How to Avoid Train Wrecks When Using Science in Environmental Problem Solving

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Interdisciplinary collaborations are increasingly common in many areas of science, but particularly in fields involved with environmental problems. This is because problems related to human interactions with the environment typically contain numerous parameters, reflect extensive human alterations of ecosystems, require understanding of physical–biological interactions at multiple spatial and temporal scales, and involve economic and social capital. Distilling useful scientific information in collaborative interactions is a challenge, as is the transfer of this information to others, including scientists, stakeholders, resource managers, policymakers, and the public. While this problem has been recognized by historians and philosophers of science, it has rarely been recognized and openly discussed by scientists themselves (but see NAS 1986).

The participation of individuals from a diverse set of scientific disciplines has the potential to enhance the success of problem solving (USGS/ESA 1998). However, obstacles often arise in collaborative efforts for several well-known reasons. First, it is often difficult to find a common language because of disciplinary specialization (Wear 1999, Sarewitz et al. 2000). Second, existing scientific knowledge (theories, models, etc.) may reflect a historical scientific and sociopolitical context that may make it ill suited to address current environmental problems and questions (see, for example, Ford 2000, NSB 2000). Third, collaborations involving multiple disciplines may create difficulties owing to mismatches in space and time scales, in forms of knowledge (e.g., qualitative versus quantitative), and in levels of precision and accuracy (see, for example, Herrick 2000). Fourth, scientists are partly conditioned by nonscientific values. A social fabric may dictate scientists' worldviews, lead them to favor certain assumptions over others, and underlie the way they study ecosystems (Boyd et al. 1991).

In this article, we argue that the success of interdisciplinary collaborations among scientists can be increased by adopting a formal methodology that considers the structure of knowledge in cooperating disciplines. For our purposes, the structure of knowledge comprises five categories of information: (1) disciplinary history and attendant forms of available scientific knowledge; (2) spatial and temporal scales at which that knowledge applies; (3) precision (i.e., qualitative versus quantitative nature of understanding across different scales); (4) accuracy of predictions; and (5) availability of data to construct, calibrate, and test predictive models. By definition, therefore, evaluating a structure of knowledge reveals limitations in scientific understanding, such as what knowledge is lacking or what temporal or spatial scale mismatches exist among disciplines.

The epistemological exercise of defining knowledge structures at the onset of a collaborative exercise can be used to construct solvable problems: that is, questions that can be an-

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swered within defined limits of precision and certainty. This requires building consensus among team members, including scientists, resource managers, and other stakeholders, regarding precision (i.e., quantitative versus qualitative understanding), dimensional scales of analysis, and what disciplines to include in an analysis. Based on this foundation, questions that were formulated before the analysis of knowledge structures may need to be modified or rejected. Finally, we recommend including the analysis of knowledge structures as a transparent and integral part of a scientific analysis and report.

We illustrate the analysis of disciplinary knowledge structures using the general topic of land use impacts on riverine ecosystems. This analysis involves the disciplines of surface water hydrology, fluvial geomorphology, and riverine ecology, because all these disciplines are necessary to the study of riverine ecosystems and because they have diverse histories. In practice, problem-solving teams may require additional disciplines.

A method for evaluating knowledge structures

Evaluation of knowledge structures begins with a question. For example, a common environmental question relevant to the management of riverine ecosystems is: How do land use practices (e.g., urbanization, logging, and damming) alter water and sediment discharge through drainage networks, and how do these alterations, in turn, affect aquatic biota and ecosystem processes? Collaborative efforts addressing this question are typically organized in a loose, hierarchical fashion. First, hydrologists assess the effects of land use on precipitation and on surface and subsurface runoff regimes. Next, geomorphologists consider how an altered hydrologic cycle will affect erosion, sediment transport, and depositional processes in channels. Finally, ecologists evaluate how alterations in flow and channel conditions affect aquatic and riparian biota and associated ecological processes and patterns.

The method we propose consists of four logical steps. First, a specific question or a general class of question is chosen. Second, each discipline defines its knowledge structure (figure 1). This involves examining the origins, methods, and limits of knowledge in each discipline (Kuhn 1970, Schaffer 1996). The research traditions contained in the different disciplines dictate what techniques are available, what variables are measured, how data are analyzed and interpreted, and thus what types of interdisciplinary collaborations are possible. This is because the knowledge contained in any discipline (e.g., theories, models, statistical relations, and empirical descriptions) is shaped by the questions that the discipline has addressed in the past and, therefore, by the scientific and sociopolitical context that determined those questions (Latour 1993, Pickett et al. 1994). Third, based on knowledge structures of individual disciplines, potential difficulties can be identified, including absence of scientific knowledge, incompatible dimensional scale or precision, and absence of data. Fourth, strategies are developed to circumvent the identified difficulties and to construct solvable technical problems. This may involve changing questions or eliminating certain types of questions.

