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Integrated simulation of physical, chemical and ecological processes for river management

Peter Goodwin and Thomas B. Hardy

ABSTRACT

River management is a rapidly evolving science and recent major floods have prompted a re-examination of traditional approaches such as channelization, levees, flood walls and dams. These flood control measures are capital intensive, require significant maintenance costs, only protect local regions, and often require a tradeoff with ecological resources. Further, recent analyses have shown that the intended benefits and hydraulic performances are not achieved. A new paradigm in river management is evolving, which requires a broad range of design objectives to be met that include reduction in flood risks, ecological enhancement, recreation and aesthetics, as well as complying with strict environmental protection legislation. These more complex projects require extensive data and simulation tools to assist decision makers and communities in selecting management strategies which offer the maximum benefits, whilst preserving and enhancing the ecological integrity of the river system. A framework for the systematic analysis of the river ecosystem is outlined and illustrated by examples from the Western USA.

Key words | ecohydraulics, river restoration, models, ecology, river management

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INTRODUCTION

Traditionally, the rivers of the world have been managed for narrow engineering-based objectives such as water supply, navigation, flood control and water quality. These economic and societal benefits are easily quantifiable from the theoretical point of view, but the ability to quantify and predict secondary effects and the sustainability of these benefits in the long-term have proven more elusive. For example, the U.S. national investment in structural flood control exceeds $25,000 million, yet flood damages continue to increase steadily and now average more than $2,000 million per year (1994 Federal Interagency Floodplain Management Task Force). One of the primary reasons for these escalating flood damages has been the failure to recognize that providing protection against the design flood does not mean the elimination of flood risks and there will always be floods generated by combinations of hydrological conditions that exceed this design level. One of the most striking examples of this planning approach was the failure of the Monarch-Chesterfield levee in the 1993 Mississippi floods (Williams 1994). A levee was constructed in 1989 to contain the 100-year flood and a new business park constructed under its protection. The floods in 1993 caused over $200 million in damages that would not have occurred before the construction of the levee.

> ‘Protection from floods is only a relative matter: eventually Nature demands its toll from those who occupy floodplains’ (Hoyt & Langbein 1955).

TRADITIONAL APPROACHES TO RIVER MANAGEMENT

These traditional approaches to river management often resulted in channelization of rivers, with the floodplain being truncated by levees or flood walls. These types of project were designed to be cost effective because the area of land required to be dedicated to the river could be minimized. Relatively little attention was given to accommodating the natural geomorphic processes such as meandering and sediment transport because maintenance was prescribed as part of the plan to contain the river, by maintaining the design section, whereby bank erosion was prevented through structural stabilization. The channel resistance was also controlled to a minimum through periodic vegetation removal or by casting the river in concrete or by introducing rip-rapped channels.

During the past decade, opportunities to evaluate these traditional approaches to river management have occurred during the recent major floods in the USA and Europe. These forensic studies of flood damage have shown that some projects have failed to provide the intended design level of flood protection. This is not an indictment of the original engineering design, but rather an indication that river hydraulics is an immensely complex yet rapidly evolving science. Large floods occur relatively infrequently, and statistically many of the flood control projects designed in the period 1940–80 are only now being tested by major flood events. The example of the San Lorenzo River in California is shown in Figure 1. This flood control project was designed to contain the standard project flood with a return period of approximately 120 years, but the City of Santa Cruz was nearly inundated by the 1982 flood which had a return period of less than 30 years.

The reasons for these traditional projects failing to convey the design discharges include:

- failure to quantify the effects of sediment or flood debris on flow resistance;
- failure to allow for changing land use patterns upon the upper watershed;
- underestimation of the role of floodplains in alleviating downstream flooding;
- unanticipated deposition or erosion trends;
- geomorphic changes to the river planform or hydraulic geometry;
- channel constrictions that create induced scouring on channel banks and levees;
- insufficient capacity of bridges or other flow constrictions.

It is also important to recognize that providing protection against the design flood does not mean the elimination of flood risks and there will always be floods that will exceed the design event. These flood control measures often require costly maintenance of vegetation, sediment management and structural remediation which were underestimated or neglected in the original design. For example the anticipated channel dredging required in the straightened San Lorenzo River was underestimated by an order of magnitude, placing severe and unacceptable costs for channel maintenance on the city of Santa Cruz.

Many projects developed for the single objective of flood control exhibit very different plant communities to the natural reaches of the river (Figure 1). Reasons include altered hydraulic geometry of the channel, changes in the geomorphic characteristics (depths of pools, size of bars), deposition and scour characteristics and channel stabilization. One frequent ramification of these changes is an increase in scouring potential of the channel, so during intermediate size flood events most of the channel vegetation is scoured. This results in a less diverse plant community and one of more uniform age than in the natural river. This altered cycle of vegetation removal and disturbance may also favour exotic non-indigenous plant species that can further diminish critical habitat. The geomorphic changes in the channel may also result in rivers with a shallower but wider cross-section, and less shade, which may be detrimental to native fish populations. Figure 1 illustrates the effects of these traditional approaches. These observed secondary effects of traditional river management approaches (see, for example, McCully 1996) have coincided with an increasing public awareness of environmental issues.

EMERGING PARADIGMS FOR RIVER MANAGEMENT

Since the first Earth Day, 30 years ago, there has been a changing public perception and a growing public determination to preserve and enhance river corridors. In the USA, this has been reflected in legislation targeted toward environmental protection such as the Clean Water Act

(1974). One element of this Act has been used in recent years by Environmental Groups to accelerate the recovery of river corridors. The implementation of Total Maximum Daily Loads (TMDLs) limits the discharge of pollutants from point and non-point sources to levels below which there should be no significant impacts upon ecological systems or socially beneficial uses. For example, in Idaho, a region renowned for its spectacular whitewater rivers, over 950 rivers or sections of rivers have been assessed to be water-quality limited. The primary pollutants have been determined to be sediment, nutrients or elevated water temperatures. The Division of Environmental Quality and the US Environmental Protection Agency (IDEQ 1996) are in the process of establishing TMDLs for all these impacted rivers and developing management plans to achieve these TMDLs within the next decade. On a broader scale, the ecosystem management plan for the Interior Columbia River Basin addresses land use management practices and river management (Haynes *et al.* 1996; USDA 1997). Other key legislation includes the federal Endangered Species Act (ESA) and state specific acts such as the California Coastal Act. This environmental legislation has made the evaluation of river management plans far more complex because a broad range of habitat, water quality and ecosystem response issues must be addressed and documented in a way to withstand challenges in law courts or public hearings.

Recent major floods have prompted a re-examination of traditional *flood control* measures such as channelization, levees, flood walls and dams. Flood control measures are capital intensive, require significant maintenance costs, only protect local regions, and often require a trade-off with ecological resources. A new paradigm of *flood management* is evolving (see, for example, Williams 1994; Gardiner 1991), which includes:

- assessing the river as an integrated and connected system. Measures taken at one location in the river will affect flood levels and ecological resources elsewhere;
- focusing on a goal of flood hazard reduction which provides flood protection up to a design event and minimizes damages or hazards at larger events;
- recognizing the natural peak flood flow reduction function of floodplains and wetlands.

In particular, attention has focused on the interaction between the river and its floodplain for flood hazard reduction, water quality, sediment distribution, and the overall functioning of the riparian ecosystem. Examples include the restoration of floodplains along the River Rhine (Dister *et al.* 1990), consideration of floodplain restoration along the Mississippi River (Interagency Floodplain Review Committee 1994; Hey *et al*. 1995; Galloway 1995) and the Willamette River floodplain restoration strategy (Philip Williams and Associates Ltd 1996). An example of this emerging philosophy is the '*Living River Strategy*' (Napa River Community Coalition 1996). In this example, the community recognized that a local flood control project provided limited benefits to local areas only. To garner sufficient support to fund a project, the project addressed a broad range of objectives including recreation, trails, fisheries enhancement, and river restoration. At the core of this planning effort was the 'Living River Strategy' developed by the Napa River Community Coalition of agencies, local government, businesses, public interest groups and local residents:

> A 'living' river and its tributaries constitute a system with structure, function and diversity. It has physical, chemical and biological components that function together to produce complex, diverse communities of people, plants, and animals. The health of the entire watershed, from the smallest headwater trickle to the broad expanse of estuary, is the summation of natural and human activities in the basin and how they affect certain undeniable physical processes common to all river systems. A living Napa River functions properly when it conveys variable flows and stores water in the flood plain, balances sediment input with transport, provides good quality fish and wildlife habitat, maintains good water quality, provides water supply, recreation, and aesthetic values and generally enhances the human environment.

There is extensive recent literature describing these new management strategies (see, for example, Friends of the River 1997; Interagency Floodplain Management Review Committee 1994; Leopold 1994) and a range of new analysis techniques is emerging. However, to apply these new management philosophies and gain agreement among stake-holders, sophisticated computer models and decision-support frameworks are required.

