establishing and calibrating such models is labour intensive, they should preferably be used when simple decisions are not possible and

customized solutions are therefore required. Moosmann *et al.* (2002) present a synthesis of the information on instream flow regimes in the Brenno catchment and propose a selection scheme to support such site-specific, customized solutions.

In the field of reservoir management considerable scientific know-how is available (Morris and Fan, 1997). In recent years, the sediment management of several high alpine reservoirs has been optimized (Gerster and Rey, 1994). In the case of the Luzzone Reservoir, sediments are flushed only during summer rainstorms, when the discharge comes close to a one-year flood event. The monitoring results of a flush event in September 1998 indicate that this concept works (Truffer *et al.*, 2002a). In comparison to natural flood events the concentrations of suspended matter, the distribution of particle size, and chemical and physical parameter were only slightly modified and caused no negative effects in the river system.

The management field of power plant structures can rely on solid knowledge on diadromous and freshwater-resident salmonid species and on fish passage technology for these migratory fish species (Clay, 1995; Odeh, 2000). So far, research has concentrated on salmonid species, which are of high economic value. Far less is known concerning the migration of cyprinids and other freshwater fish species, previously regarded as being non-migratory (Lucas and Baras, 2001). Management practices and migration facilities suitable for salmonids are often inappropriate for other species. A close cooperation between fish biologists and hydraulic engineers is needed to secure migration and survival of fishes.

The two management domains of hydropeaking and bedload management were identified as future research priorities. As in other countries, hydropeaking operations are not well regulated in Switzerland. Although there have been an increasing number of investigations during the last 20 years (Cushman, 1985; Irvine and Jowett, 1987; Moog, 1993; Vehanen *et al.*, 2003) practical advice on hydropeaking management is still vague. A recent literature analysis of more than 200 papers shows a clear lack of knowledge according to the ecological impacts of peak frequency and magnitude but emphasizes the importance of riverbed morphology for assessing the ecological impacts of hydropeaking (Baumann and Klaus, 2003). According to this, only individual investigations allow an adequate evaluation of the actual environmental damage. Evaluating hydropeaking in a lowland river with several seasonal storage facilities in the headwaters is an especially difficult task because the different effects interfere. Limiting the rate of changes in discharge affects the capacity of peak production, the main competitive advantage of storage reservoirs. Ecological mitigation of hydropeaking should therefore combine an optimization of flood protection and hydropower production with an ecological upgrading of the river morphology. Compensation reservoirs used to store peak discharges or bypass channels can reduce the hydropeaking effects significantly (Baumann and Klaus, 2003). The concept of ecological investments provides a new mechanism to support the implementation of such technologies for integrated river management.

In the case of bedload management the experimental flood in the Grand Canyon (USA) illustrated the problems and challenges of mitigating negative morphological developments in the riverbed due to hydropower use (Webb *et al.*, 1999). In the Swiss National Park artificial flooding was used to restore more natural flow conditions to the River Spöl (Robinson *et al.*, 2002). The results show that artificial floods can mitigate the effects caused by reduced flows and clogged streambeds. They can also change the abundance of algae and zoobenthos, reducing species favoured by river regulation (Robinson *et al.*, 2002). However, further research is required to optimize the timing and magnitude of artificial flood events. In the case of many alpine rivers such artificial floods can only develop their potential for restoring the river morphology if flood protection measures are modified accordingly.

The requirements for the management of each of the five environmental fields were developed based on the experience we gained during the Brenno case study and the wider background experience provided by experts. Later, they were discussed and supplemented on a broader basis to make them applicable across all types of hydropower plants and schemes. For very small hydropower plants, simplified regulations were developed. So far, the framework could successfully be used for 'real world' certifications of very different types of hydro-facilities.