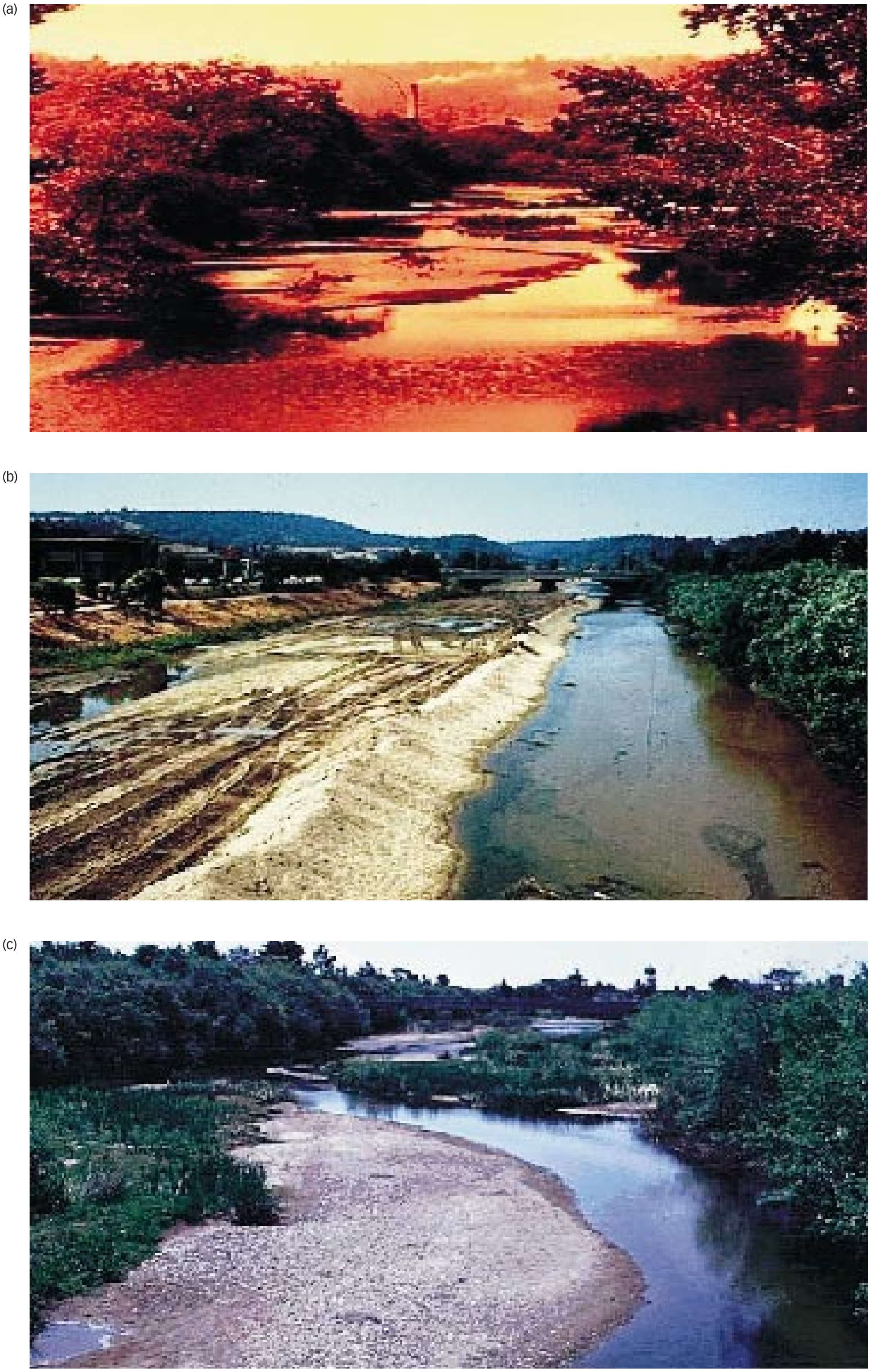

Figure 1 | San Lorenzo River, Santa Cruz, California. From top to bottom: (a) *ca.* 1950; (b) 1982; (c) 1992.

A FRAMEWORK FOR INTEGRATED RIVER MANAGEMENT

Multi-objective river management requires the blending of several different disciplines and evaluation of concerns from a broad range of stake-holders. To ensure all pertinent issues are addressed, and data-collection programmes assemble relevant and necessary information, a coherent framework with continuous feedback of data and opinions is required (see, for example, Parson and Fischer-Vanden 1995; Simic 1996; World Bank 1991, 1993*a*, *b*, *c*). A typical sequence of steps required to implement a successful plan is shown in Figure 2.

Applied river management has historically focused on one or at most a few of the physical, chemical or biological components which were thought to represent controlling factors for a given project. Recently, this narrowly defined approach has received increasing criticism in the literature, with a call for a more ecologically based orientation, focusing on integrated system processes. This has resulted in a resurgence of research efforts on methods and application frameworks aimed at delineating the process-driven linkages between flow, sediment transport, channel structure, riparian community, and aquatic resources (Hill *et al*. 1991; Nillson *et al*. 1991; Rabeni & Jacobson 1993; Stromberg *et al*. 1991; Stromberg 1993). One focus of this research includes attempts to integrate the temporally and spatially variable characteristics of the physical, chemical and biological template of river systems. From an ecological view, the suitability of environmental conditions for aquatic resources are directly related to these characteristics of linked processes inherent in the flow régime. These same linkages are also important to maintain adequate protection to other flow-dependent resources such as wildlife, recreation and aesthetics.

In essence, river management decisions must incorporate the spatial and temporal aspects of flow régimes necessary to ensure long-term protection of the flow-dependent resources by maintaining key physical, chemical and biological processes. At a pragmatic level, approaches to quantification can be broken down into several basic ‘within-year’ flow components (e.g. Petts *et al*. 1995; Hill *et al*. 1991). These may include components for aquatic habitat base flows, channel maintenance flows, riparian flows, and recreation-based flow opportunities. In addition, the component of the flow régime representing both inter- and intra-annual flow variability is also recognized as an important element in the temporal domain for many flow dependent resources (e.g. Poff *et al*. 1997; Richter *et al*. 1996). Although the specific methods by which these flow components and their linkages to specific resources are quantified remain the subject of different research approaches, they are essential to maintaining the various resource bases of stream systems (Hill *et al*. 1991). Resource management agencies, researchers and practitioners recognize that the analytical procedures and assessment frameworks being developed, validated and applied in river management must rely on inter-disciplinary perspectives that strive to understand and then predict process-driven linkages and responses to flow characteristics (Orth 1995; Stanford 1994; Hardy 1998).

An important focus of the emerging state-of-the-art in ecohydraulics is the development, testing and application of innovative methodologies, which can address the requirements of overlapping, multidisciplinary components as well as meet long-term monitoring and assessment needs. This focus also recognizes the necessity to address the efficacy of management decisions under adaptive management paradigms. Pragmatically, this dictates that data acquisition and analyses at micro-habitat or reach levels and subsequent scaling to broader spatial and temporal domains, such as the watershed level, must be able to address a wide array of discipline-specific components and process-specific modelling. This includes the delineation of channel topographies for use in hydrodynamic modelling, water quality modelling, sediment transport modelling, aquatic resource utilization and habitat modelling, aquatic population dynamics, riparian community dynamics, and recreation. Furthermore, owing to time and cost constraints at the application level, characterization of physical, chemical and biological processes are typically made at a finite number of specific localities during relatively short time periods. These data are then applied within the context of specific methodologies and the analytical or modelling results are used to infer process dynamics and their resource-specific importance over much broader spatial and temporal scales. Although the assessment of these

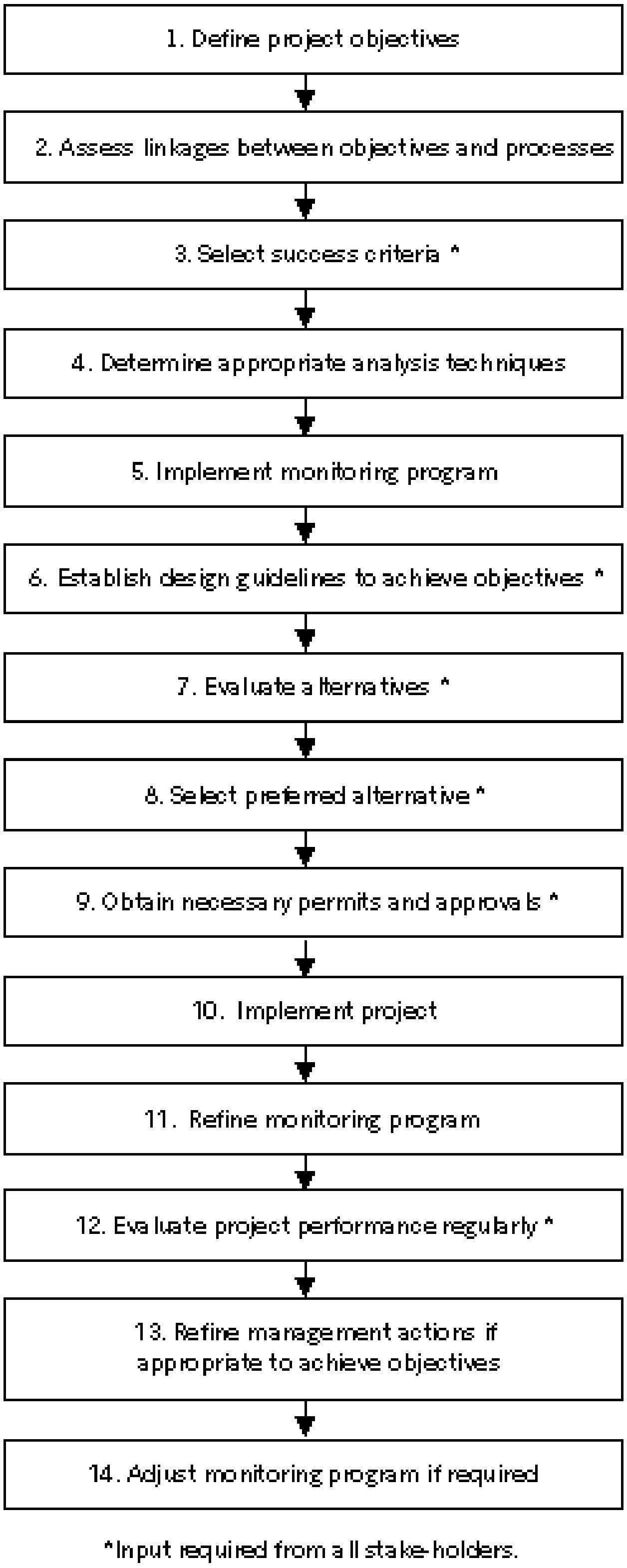

Figure 2 | An approach for multi-objective river management.

components has historically been undertaken from a narrowly defined or resource-specific view, the current trends are toward more integrated data collection and linkages between simulation tools within Geographical Information Systems (GISs) and integrated analysis systems. This trend in the use of GIS and integrated analysis systems also provides an expanded set of analytical capabilities upon which more complex and integrated assessment and monitoring frameworks can be accomplished (Hardy 1998; Hardy & Addley 1999). The following examples are used to illustrate an emerging multidisciplinary approach to river management which focuses on delineating the physical, chemical and biological processes as well as their linkages within assessment frameworks, where both hydrology and hydraulic modelling represents the core of modelling the process linkages. It also highlights the application of several emerging technologies that focus on data acquisition techniques suitable for reach-specific process modelling and linked process simulations, scaling to watershed level domains, while addressing long-term monitoring needs, and relying on both GIS and integrated analysis systems.

HYDROLOGICAL PROCESSES

One of the most fundamental components upon which river management decisions are made is the quantitative assessment of expected river flows at specific locations at specific times. This may vary from short-term within-day forecasts to long-term assessments of the effect of climatic change on potential water supply. In other places, this may include the ability to assess existing or proposed operating régimes under current or hypothetical conditions. An area that has received little attention in applied river management is the application of stochastic time-series models for the generation of synthetic hydrographs. In typical applications, existing or revised project operations are imposed on a single historical period of the total record in the assessment process. This approach assumes that the sequence of flows observed in the past will be repeated in the future. This of course is not the nature of river flows since hydrological time series are a stochastic process and at best only the underlying statistical properties of the time series can represent the inherent characteristics of the flows (Salas 1980). Incorporation of stochastic time series generation capabilities as an integral part of the hydrological modelling of assessment frameworks also represents one way of addressing the uncertainty in future flows and can allow incorporation of environmental risk assessment in the decision process. These techniques are well established and taught in most graduate programs in water resource engineering; their absence in applied river management studies is unwarranted. Time-series modelling is available in a wide array of commercially available analysis packages and existing desk top computer capabilities pose no computational limitations.

A variety of modelling tools are available that can be utilized to represent simple to extremely complex stream network systems. These systems may include multiple service areas with complex, seasonally varied water demands (e.g. hydropower, municipal water supply, agriculture and fisheries) and require time-varying rules on use of existing or proposed reservoir systems. Figure 3 illustrates the underlying hydrology model structure for the Weber Basin Decision Support System which can be linked to real-time forecasts of short (hourly/daily) or long term (monthly, seasonal, and annual) runoff, either based on empirical data or simulated system-wide operations (Stevens *et al.* 1997). Flow routing within specific stream network components can accommodate steady-state modelling or linkages to dynamic flow routing models. Existing hydrology models are often provided within the framework of simulation systems that provide end-users with easily modifiable, system-wide project operations that link stream and reservoir water quality to measures of other resource, such as those of fish and recreation (Stevens *et al.* 1997; Williamson *et al.* 1993).

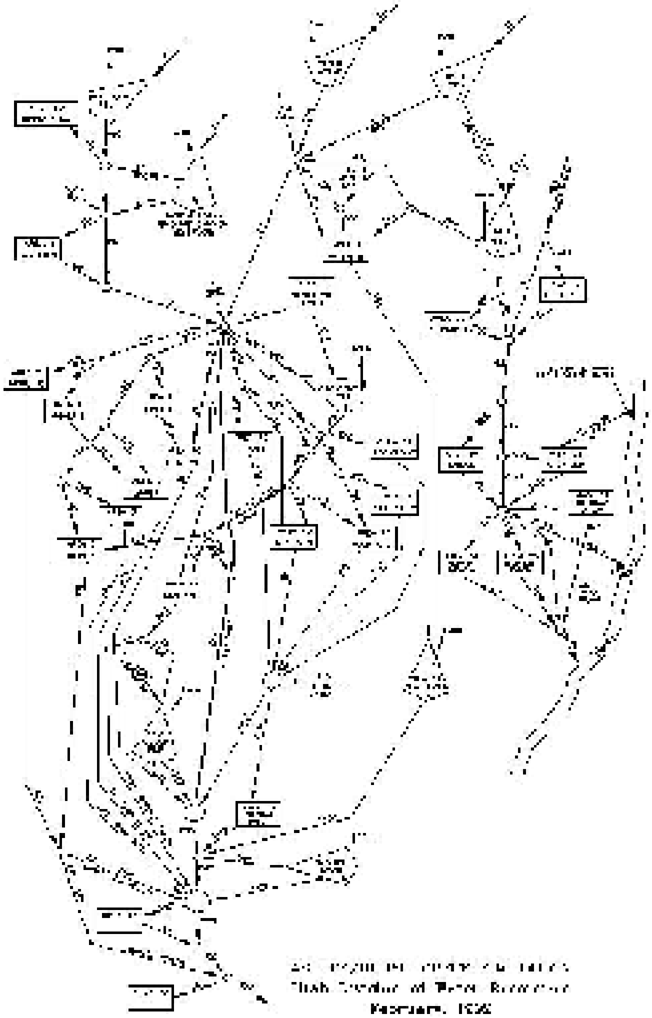

Figure 3 | Water balance modelling structure for the Ashley Creek component of Weber Basin Decision Support System.

SPATIAL CHARACTERIZATIONS AT THE WATERSHED LEVEL

One of greatest challenges in river management is the adequate characterization of the spatial domain when the area of interest may encompass many hundreds of miles and include tributary systems. This is often the case when target resources include migratory or anadromous species and recreation. The data needs of specific disciplines often require labour-intensive data collection efforts at selected reaches in a manner that provides quantitative delineation of both within river features (e.g., fish habitats) and active channel characteristics, such as riparian community distributions, yet will allow extrapolation of results over much longer spatial domains. These data collection efforts must also consider the need to meet long-term monitoring requirements under adaptive management programmes.

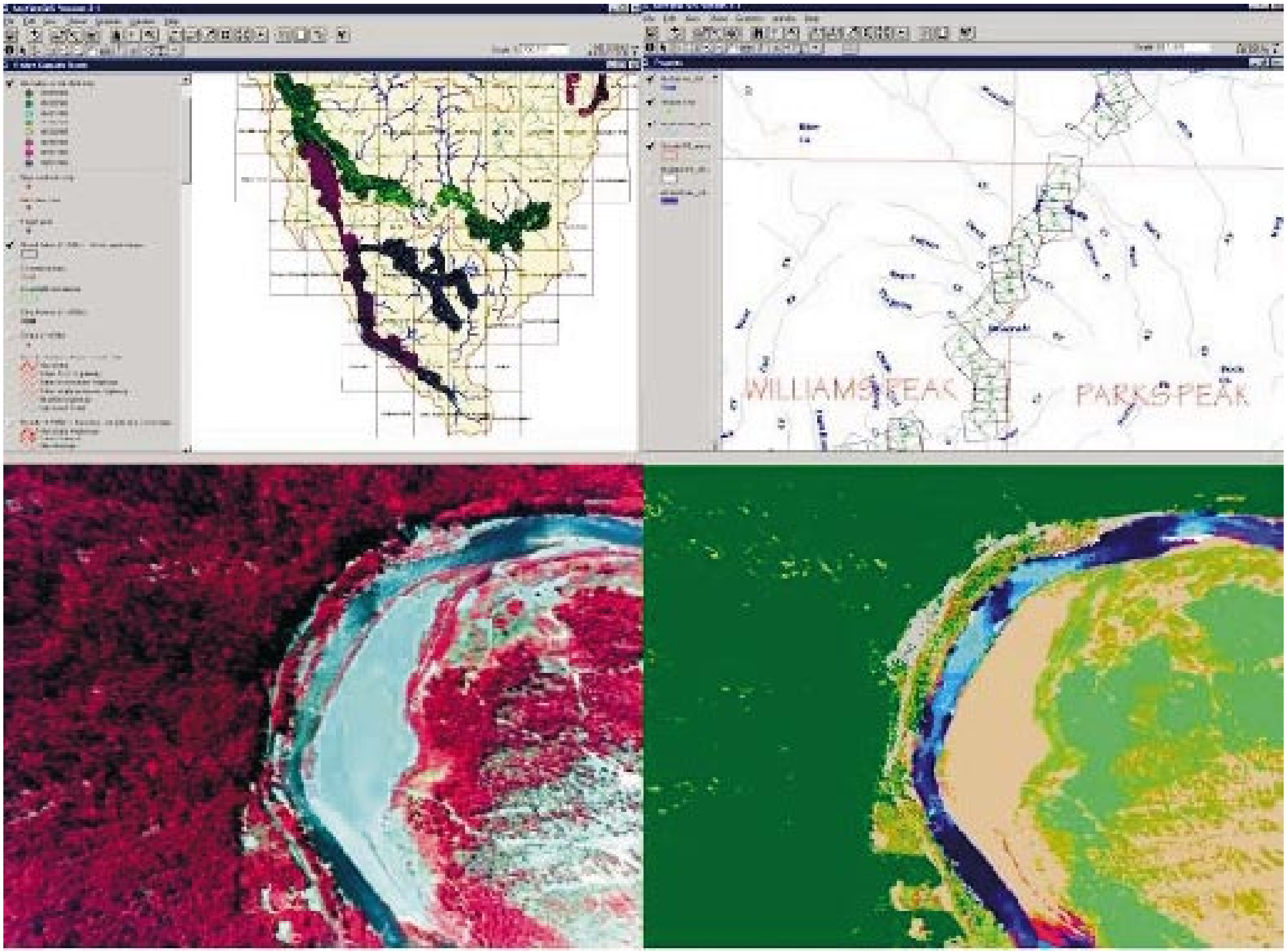

Figure 4 | *Top left:* flight line tracking of aerial digital multi-spectral sensing aircraft; *top right:* GIS coverage of individual image ground footprints for a single flight line; *bottom left:* three-band false colour composite digital multi-spectral image of the Klamath River; *bottom right:* GIS resource classification of digital image shown in Panel C.

The existing high spatial and spectral resolution of both satellite and airborne remote sensing platforms, such as can acquire digital imagery over extensive spatial domains, are now readily available (Baker 1986; Muller *et al*. 1993; Milton *et al*. 1995; Hardy *et al*. 1994). For example, the data shown in Figure 4 represent the flight path of an airborne remote sensing platform that acquired digital multi-spectral data at 0.5 metre resolution for over 600 miles within the Klamath River Basin during a one week period. This figure also shows the corresponding GIS layer which identifies the ground footprint of each successive image that links the acquired imagery to a rectified map base so that resource managers and researchers can retrieve specific scenes. The third panel in this figure illustrates one 3-band composite multi-spectral image for a single scene covering approximately 0.5 kilometres of river channel. Finally, the last panel illustrates the resulting riparian vegetation and fish habitat classifications derived from the digital multi-spectral image.

These data were utilized to establish a basin-wide baseline of available fish habitat and riparian community composition and distribution for long-term monitoring purposed as part of the adaptive management programme within the basin. The imagery was also utilized to help establish the location and spatial extent of 'representative reaches' where high-intensity data collection efforts were established for more quantitative process-based studies of flow, fish habitat utilization, long-term riparian community responses, sediment transport on the basis of which related studies could be undertaken. This imagery is also utilized to integrate ground-based sampling of water quality, fish and invertebrate distributions within a GIS and utilized in the extrapolation or linkage of intensive study site results to the broader spatial domains of the respective tributaries and main-stem river.

SPATIAL CHARACTERIZATIONS AT THE REACH LEVEL

At a practical level, most studies rely on intensive work at one or more reach level locations to derive the underlying quantitative assessments upon which river management decisions are ultimately made. For example, hydraulic modelling at the reach level is necessary to quantify and model the flow-dependent linkages between such factors as sediment transport, water quality, and biological processes. This has historically relied on the collection of cross section profiles of the channel at a few locations within each study reach. Use of high-resolution, low-elevation aerial photography with soft-copy photogrammetry techniques are currently capable of generating digital terrain models with less than 0.01 metre horizontal and vertical spatial errors for reaches in excess of several kilometres (Figure 5). These approaches are also capable of obtaining acceptably accurate subsurface topographies under clear water conditions (Winterbottom & Gilvear 1997; Gilvear *et al*. 1995; Hardy *et al*. 1994). However, even under turbid conditions, the integration of these photogrammetric results with high precision GPS-linked hydroacoustic mapping of within-water channel topographies is also possible (e.g. Figure 5). These types of spatially accurate data are invaluable for the quantitative detection of channel form changes, direct linkage of 3-dimensional channel topographies to higher-order hydraulic modelling approaches and to meet spatially accurate quantitative assessments of monitoring programmes. Data acquisition utilizing these approaches is inherently GIS compatible and can be used in a variety of physical, chemical and biological model development, calibration, verification, and validation efforts as part of adaptive management programmes. Furthermore, the utilization of the data within GIS allows the overlay of other spatial layers such as vegetation mapping, substrate mapping, or cover mapping, which may be important in the overall evaluation of aquatic, wildlife and recreation resources.