Applying the assessment scheme

According to a recent review, the criteria for the *Green Hydro* assessment procedure fulfil the highest ecological standard among eco-labelling schemes in Europe and represent a credible basis for consumers (Busch and Gasser, 2001). With the exception of the standard required by the Low Impact Hydropower Institute (LIHI) in Portland

(USA), most of the current eco-labelling schemes for green hydropower still use general and simplistic criteria like the age of the power plant or an upper boundary for the installed capacity (Markard *et al.*, 2001). In particular, none of these certification procedures accounts for environmental impacts on local river systems. By avoiding expensive investigations, such ecologically meaningless criteria are easier to check and therefore often used. Immediately after the announcement of the more sophisticated *Green Hydro* approach critical stakeholders argued, therefore, that such a complex assessment procedure would never play any relevant role in practice and might even harm the Swiss hydropower industry. Several members of the Swiss Hydropower Association (VSE/AES), however, relied on studies on green market development saying that only scientifically credible eco-labels would remain successful in the long term. As a reaction, they launched the private Association for Environmentally Sound Electricity (VUE), where electricity producers, distributor companies, environmental and consumer NGOs are represented equally. Even against strong opposition from parts of the hydropower industry, this association agreed to use the *Green Hydro* procedure whenever a hydropower scheme wants to be certified with their independent eco-label called ‘naturemade star’.

To date, 13 facilities have successfully passed the certification procedure and five are currently in their screening phase (VUE, 2003). The range of certified schemes includes all relevant types of power plants such as large storage schemes in the Alps, large run-of-the-river plants on the Swiss Plateau and several types of small hydropower units. They cover a range of installed capacity and annual production of 250–18 000 KW and 1000–86 500 MWh a^{-1}, respectively (VUE, 2003). In total, *Green Hydro* certified schemes provide 186 GWh electricity per year, an amount almost equivalent to the consumption of 40 000 households in Switzerland (Mutzner, 1995). Theses certifications were accompanied by ecological benefits, which would not have occurred without the eco-labelling process. Since June 2003, a new bypass system reconnects a side channel with the impoundment of a larger run-off-the river plant and eco-investments have been used to improve aquatic habitats, riparian zones, and conditions for fish and beaver migration. In an alpine storage plant the *Green Hydro* certification triggered the implementation of a minimum flow regime, which exceeds legal requirements significantly. In a smaller power plant a fish ladder will be replaced by a bypass channel within the next five years. This channel will be designed as a result of ongoing video monitoring of fish migration, which was required for certification.

Meanwhile, green electricity represents not only an elusive vision for ecologically concerned individuals but offers an attractive option for major electricity customers. The Swiss National Exhibition (Expo. 02), the telecommunications company Swisscom, and the Ski World Cup 2003 in St. Moritz have bought green electricity and used this fact successfully in their public relations efforts.

CONCLUSION

The close interaction with the stakeholders from the hydropower industry, consumer groups, and environmental NGOs allowed us to develop and implement the first labelling scheme for green hydropower, which is based on clearly defined scientific criteria from river ecology. So far the corresponding certification scheme has competed very well against simple marketing efforts to repackage existing hydropower offerings as green power (Busch and Gasser, 2001). The clear but flexible approach with basic criteria and eco-investments in the form of an environmental management matrix has been well received among hydropower producers, consumer organizations, and environmental NGOs and has already resulted in the certification of 13 facilities.

In Europe the *Green Hydro* procedure could also help implementation of the EC Water Framework Directive, which demands a ‘good status‘ of river systems by 2015 (EU, 2000). Hydromorphological quality assessment plays a crucial role in the Directive to discriminate between intact and ‘heavily modified’ conditions of rivers. The *Green Hydro* standard offers operational criteria and guidelines for achieving a good status in rivers affected by hydropower use.

However, in the long run a careful evaluation of certified schemes is necessary to document the ecological benefits realized in *Green Hydro* power plants. Such credible results are needed for moving green electricity from a niche product to the mass market (Wüstenhagen, 2000). The clear formulation of ecological goals will help in assessing the success or failure of the certification scheme (Bernauer, 2002). Rather than implementing general bureaucratic monitoring requirements, the scientific community should realize that upgrading hydropower plants represents large-scale ecological experiments (Webb *et al.*, 1999), which provide ample opportunity to answer

fundamental questions regarding the driving forces and adaptability of aquatic ecosystems in rivers affected by hydropower production.