SIMULATION OF HYDRAULIC PROCESSES

One of the difficulties facing watershed managers and flood control engineers is determining the appropriate level of analysis to answer these complex issues. Further, many of the familiar tools, such as the HEC-2 or HEC-RAS models used by the Federal Emergency Management Agency for flood insurance studies, may be inadequate to quantify many of the critical processes influencing flood risk analysis and multi-objective river management. Other more complex 1-dimensional models developed to assess the flow dynamics and/or parameters for the evaluation of ecological response include widely used models such as MIKE-II, IFIM, SOBEK and ISIS.

Computer codes have matured during the past two decades, evolving from custom-designed applications to user-friendly packages requiring little knowledge of programming, hydrology or ecology for their operation provided the model is set up professionally. This evolution has been classified as the five generations of computer modelling (Abbott 1991). Although development of codes to overcome specific problems still remains a productive research area, most attention is being placed upon the integration of existing codes to simulate the linkages between the physical processes (hydrology and geomorphology), chemical processes (water quality) and the responses within ecological processes (habitat and biological responses). In particular, attempts to quantify the uncertainty and gaps-in-knowledge of these linkages are of particular concern. The emergence of powerful and cheap computers provides easy access to sophisticated models once restricted to main frames or super computers.

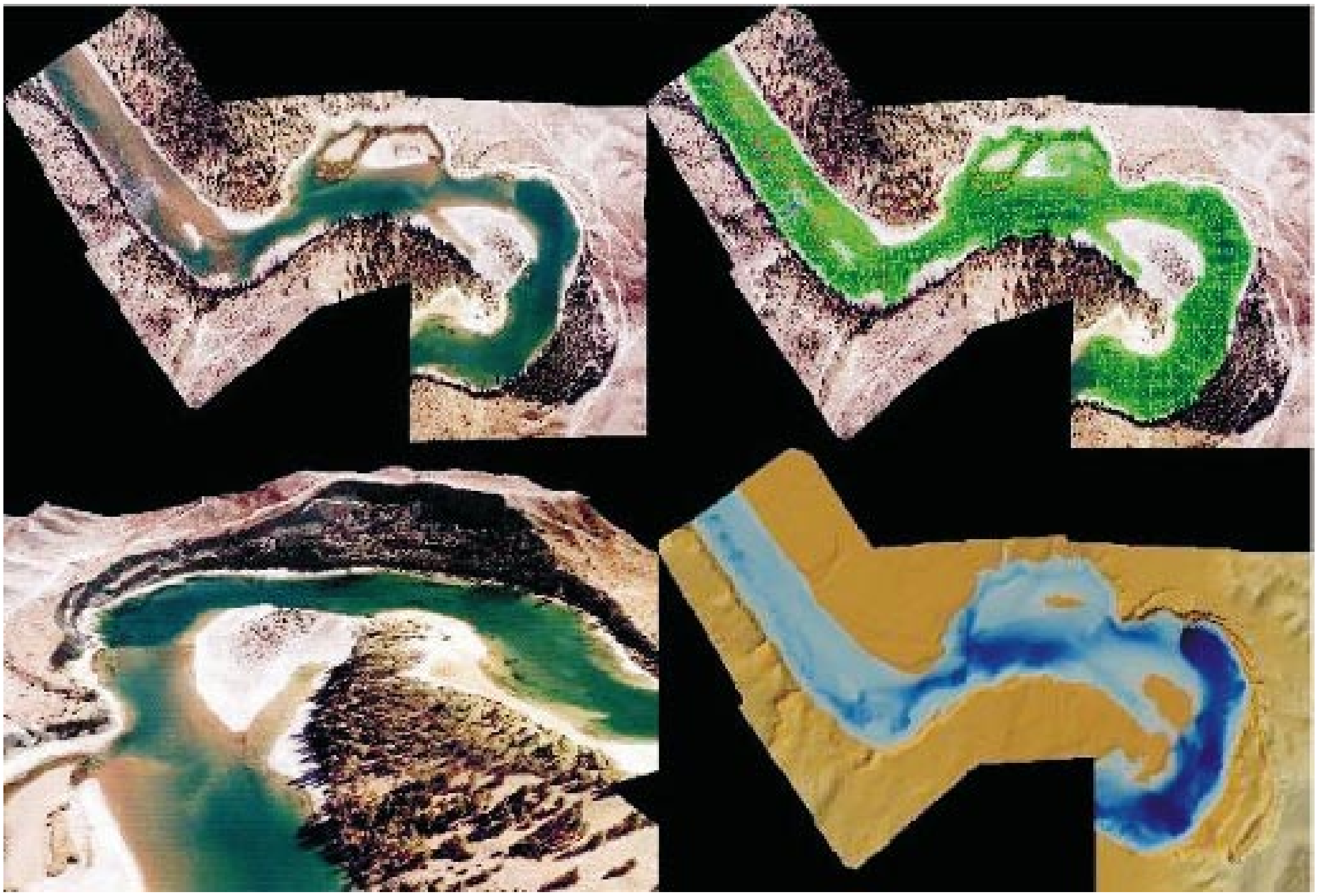

Figure 5 | *Top left:* high-resolution digital aerial photograph of an intensive study site used to generate digital terrain model; *top right:* GPS-coupled hydro-acoustic mapping tracks of channel topographies; *bottom left:* digital aerial photograph draped over 3-dimensional terrain model of study site; *bottom right:* 3-dimensional terrain relief for study reach in GIS format.

Frequently, flood management analyses require more sophisticated methods than the steady-state, gradually varied flow models used for flood insurance studies and floodplain zoning issues. Potential liability or increased hazards to communities resulting from decreased channel maintenance for ecological purposes or budgetary cutbacks, flood plain restoration or preservation, as well as reservoir operation, all require careful analyses that are both transparent and defensible before a broad range of interest groups.

Some of these physical processes are well understood, such as the attenuation of a floodwave in a 1-dimensional system (Chow *et al*. 1988) and the variation of roughness coefficients with stage (van Rijn 1993). Most of the research and model development has focused on 1-dimensional or pseudo-2-dimensional models. Floodplains are treated as either offstream storages or are incorporated into the conveyance of the main channel. The conveyance of the entire channel can be estimated as a single section with weighted hydraulic characteristics or by the 'method of slices'. In the method of offstream storages, there is no dynamic connection between the floodplain and river, and only the conservation of mass component of the St. Venant equations is considered (Cunge *et al*. 1980).

Recent findings from the Science and Engineering Research Council Flood Control Facility (FCF) at HR Wallingford, UK (Ackers 1993; Greenhill & Sellin 1993;

Willetts & Hardwick 1993) have shown that errors using these methods can be significant. For example, predictions of discharge can be in error by as much as the bankfull discharge in the main channel (or up to 35% of the total discharge) under extreme circumstances. There are two main processes accounting for this discrepancy (Ackers 1992):

- the shear between flow on the floodplain and in the main channel may not be negligible as assumed in 1-dimensional representations of flow in composite channels;
- the exchange of momentum as fast moving water from the main channel flows onto the floodplains and a return flow of sluggish water back into the main channel may be significant.

The processes such as the exchange of flows with the floodplain will vary under different flow events and the predictive capability of a 1-dimensional model may be very poor. A recent study of the Willamette River showed how the floodwave travel times vary depending upon the river stage and the relative contribution of the floodplain interaction (Philip Williams and Associates 1996). To correctly simulate these types of process, a pseudo-2-dimensional or full 2-dimensional model is required.

Existing capabilities of both computer hardware and software systems now allow exploitation of 2- and 3-dimensional hydraulic simulation tools for modelling physical, chemical, and biological processes (see, for example, Leclerc *et al*. 1995; Tarbet & Hardy 1996; Refsgaard *et al*. 1994; Zhao *et al*. 1994). The application of these higher-dimensional hydraulic tools, however, is critically dependent on the quality of the characterization of the 3-dimensional bed topographies relied upon to generate the computational meshes of the hydraulic simulation routines (Figure 5). As mentioned in the previous section, existing technologies can achieve a spatial resolution that effectively eliminates this constraint in many systems. Another inherent advantage to these classes of hydraulic models is their ability to represent complex flow patterns within the river channel. These links those attributes of the spatial flow patterns important to understanding biological processes more realistically. The use of 1-dimensional flow models will remain important for many applications but these tools are incapable of representing those complex flow patterns that are important for understanding and modelling aquatic resource utilization at both the micro-habitat and reach level. For example, 2-dimensional models are capable of predicting eddy re-circulation zones and velocity shear zones as a function of channel topographies and flow changes (Figure 6). These types of feature represent very important physical attributes of flow that often determine whether a particular spatial location is suitable for a specific life stage of fish. Current hydraulic modelling software systems are now providing more integrated linkages to quantitative assessments of shear stress, sediment transport dynamics, and water quality modelling (e.g. SMS, WinXPro, TELEMAC, MIKE suite of models, DELFT3-d, RMA-2, CEQUAL-W2).

LINKAGES TO AQUATIC RESOURCE MODELLING

The inherent linkage derived from the utilization of high-resolution, larger-scale channel mapping and 2- or 3-dimensional hydraulic simulations within GIS provides the ability to develop, implement and validate emerging approaches to aquatic resource modelling. This includes a wide array of mechanistically based bioenergtic approaches (e.g. Jager *et al*. 1993; Addley 1993; Rose & Cowen 1993; Van Winkle *et al*. 1993; Van Winkle *et al*. 1998; Hill & Grossman 1993; Judson 1994; Babovic 1996; Alfredson 1998; Guensch 1999). These approaches assess the potential value of the stream environment at specific flow rates for target aquatic resources (i.e. fish) from an energy perspective and permit the direct linkage of modelling results to field validation data sets, as illustrated in Figure 7.