Most new hydropower schemes are now being planned in Asia, Africa, or South America. Improving the ecological performance of such large-scale projects remains an enormous challenge (WCD, 2000). Although the *Green Hydro* procedure was developed to assess existing hydropower schemes in the Alps, we are confident that it offers a first useful step towards resolving environmental issues in this wider context as well. At least the procedure provides an 'apolitical mechanism for redistributing the costs' (Allen, 2003) of a more sustainable electricity production without ignoring the emerging environmental problems on the local scale.

ACKNOWLEDGEMENTS

We thank the Swiss Federal Institute for Environmental Science and Technology (EAWAG) for the continued financial support for this project. Additional funds from the Swiss Association for Electricity (VSE/AES) are gratefully acknowledged. Directors and staff members of the OFIBLE power plant in the Brenno valley were very helpful during our field studies. The expert panel provided invaluable advice and suggestions during the development of the basic criteria. We thank Mathias Jungwirth (Vienna), Peter Ergenzinger (Berlin), Andreas Stalder (Bern), Christian Moritz (Innsbruck), Lukas Hunzinger (Bern), and Ursula Grasser (Vienna). The Swiss Association for Environmentally Sound Electricity (VUE) was our partner in the development process of the assessment scheme. We thank Bernd Kiefer, Cornelia Brandes and Stefan Vollenweider for their energetic enthusiasm. MeteoSwiss and the Federal Office for Water and Geology (BWG) provided monitoring data. Peter Baumann, Arthur Krichhofer, and Thomas Wagner from the consulting companies Limnex, WFN, and Sigmaplan conducted the pilot certifications. Jürg Bloesch, Matthias Brunke, Andreas Frutiger, Mark Gessner, Tom Gonser, Edi Hoehn, Lorenz Moosmann, and many others contributed significantly to the *Green Hydro* project. In addition we acknowledge the assistance of Luzia Fuchs, the continuous support by Ueli Bundi, and the helpful comments by Johny Wüest, Rolf Kipfer, and two anonymous reviewers.

REFERENCES

Allen M. 2003. Liability for climate change. *Nature* **421**: 891–892.

Baumann P, Klaus I. 2003. *Gewässerökologische Auswirkungen des Schwallbetriebs: Ergebnisse einer Literaturstudie.* Bundesamt für Umwelt, Wald und Landschaft (BUWAL)—Mitteilungen zur Fischerei 75: Bern.

Bernauer T. 2002. Explaining success and failure in international river management. *Aquatic Sciences* **64**: 1–19.

Bird L, Wüstenhagen R, Aabakken J. 2002. A review of international green power markets: recent experience, trends, and market drivers. *Renewable and Sustainable Energy Reviews* **6**: 513–536.

Boon PJ, Holmes NTH, Maitland PS, Rowell TA, Davis J. 1997. A system for evaluating rivers for conservation (SERCON): development, structure and function. In *Freshwater Quality: Defining the Indefinable*? Boon PJ, Howell DL (eds). The Stationery Office: Edinburgh; 299–326.

Bratrich C, Truffer B. 2001. *Green Electricity Certification for Hydropower Plants—Concepts, Procedure, Criteria*. EAWAG Ökostrom Publikationen 7: Kastanienbaum.

Brunke M. 2002. Floodplains of a regulated southern Alpine river (Brenno Switzerland): ecological assessment and conservation options. *Aquatic Conservation of Marine and Freshwater Ecosystems* **12**: 583–599.

Bundi U, Peter A, Frutiger A, Hütte M, Liechti P, Sieber U. 2000. Scientific base and modular concept for comprehensive assessment of streams in Switzerland. *Hydrobiologia* **422/423**: 477–487.

Busch E, Gasser S. 2001. *Ökostrom—Analyse und Bewertung von Labels und Produkten auf dem Schweizer Markt*. SAFE (Swiss Agency for Efficient Energy Use): Felsberg/Zürich.

Cheremisinoff NP, Bendavid-Val A. 2001. *Green Profits—The Manager's Handbook for ISO 14001 and Pollution Prevention*. Butterworth Heinemann: Boston.

Chovanec A, Jäger P, Jungwirth M, Koller-Kreimel V, Moog O, Muharh S. 2000. The Austrian way of assessing the ecological integrity of running waters: a contribution to the EU Water Framework Directive. *Hydrobiologia* **422/423**: 445–452.

Cushman RM. 1985. Review of ecological effects of rapidly varying flows downstream from hydroelectric facilities. *North American Journal of Fish Management* **5**: 330–339.

Clay CH. 1995. *Design of Fishways and Other Fish Facilities*. CRC Press: Boca Raton.

DeShon JE. 1995. Development and application ot the Invertebrate Community Index (ICI). In *Biological Assessment and Criteria*, Davis WS (ed.). Lewis Publishers: Boca Raton; 217–243.

Edwards AJ. 2001. *ISO 14001 Environmental Certification Step by Step*. Butterworth Heinemann: Oxford.
EU. 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. http://projects.dhi.dk/waterdir/Water%20framework%20directive%20UK.pdf [July 2003].
Friedl G, Wüest A. 2002. Disrupting biogeochemical cycles—Consequences of damming. *Aquatic Sciences* **64**: 55–65.
Frischknecht R, Hofstetter P, Knoepfel I, Dones R, Zollinger E. 1994. *Ökoinventare für Energiesysteme*. ETH Zürich & Paul Scherrer Institut: Zurich.
Gerster S, Rey P. 1994. *Ökologische Folgen von Stauraumspülungen*. Bundesamt für Umwelt, Wald und Landschaft (BUWAL): Bern.
Gibbins CN, Acornley RM. 2000. Salmonid habitat modelling studies and their contribution to the development of an ecologically acceptable release policy for Kielder Reservoir, North-east England. *Regulated Rivers: Research and Management* **16**: 203–224.
Gleick PH. 1998. *The World's Water 1998–1999, The Biennial Report on Freshwater Resources*. Island Press: Washington, DC.
Graedel TE, Allenby BR. 1995. *Industrial Ecology*. Prentice Hall: Englewod Cliffs, NJ.
Greenprices. 2001. Green energy in Europe. http://www.greenprices.com [11 July 2001].
Hardy T. 1998. The future of habitat modeling and instream flow assessment technologies. *Regulated Rivers: Research and Management* **14**: 405–420.
Hart DD, Johnson TE, Bushaw-Newton KL, Horwitz RJ, Bednarek AT, Charles DF, Kreeger DA, Velinsky DJ. 2002. Dam removal: challenges and opportunities for ecological research and river restoration. *Bioscience* **52**: 669–681.
Hawkins CP, Norris RH, Hogue JN, Feminella JW. 2000. Development and evaluation of predictive models for measuring the biological integrity of streams. *Ecological Applications* **10**: 1456–1477.
Holocher J, Matta V, Aeschbach-Hertig W, Beyerle U, Kipfer R. 2001. Noble gas and major element constraints on the water dynamics in an Alpine flood plain. *Groundwater* **39**: 841–852.
Holt AE. 1997. *Green Pricing Resource Guide*. Gardiner: Maine.
Hygum B. 2001. Water and Wetland Index: assessment of 16 European Countries—Phase 1 Results, WWF European Freshwater Programme. http://www.wwf.ch/images/progneut/upload/report.pdf [March 2003].
IEA. 2001. Needs for renewables—developing a new generation of sustainable energy technologies. 11 October 2000. International Energy Agency (IEA): Paris, France. http://www.iea.org/techno/renew [March 2003].
IEA. 2002. Key world energy statistics from the IEA. www.iea.org [March 2003].
Irvine JR, Jowett IG. 1987. Flow control. In *Aquatic Biology and Hydroelectric Power Development in New Zealand*, Henriques PR (ed.). Oxford University Press: Auckland; 94–112.
Johnson N, Revenga C, Echeverria J. 2001. Managing water for people and nature. *Science* **292**: 1071–1072.