These energy-based approaches also provide a direct linkage between key flow-dependent physical, chemical and biological processes within the river such as temperature and food resource availability necessary to estimate expected growth rates or even population dynamics (Guensch 1999; Williamson *et al*. 1993). Integration of these data in GIS also permits the derivation of a variety of spatial-based physical and biological metrics that quantify the linkages between functional responses of individuals,

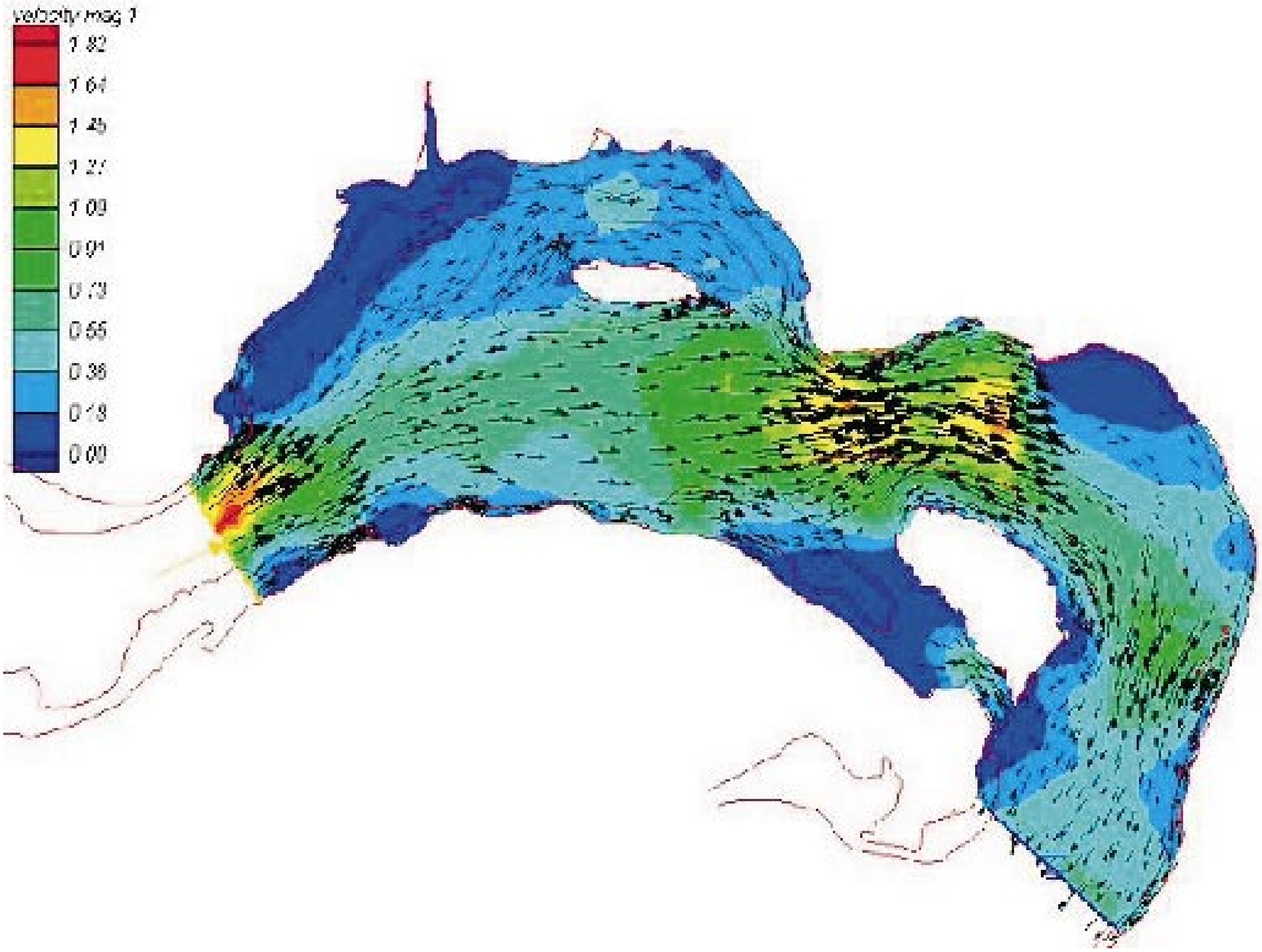

Figure 6 | Simulated velocity vectors and magnitudes derived from 2-dimensional hydraulic simulations of 3-dimensional channel topographies shown in Figure 5.

populations or communities as a function of the flow-dependent spatial heterogeneity of the habitat mosaic (e.g. Bain 1995; Aadland 1993; Freeman & Grossman 1993; Fausch & White 1981; Southall & Hubert 1984; Addley 1993; Stanford 1994; Lobb & Orth 1991; Rabeni & Jacobson 1993; Bovee *et al*. 1994). These physical and biological metrics describe various aspects of flow-dependent spatial heterogeneity that may be linked to functional responses of various species, or to community dynamics such as species dispersal, colonization potential, foraging efficiency, predator avoidance and species replacement (Li & Reynolds 1994; Bain 1995; Aadland 1993; Jowett 1992). Specific metrics that can be derived from these data include fractal–dimensional features (Burrough 1986; O'Neill *et al*. 1988), dominance (O'Neill *et al*. 1988), contagion (O'Neill *et al*. 1988; Turner *et al*. 1989; Li & Reynolds 1994), habitat diversity and relative evenness (Shannon & Weaver 1962; Pielou 1969; Romme 1982), and edge effect (Malcolm 1994). The spatial and temporal characteristics of these flow-dependent process linkages define gradients in depth, velocity, heterogeneity of habitat patch size, persistence of habitat types over ranges of discharges and other biologically significant response measures (e.g. Jowett 1992; Bain 1995; Changeux 1995;

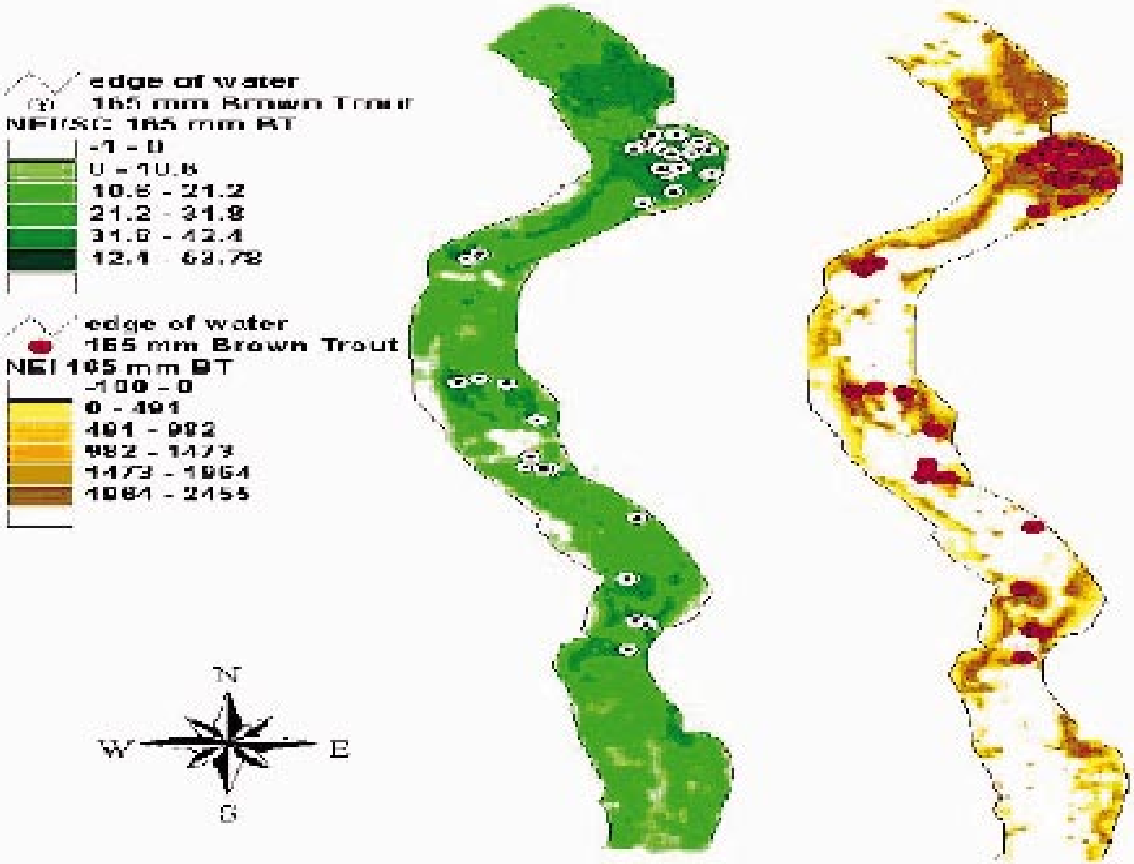

Figure 7 | Predicted versus observed fish locations based on two variations in net energy modelling in GIS for use in model validations (after Guensch 1999).

Barnard *et al*. 1995; Milner *et al*. 1995). These types of analysis will be important tools in implementation of adaptive management programmes because they can expose previously unknown relationships between the habitat mosaic and community structure, and their responses to prescribed flow régimes.

LINKAGES TO WATER QUALITY

Perhaps one of the most important aspects of the direct linkage between high-resolution channel topography, hydrology and hydraulics is the assessment of flow-dependent water quality and temperature dynamics on aquatic resources. This ranges from the assessment of flow- and channel-topography-dependent thermal refugia to spatially explicit differences in temperature regimes between side channel and main channel habitats. For example, de-stratification of thermal refugia in pool habitats due to excessive flow can occur in some systems and be extremely deleterious to rearing life stages of young salmonids dependent on these microhabitats. Accurate 3-dimensional channel topographies linked to 3-dimensional hydraulic and water temperature models are capable of assessing the relationship between flow and mixing potential to address this issue. It is also recognized that for a variety of species and life stages of fish, one of the most important factors that control growth and population dynamics can be the access to and the characteristics of side-channel or back-water habitats. The characteristics of these habitats are important in terms of their hydraulic properties, water quality and temperature, and the evaluation of the spatial differences between main channel and side channel or back water habitats is not readily feasible utilizing conventional 1-dimensional hydraulic and water temperature simulations. Incorporation of the time-dependent simulations of the flow régime over seasonal periods can also help in the assessment of differential growth rates, based on the persistence and characteristics of these habitats for young fish.

At a broader watershed scale, the linkage between hydrology simulations, reservoir and river reach water quality has been utilized to assess the potential for different integrated reservoir management operations to affect treatment costs of municipal water supplies. Other applications have relied on these linked process modelling efforts to evaluate waste load allocations, selenium dynamics in spatial patterns of return flows, and within-year water allocation strategies in conjunctive reservoir operations to meet competing municipal, agricultural and aquatic resources needs (Stevens *et al*. 1997).

LINKAGES TO INTEGRATED SEDIMENT DYNAMICS

Several existing software systems are capable of integrating hydrology, hydraulics and sediment dynamics to assess changes in channel topography and spatial patterns of shear stress important to other physical, chemical, and biological processes. For example, several modelling systems permit time-step dynamic changes in the spatial bed topography and resulting changes in the spatial distribution and characteristics of sediment and hydraulic properties. These types of model have not yet received much attention in their linkages to aquatic resource modelling such as for fish or macroinvertebrates. However, the linkage between flow, sediment characteristics and spatial distribution with aquatic invertebrate community structure will represent an important area of research in the future utilization of bioenergetic based approaches to fish modelling as described above. In addition, the use of these linked modelling systems to assess longer-term changes in plan-form channel topography under alternative flow régimes represents an important component for guiding restoration efforts under adaptive management guidelines. This is often approached from the assessment of changes in flows near one-half to above-bank, full-type discharges with implications for sediment budgets characterised by size-class distributions. Other elements important to these assessments are temporal distributions of the flow régime to match timing of other ecological processes such riparian seed dispersal or conditioning of spawning gravel and pool scour for fish.

LINKAGES TO RIPARIAN COMMUNITY DYNAMICS

Historically, the importance of maintaining the linkage between sediment transport and flow timing, magnitude, duration and frequency with the riparian community were largely overlooked in river management applications. Long-term alterations in the stream channel characteristics with delayed but deleterious consequences on water quality, temperature and aquatic resources have now been firmly acknowledged and play a central role in many restoration programmes. The integration of technologies such as multi-spectral imagery with high-resolution digital terrain models (see Figure 8) provides expanded opportunities to assess linkages between flow régimes and riparian process dynamics. The modelling of flow patterns in conjunction with the hydraulic characteristics at larger spatial scales can better define the important components of flow, channel topographies, and sediment dynamics on existing riparian community distribution and structure. The elucidation of these linked processes can then serve as a basis for assessing alternative flow scenarios or restoration strategies in applied river management.

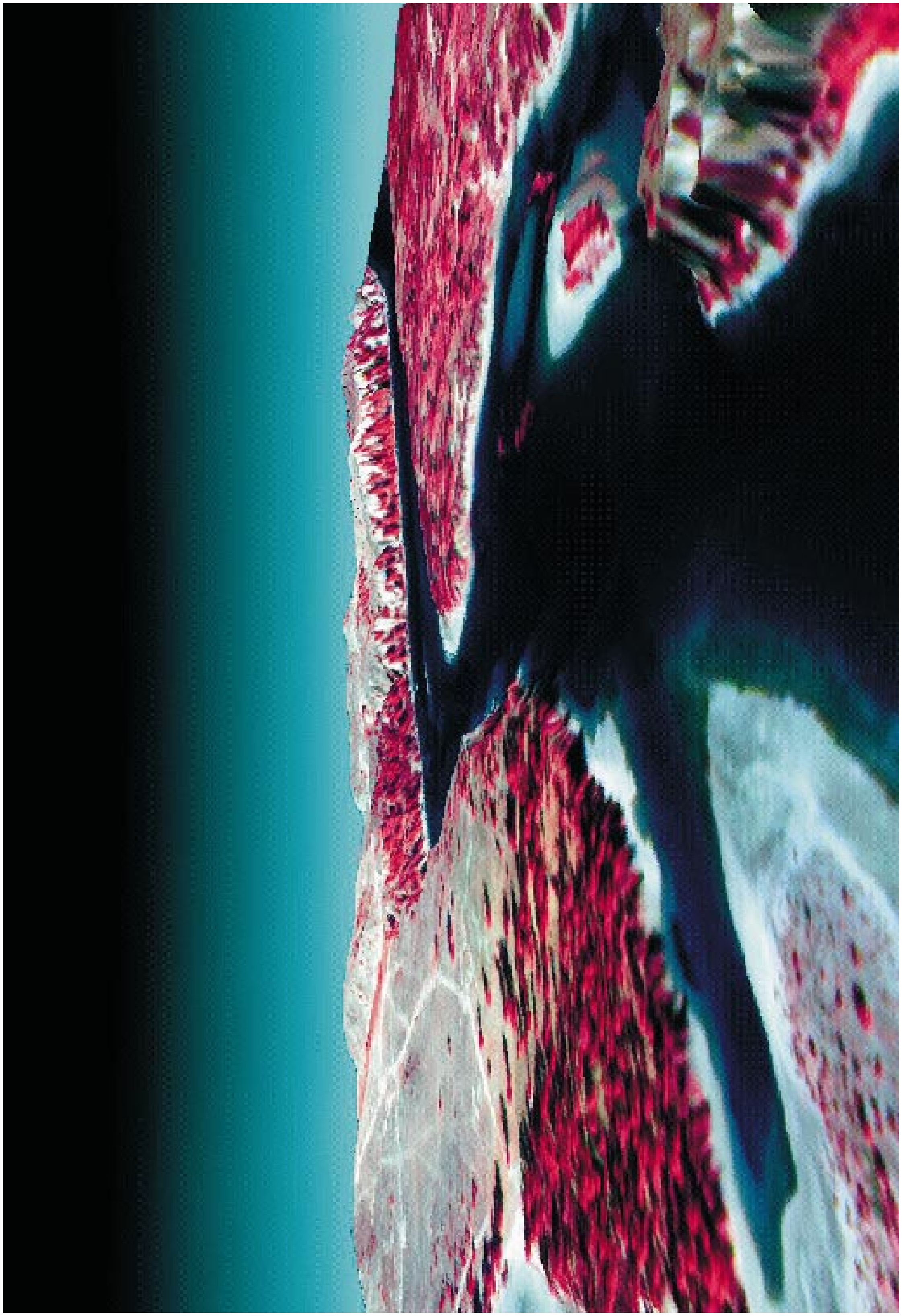

Figure 8 | Digital multi-spectral imagery draped over 3-dimensional digital terrain model shown in Figure 5.

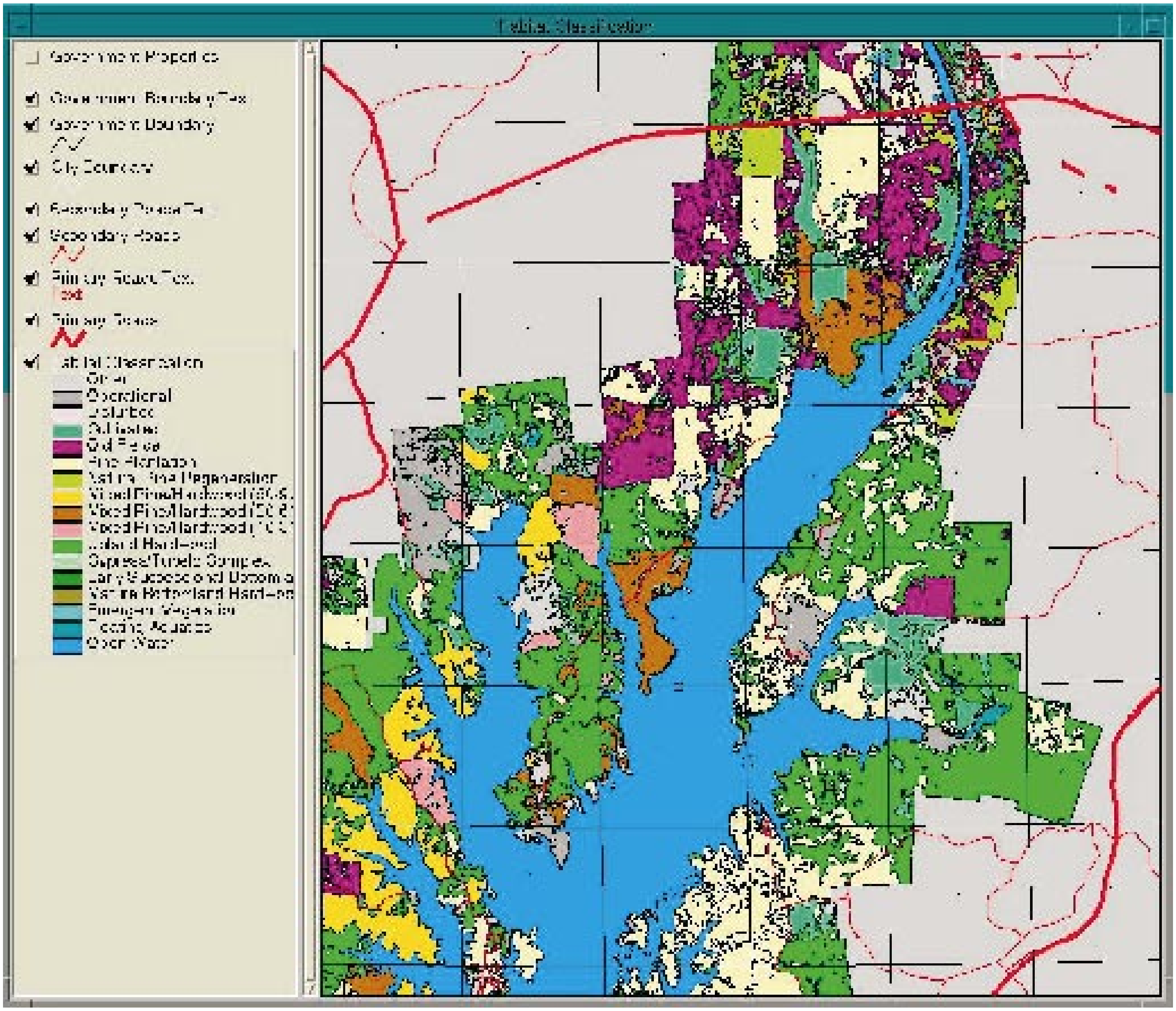

Figure 9 | Habitat values predicted for bobcat within the Tennessee Tom-Bigbee Waterway.

LINKAGES TO WILDLIFE MODELLING

The acquisition of broad spatial-scale data over extensive watershed areas using digital multi-spectral (or other remotely sensed) data has broad potential in river basin management. This type of imagery has been employed to develop sophisticated applications based on GIS for wildlife management (Hardy *et al.* 1999). In this example, the U.S. Army Corps of Engineers has acquired digital multispectral imagery for over 200 miles of the Tennessee – Tom Bigbee waterway in Louisiana and Mississippi. This imagery, with ground-truth data sets, was utilized to develop a GIS that relied on an image-derived classification of the landscape mosaic using 12 different vegetation-based habitat and land-use types (Figure 9). This imagery and resulting habitat and land-use coverage extends over approximately a one-mile strip on each side of the waterway, thereby including mitigation lands and management responsibilities. The GIS system links dynamically over 10 different wildlife species with management interest to the Corps by using U.S. Fish and Wildlife habitat-suitability models. This system allows the Corps to assess changes in land use practices within the GIS, such as replacement of an old field plot with a managed food plot, and assess the expected changes in habitat suitability for all target species. These evaluations are conducted in the office to determine the best cost: benefit ratios for annual mitigation actions or to provide environmental assessments of proposed third party actions to meet U.S. National Environmental Protection Act compliance requirements. The system was also designed to allow integration of other remote sensing data sets (such as aerial photogrammetry or new digital multispectral data sets) in the future, so as to assess quantitative changes in land use throughout the river corridor.

THE ROLE OF MONITORING

Monitoring is an essential component of any management plan. Data is collected for a range of purposes and the spatial density and frequency of measurement depends upon the use. The objectives of monitoring can be summarised as:

Research: to further our understanding of fundamental processes;
Analysis: to provide the basic data necessary for design and simulation;
Permit Compliance: to ensure any regulatory conditions associated with the plan are satisfied;
Construction Monitoring: to protect adjacent resources from adverse impacts associated with implementation;
Validation: to assess design assumptions for accuracy;
Success: to gauge the performance of the project and compare this with the original expectations;
Maintenance: to evaluate the extent and frequency of any maintenance actions based on project performance;
Adaptive Management: to determine whether any alterations in management approaches will result in improved performance;
Knowledge Base: to develop databases from which design criteria can be derived for future projects on the same site or on other similar systems in the region.