Jorde K, Bratrich C. 1997. River bed morphology and flow regulations in diverted streams on bottom shear stress pattern and hydraulic habitat. In *Advances in River Bottom Ecology IV*, Bretschko G, Helesic J (eds). Backhuys Publishers: Leiden; 47–63.
Kaltschmitt M, Wiese A. (eds). 1997. *Erneuerbare Energien: Systemtechnik, Wirtschaftlichkeit, Umweltaspekte*. Springer: Berlin.
Karr JR, Chu EW. 1999. *Restoring Life in Running Waters: Better Biological Monitoring*. Island Press: Washington, DC.
Kondolf GM. 1998. Lessons learned from river restoration projects in California. *Aquatic Conservation of Marine and Freshwater Ecosystems* **8**: 39–52.
Lucas MC, Baras E. 2001. *Migration of Freshwater Fishes*. Blackwell Science: Oxford.
Markard J. 1997. *Green-Pricing: welchen Beitrag können freiwillige Zahlungen von Stromkunden zur Förderung regenerativer Energien leisten*? Öko-Institut-Verlag: Freiburg.
Markard J, Truffer B, Bratrich C. 2001. Green marketing for hydropower. *Hydropower & Dams* **8**: 81–86.
McCully P. 1996. *Silenced Rivers—The Ecology and Politics of Large Dams*. Zed Books: London.
Meier WK. 2002. *Modellierung der Auswirkungen von Wasserkraftanlagen auf physikalische und chemische Eigenschaften von Bergbächen*. EAWAG Ökostrom Publikationen 11: Kastanienbaum.
Meier WK, Bonjour C, Wüest A, Reichert P. 2003. Modelling the effect of water diversion on the temperature of mountain streams. *Journal of Environmental Engineering* **129**: 755–764.
Moog O. 1993. Quantification of daily peak hydropower effects on aquatic fauna and management to minimize environmental impacts. *Regulated Rivers: Research and Management* **8**: 5–14.
Moosmann L, Jorde K, Schneider M, Meier W, Peter A, Wüest A. 2002. *Restwasserbemessung für Ökostrom mit Beispiel Brenno (Bleniotal, TI)*. EAWAG Ökostrom Publikationen 9: Kastanienbaum.
Morris GL, Fan J. 1997. *Reservoir Sedimentation Handbook—Design and Management of Dams, Reservoirs and Watersheds for Sustainable Use*. McGraw-Hill: New York.
Muhar S, Jungwirth M. 1998. Habitat integrity of running waters—assessment criteria and their biological relevance. *Hydrobiologia* **386**: 195–202.
Mutzner J. 1995. *Die Stromversorgung der Schweiz, Entwicklung und Struktur*. VSE (Verband Schweizerischer Elektrizitätswerke): Zürich.
Naiman RJ, Beechie TJ, Benda LE, Berg DR, Bisson PA, MacDonald LH, O'Connor MD, Olson PL, Ste EA. 1992. Fundamental elements of ecologically healthy watersheds in the Pacific Northwest coastal ecoregion. In *Watershed Management: Balancing Sustainability and Environmental Change*, Naiman RJ (ed.). Springer Verlag: New York; 127–187.
Norris RH, Hawkins CP. 2000. Monitoring river health. *Hydrobiologia* **435**: 5–17.
Odeh M. (ed.). 2000. *Advances in Fish Passage Technology: Engineering Design and Biological Evaluation*. American Fisheries Society: Bethesda, MD.
Parasiewicz P, Dunbar M. 2001. Physical habitat modelling for fish—a developing approach. *Archiv für Hydrobiologie Suppl.* **135**: 239–268.

Pringle CM. 2001. Hydrologic connectivity and the management of biological reserves: a global perspective. *Ecological Applications* **11**: 981–998.

Raphals P. 2001. *Restructured rivers—Hydropower in the Era of Competitive Markets*. International Rivers Network: Berkeley, CA.

Raven PJ, Holmes NTH, Dawson FH, Fox PJA, Fozzard IR, Rouen KJ. 1998. *River Habitat Quality*. Environment Agency: Bristol.

Reichert P. 1994. AQUASIM—a tool for simulation and data analysis of aquatic systems. *Water Science and Technology* **30**: 21–30.

Renn O. 1999. A model for an analytic-deliberative process in risk management. *Environmental Science and Technology* **33**: 3049–3055.