Typical parameters that may be monitored include the hydroperiod in wetlands and floodplains, turbidity, temperature, sediment transport and substrate composition, bank erosion, bathymetric changes in the river channel, groundwater variations adjacent to the river, vegetation type and density, water quality and the diversity and populations of indicator organisms. The frequency and spatial density of monitoring should be selected based on the purpose, and may vary at different stages of the project.

A CASE STUDY: LOWER RED RIVER RESTORATION PROJECT, IDAHO, USA

The Red River is a tributary of the South Fork Clearwater River, an important anadromous fisheries stream in central Idaho, USA. The Red River is the eastern-most drainage of the South Fork Clearwater River. The stream originates in north-central Idaho at an elevation of approximately 2000 m above sea level, and flows west about 45 km to its confluence with the American River near Elk City, Idaho. The Lower Red River Meadow Restoration project is located on the Red River Wildlife Management Area (RRWMA), owned by the Idaho Department of Fish and Game (IDFG), approximately 5 km downstream from the confluence of the South and Main Forks of the Red River. Elevations at the project site are around 1280 m, and the meadow receives an average of 75 cm of precipitation per year. The project development has generally followed the framework outlined in Figure 2.

The overall objectives of the Lower Red River Meadow Restoration Project include:

- Restore the natural river channel shape, meander pattern, and substrate conditions to enhance the quality and quantity of spawning and rearing habitat

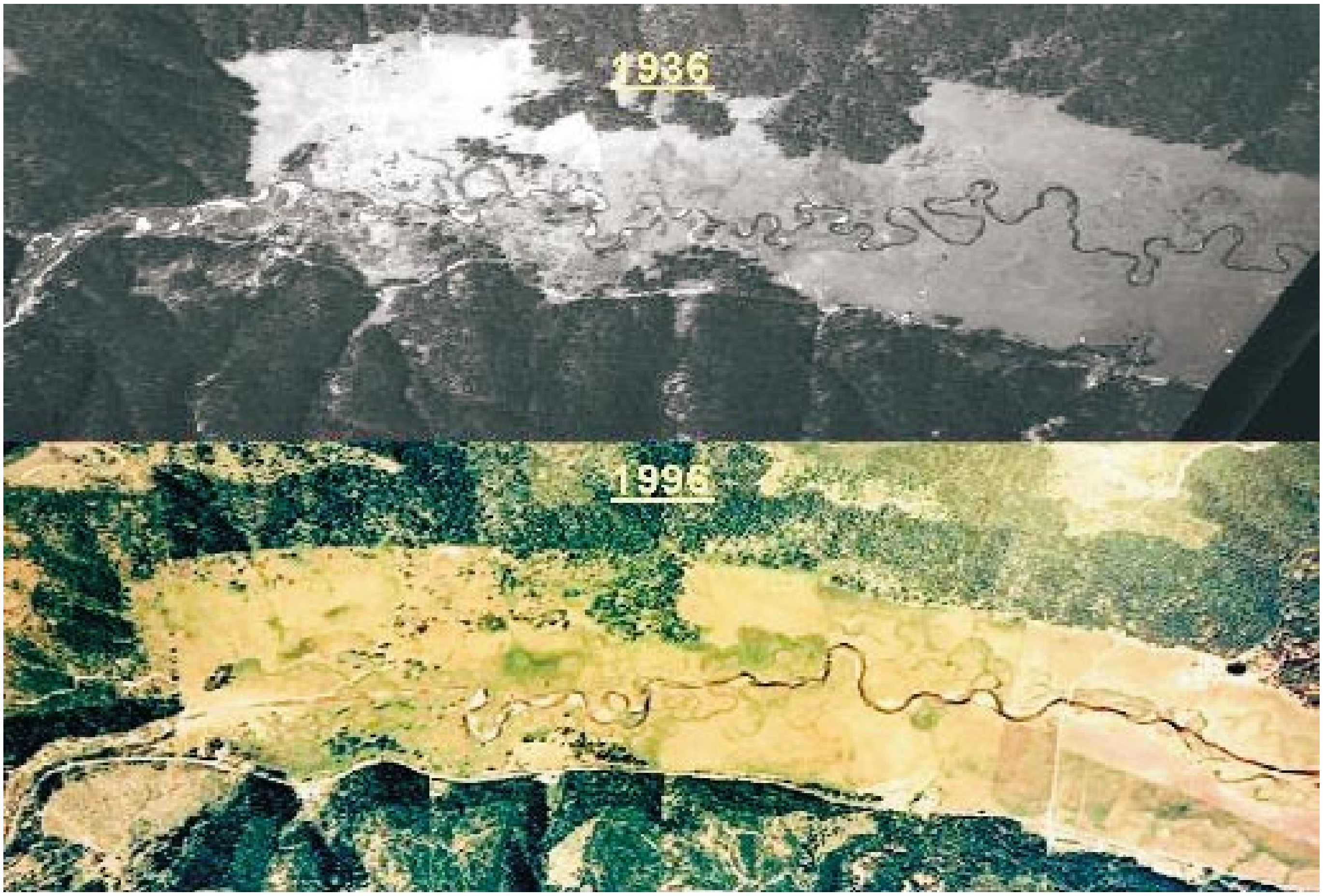

Figure 10 | 1936 and existing conditions at the Red River Wildlife Management Area.

for chinook salmon (*Oncorhynchus tshawytscha*), steelhead trout (*Oncorhynchus mykiss*), bull trout (*Salvelinus confluentus*), and other anadromous and resident fish species.

- Restore meadow and riparian plant communities to enhance fish and wildlife habitat, stabilize stream banks, and reduce water temperatures.
- Measure and document progress in satisfying short- and long-term project goals, objectives, and outcomes.
- Promote public and agency awareness and scientific knowledge of watershed restoration principles and techniques

The project is one element of a watershed-wide management programme targeted at salmon recovery and other ecological enhancements (Columbia Basin Fish and Wildlife Authority 1991; Northwest Power Planning Council 1996). As early as the turn of the 20th century, reaches of the Red River were channelised through mining and agricultural activities; the changes observed between 1936 and 1996 are illustrated in Figure 10. The channelising has resulted in channel incision of about 1 m and most of the riparian vegetation has been removed, resulting in several different ecological impacts. The channel now conveys larger flood flows, resulting in less frequent inundation of the meadow. The shallow groundwater in the meadow has been lowered to the new low-flow elevation in the river during the dry season resulting in draining of some floodplain wetlands and altered plant communities. The greater depths and velocities in the straightened channel at high flows have altered the sediment transport through the reach and reduced the deposition of fine sediments on the floodplain. The geomorphic changes in the channel include a reduction in pool habitat and an increase in the width:depth ratio at low flows. The combination of these geomorphic changes and the loss of shading by riparian vegetation have resulted in elevated water temperatures and a significant loss of spawning and rearing habitat. The restoration project is an effort to improve the fish and wildlife habitat and is managed by a 20-member Technical Advisory Committee (TAC), composed of agency and tribal representatives, and a team of consultants. Phases I and II were constructed in 1996 and 1997, respectively, and Phases III and IV, on the Red River Wildlife Management Area (RRWMA) will be completed in 1999.

The RRWMA project site has considerable potential for restoring and protecting a wide variety of fish and wildlife resources (IDFG 1999). Historically, the Red River supported a large diversity of anadromous and resident salmonid species including chinook salmon (*Oncorhynchus tshawytscha*), steelhead trout (*Oncorhynchus mykiss*), Westslope cut-throat trout (*Oncorhynchus clarki lewsi*), bull trout (*Salvelinus confluentus*), and mountain whitefish (*Prosopium williamsoni*). Other resident fish species include smaller populations of brook trout (*Salvelinus fontinalis*), mountain sucker (*Catostomus platyrhynchus*), longnose dace (*Rhinichthys cataractae*), speckled dace (*Rhinichthys osculus*), Pacific lamprey (*Lampetra tridentata*), and sculpin (*Cottus* spp.). Part of the decline of both resident and anadromous fish populations in the Red River has been linked to habitat and water quality degradation (Northwest Power Planning Council 1994; University of Idaho 1999).

The Red River meadow also provides important habitat for several game and non-game wildlife species. Elk (*Cervus elaphus*)†, moose (*Alces alces*), and white-tailed deer (*Odocoileus virginianus*) graze in the meadow and utilize adjacent timbered edges for calving and fawning areas. From late March to late May, up to 200 elk can be seen in the meadow on the RRWMA. In late May and early June, as many as 40 elk cows use the meadow and surrounding timber for calving (IDFG 1999).

With numerous oxbows and other wetland areas, the RRWMA has good potential for attracting resident and migratory birds. Canada geese (*Branta canadensis*) and mallards (*Anas platyrhynchos*) nest in the meadow, and a variety of birds such as blue herons (*Ardea herodias*), shorebirds, sandhill cranes (*Grus canadensis*), and osprey (*Pandion haliaetus*) migrate through the area. A pair of red-tailed hawks (*Buteo jamaicensis*) nests in one of the lodgepole pine (*Pinus contorta*) stands each year. Northern goshawks (*Accipiter gentilis*) have been sighted along the timbered edges (IDFG 1999). Waterfowl and neotropical migrant songbirds are already utilizing habitat created as part of the restoration project. Amphibians are present throughout the meadow.

The project will restore channel planform, slope, and cross-section dimensions to conditions similar to those before the channelization and other disturbances along a 6.5 km reach (Table 1). Utilizing an adaptive management process, this design incorporates results from an extensive monitoring effort underway at the site. Several restoration alternatives, ranging from no action to the creation of a theoretical planform alignment, have been considered. The preferred alternative includes an 18% increase over the existing sinuosity, a 13% decrease in gradient, channel cross-section dimensions changed to decrease water temperatures by decreasing the low flow width:depth ratio, and the promotion of riparian vegetation.

The design is based on the concept of restoring the physical conditions close to dynamic equilibrium in the meadow (Barinaga 1996). The new channel has three primary features: a low-flow channel, a bankfull-capacity-sized channel to match the dominant (or channel-forming) discharge (Knighton 1984; Leopold *et al*. 1964; Wolman & Miller 1960; Williams 1978), and a floodplain to convey flows greater than the bankfull flow. The low flow channel will convey approximately 0.6 m^3/s and the bankfull discharge will be approximately 17 m^3/s, which corresponds to an approximately 1.5 year return period.

The alignment of the channel has been selected based on the historic channel position, increased sinuosity to restore geomorphic characteristics, current conditions and existing elevations at the site, and minimization of disturbance to existing wildlife resources. Other key design constraints include:

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†U.S. taxonomy used.

Table 1 | Selected channel characteristics in restoration area.