Resh VH, Brown AV, Covich AP, Gurtz ME, Li HW, Minshall GW, Reice ME, Sheldon AL, Wallace JB, Wissmar RC. 1988. The role of disturbance in stream ecology. *Journal of the North American Benthological Society* **7**: 433–455.

Richter BD, Baumgartner JV, Powell J, Braun DP. 1996. A method for assessing hydrologic alternation within ecosystems. *Conservation Biology* **10**: 1163–1174.

Richter BD, Baumgartner JV, Wigington R, Braun DP. 1997. How much water does a river need? *Freshwater Biology* **37**: 231–249.

Robinson CT, Uehlinger U, Monaghan MT. 2002. Stream response to experimental floods. *EAWAG News* **54e**: 27–29.

Schaltegger S, Sturm A. 1995. *Öko-Effizienz durch Öko-Controlling: Zur praktischen Umsetzung von EMAS und ISO 14'001*. Schäffer-Poeschel: Stuttgart.

Schneider M. 2001. *Habitat- und Abflussmodellierung für Fließgewässer mit unscharfen Berechnungsansätzen*. Eigenverlag der Universität Stuttgart: Stuttgart.

Schneider M, Jorde K, Zöllner F, Kerle F, Eisner A. 2002. Use of habitat models for decision support in water resources management. In *International Conference on Water Resources and Environment Research* (ICWRER). TU Dresden: Dresden.

St. Louis V, Kelly C, Duchemin E, Rudd JWM, Rosenberg DM. 2000. Reservoir surfaces as sources of greenhouse gases to atmosphere: a global estimate. *Bioscience* **50**: 766–775.

The World Bank. 1993. *The Worldbank and Environmental Assessment: An Overview*. The World Bank: Washington, DC.

Truffer B, Markard J, Bratrich C, Wehrli B. 2001. Green Electricity from Alpine Hydropower Plants. *Mountain Research and Development* **21**: 19–24.

Truffer B, Bloesch J, Bratrich C, Gonser T, Hoehn E, Markard J, Peter A, Wehrli B, Wüest A. 2002a. *Ökostrom aus Wasserkraft—Schlussbericht*. EAWAG Ökostrom Publikationen 10: Kastanienbaum.

Truffer B, Bruppacher S, Behringer J. 2002b. *Nachfrage nach Ökostrom—Ergebnisse einer Fokusgruppenerhebung in den Städten Bern, Zürich und Stuttgart*. EAWAG Ökostrom Publikationen 8: Kastanienbaum.

Truffer B, Bratrich C, Markard J, Peter A, Wüest A, Wehrli B. 2003. Green hydropower: the contribution of aquatic science research to the promotion of sustainable electricity. *Aquatic Sciences* **65**: 99–110.

Vehanen T, Huusko A, Yrjana T, Lahti M, Maki-Petays A. 2003. Habitat preference by grayling (*Thymallus thymallus*) in an artificially modified, hydropeaking riverbed: a contribution to understand the effectiveness of habitat enhancement measures. *Journal of Applied Ichthyology* **19**: 15–20.

VUE. 2003. Association for environmentally sound electricity (newsletter 03/2003). www.naturemade.ch [March 2003].

WCD. 2000. *World Commission on Dams: Dams and Development—A New Framework for Decision-Making*. Earthscan: London.

Webb RH, Schmidt JC, Marzolf GR, Valdez RA. (eds). 1999. *The Controlled Flood in the Grand Canyon*. American Geophysical Union: Washington, DC.

Wenger RB, Harris HJ, Devault DS. 2000. An assessment of ecosystem risks in the St. Croix National Scenic Riverway. *Environmental Management* **25**: 599–611.

Wright JF. 1995. Development and use of a system for predicting the macroinvertebrate fauna in flowing waters. *Australian Journal of Ecology* **20**: 181–197.

Wüstenhagen R. 2000. *Ökostrom—von der Niesche zum Massenmarkt. Entwicklungsperspektiven und Marketingstrategien für eine zukünftige Elektrizitätsbranche*. VdF Verlag: Zürich.