	Estimate of historic (1936) conditions (entire RRWMA)	Pre-construction (1995) conditions (entire RRWMA)	Phase I and II (completed)	Phase III and IV (scheduled 1999)
Channel length/metres	3,750	2,430	3,950	4,200
Channel slope	0.0017	0.0026	0.0016	0.0015
Sinuosity	2.41	1.56	2.54	2.71

- The frequency and depth of inundation of downstream properties should not increase as a result of restoration activities at the RRWMA;
- Heavily-engineered bank stabilization and grade control elements of the design should be minimized to the greatest extent feasible;
- Channel cross-section dimensions and planform should utilize historic channels where feasible, be designed for equilibrium conditions, and promote the creation of micro-habitats for aquatic species.

Table 1 summarizes the channel conditions in the meadow before, during and after all four phases of construction; the new channel planform is shown in Figure 11. Table 1 also demonstrates that after the completion of Phases III and IV the sinuosity of the channel will be slightly greater than the 1936 condition because there appears to be some evidence of channel straightening before then (Figure 10).

The design philosophy has been to try to recreate the physical processes before the intervention of European settlers, but an important task is to evaluate the success in achieving the primary objective of improving fish habitat—and eventually contributing to the recovery of certain species.

Of particular interest is the attempt to develop metrics to quantitatively evaluate the progress towards the primary purpose of increasing anadromous fish populations. Periodic direct population counts have great scatter and the population is influenced by many external influences, which are difficult to measure. Thus two main goals have been defined (Bauer *et al*. 1998):

GOAL 1. Restore natural river channel shape, meander pattern, and substrate conditions to enhance the quantity and quality of spawning and rearing habitat for chinook salmon, steelhead trout, bull trout, and other anadromous and resident fish species.

GOAL 2. Restore meadow and riparian plant communities to enhance fish and wildlife habitat, stabilize streambanks, and improve water quality.

A series of objectives have been established for each goal, with success criteria that can be monitored and reported.

OBJECTIVE 1.1 Design and construct natural, stable cross-section geometry, meander pattern, and profile given current watershed characteristics. Performance measures include channel length, gradient, and sinuosity at the reach level; cross-sectional dimensions and local bank erosion. More than 80 cross sections and microhabitat areas have been documented and are surveyed annually to detect changes and more than 12,000 topographic points define the topography and bathymetry of the site.

OBJECTIVE 1.2 Design and construct the channel to maintain the dynamic equilibrium of sediment balance throughout the Red River Meadow. Performance measures include assessment of sediment balance, aggradation/degradation, bank erosion, and surface substrate composition.

OBJECTIVE 1.3 Design and construct a self-maintaining channel geometry to increase the quantity and quality of spawning and rearing habitat for chinook salmon and other native species. Performance measures include macro-habitat features—the change in quantity of pool/

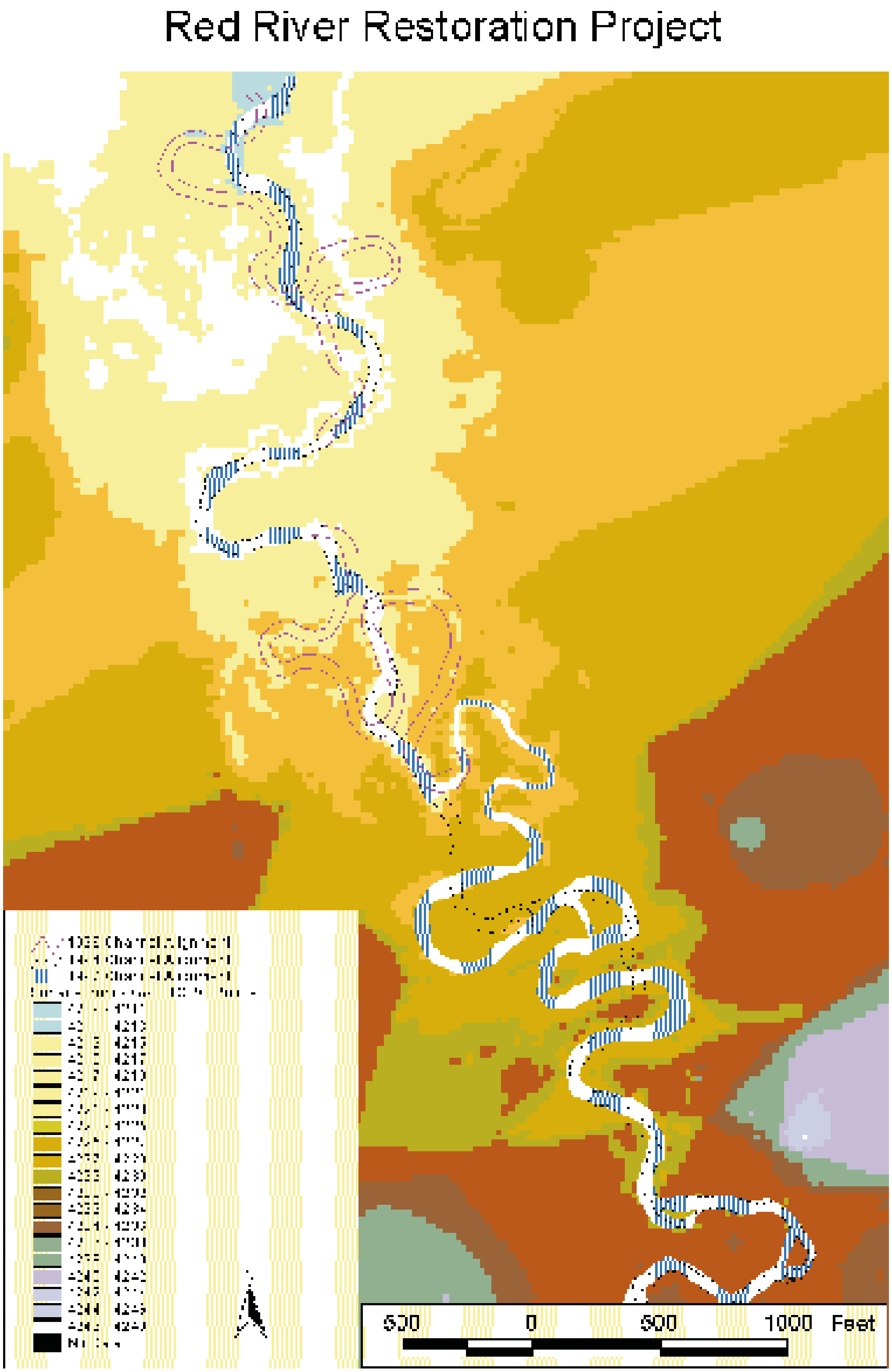

Figure 11 | Proposed Phase II and IV channel alignment for the Red River Restoration Area.

riffle sequences, residual pool depth, channel dimensions; and micro-habitat features such as velocity, depth, substrate quality, and habitat cover. Temperature is a measure of the quality of habitat throughout the reach.

OBJECTIVE 2.1 Restore floodplain function and soil moisture régime required for the establishment and sustainability of indigenous riparian plant community. Changes in the soil moisture régime are measured through the decrease in depth-to-water at locations for riparian plant communities, both in aerial extent and duration of saturation. Performance measures include the difference between top-of-bank and water surface at low flows, depth-to-water in riparian and wetland zones, extension of the flooded zone, and extension of the hydro-period.

OBJECTIVE 2.2 Design and establish a sustainable riparian plant community in the riparian zone to stabilize streambanks, provide fish habitat cover, increase shade and canopy, reduce water temperature, and improve habitat for riparian-dependent wildlife. Performance measures include growth and survival of planted riparian vegetation, change in riparian community composition, increase in fish habitat cover components (bank undercuts, overhanging vegetation, shade and canopy), and increase in wildlife habitat cover (riparian and wetland plant community structure and canopy).

OBJECTIVE 2.3 Design and establish off-channel wetland/ponds and wet meadow habitat conditions suitable for a diversity of waterfowl, shorebirds, songbirds, and other wildlife. Performance measures include the duration and extent of seasonal inundation; and the increase in riparian and wetland plant community (structure and canopy) useful as wildlife habitat cover.

The simulation model of hydrology, water quality, sediment transport and geomorphic evolution is integrated using GIS to display many of these performance measures. Management decisions are then made by the TAC, on the basis of these simulated and observed parameters.

Information presented to the TAC on an annual basis to track progess toward project goals and any direct management actions are decided before each field season. Further information on the annual monitoring programme, real-time images and continuous monitoring data are accessible on the project web page at *http://uidaho.boise.edu/redriver*.

FUTURE DEVELOPMENTS IN THE ERA OF HYDROINFORMATICS

Clearly, a future hydroinformatics will in large part focus on the better integration of spatially explicit data collection efforts, coupled to process linked modelling of hydrology, hydraulics, sediment transport, water quality/temperature, and flow-dependent resources such as fish and recreation. The importance and role of both hydrology and hydraulics in this linkage cannot be overstated and the assessment of higher-order hydraulic models, as well as integration of more forecasting-directed capabilities of the hydrology will continue. The utilization of GIS to integrate high resolution spatial data and modelling results, coupled to more mechanistic-based modelling of aquatic resource elements, will also be critical to improving our understanding of these linked processes. The increasing importance of quantitative long-term monitoring capabilities within the overarching paradigm of adaptive management will remain critical when developing the data sets upon which future development, refinements, and validations of emerging approaches can be assessed. The continued improvements in computing power and sophistication of analytical software systems will provide access to more integrated modelling capabilities that span spatial scales from micro-habitat, through the reach level, to more watershed level analyses. However, the application of technology and modelling approaches should always be driven by the need to understand processes and the subsequent application of these tools should be undertaken with a view toward the validation of the modelled processes and its inherent linkages. It is also anticipated that the incorporation of more stochastic time-series generation techniques and formal mechanisms for integrating environmental risk assessment into the decision process will occur. This will be driven by the increasing demands for beneficial out-of-stream use of limited water resources, which must be balanced against competing demands for more protection of the instream flow-dependent resources that are imposed by the prevailing political, institutional and litigative environment of river management today.

CONCLUSIONS

Applied river management has lagged behind demonstrated existing state-of-the-art technologies and modelling capabilities. Judicious application of these capabilities will provide their greatest benefits when undertaken within the framework of adaptive management and when oriented toward better understanding and representation of those flow-dependent linkages that are present in physical, chemical, and biological processes in river systems. The role of GIS will become increasingly important as the complexity in the data visualization capabilities of these linked technologies and modelling efforts increases. GIS provides an important tool for the integration of modelling components, for the assessment of change detection procedures in monitoring programs, and for allowing access to the modelling of spatial and temporal components of the river system not readily available from the application of component process models. As the complexity of the integrated assessment framework increases, resource managers will need to rely on integrated software such as decision support systems to aid in the application and interpretation of modelling results to evaluate management alternatives. These systems represent a major challenge for the research community to allow participation and review by non-technical stakeholders within the socio-political arena of river basin management.

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