The analysis of knowledge structures with respect to our general riverine ecosystem question is summarized in boxes 1–3. The spatial and temporal scales addressed by the various forms of knowledge are plotted in more detail in figure 2, representing detailed enlargements of the diagrams displayed in figure 1. The comparative analysis reveals knowledge incompatibilities when the three natural science disciplines come together. For example, the development of hydrology was driven in the late 19th and early to mid-20th centuries by practical engineering concerns related to the protection of human structures from floods and the construction of stable artificial waterways. Consequently, the field of hydrology is often successful at predicting runoff and discharge in relatively well-defined urban catchments where detailed information on impervious area, channel networks, and topography exists. More recently, hydrology has focused on forecasting the effects of altered vegetation pat-

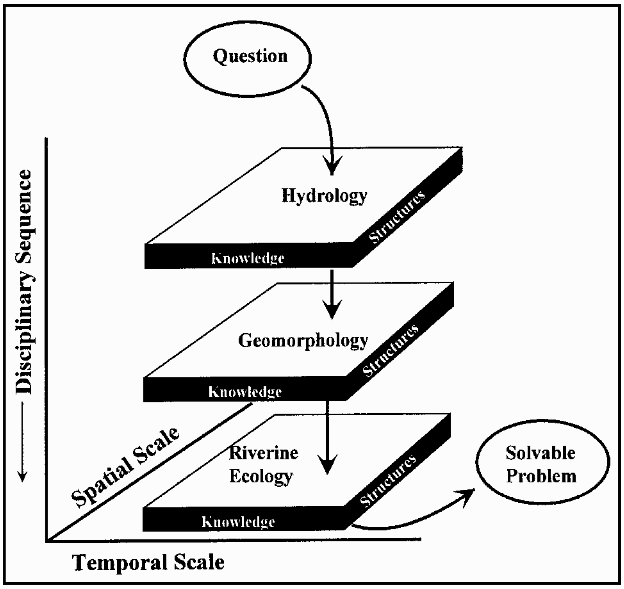

Figure 1. An illustration of the comparative analysis of knowledge structures of three disciplines that are commonly involved with questions involving land use impacts on riverine ecosystems. The fields are arrayed hierarchically to illustrate cause-and-effect relationships between physical and biological processes. Different forms of knowledge in each discipline are mapped onto the surfaces and correspond to the spatial and temporal scales at which that knowledge applies. Notice the changing fields of knowledge across disciplines (figure 2). The structure of knowledge contains information on disciplinary history and available scientific knowledge; spatial and temporal scales at which that knowledge applies; precision, that is, qualitative versus quantitative nature of understanding; accuracy of predictions; and availability of data to construct, calibrate, and test predictive models.

Box 1. Surface water hydrology

The field of surface water hydrology is primarily dedicated to understanding the hydrologic cycle, which spans precipitation, hillslope runoff processes, groundwater, evapotranspiration, and flow routing through channel networks. Hydrology emerged in the late 19th and early 20th centuries as an engineering discipline focused on the construction and maintenance of urban water supply and irrigation systems, on flood protection, and, to a lesser degree, on the maintenance of navigable channels. Traditional engineering approaches use empirical relationships and quantitative techniques (e.g., flow forecasting) primarily for designing structures rather than for understanding natural processes (Klemes 1988). Empirical analyses of discharge data (e.g., flood frequency analysis) can be conducted across a broad range of spatial scales (10^1 to 10^6 square kilometers [km^2]). Because streamflow integrates a diverse set of watershed characteristics, including many characteristics affected by land use, flood frequency analysis generally is not used to predict hydrological changes caused by land use changes. However, empirical comparisons of discharge data from paired catchments (disturbed versus control basins) can be used to examine the effects of land use changes on hydrological regimes (e.g., Bosch and Hewlett 1982), but natural variability in precipitation, topography, land use, and channel structure limit the degree to which data from these field experiments can be extrapolated to other sites. Similarly, the development of empirical relationships between discharge and land use (e.g., the rational method) has also been widely used; however, simplifying assumptions, such as a linear relationship between land use and runoff, result in considerable uncertainty and limited applicability (Dunne and Leopold 1978).

In the last few decades, however, there has been mounting scientific interest in understanding hydrologic processes that are an integral part of ecosystems, leading to the development of conceptual, lumped, and spatially distributed hydrologic models (reviewed in Baird 1999). These models have extended the focus of hydrology from the engineering analysis of streamflow patterns to an analysis of hydrological processes within catchments (evaporation, interception, infiltration, etc.) that influence both water quality and water quantity. Spatially distributed hydrological models are used to predict relationships between land use and streamflow for small catchments when data are available on basin characteristics and flows. However, lack of data (precipitation and flow records) in basins typically precludes the application of spatially distributed models to all small streams draining a basin. To circumvent this limitation in large watersheds, small-scale variation in hydrological behavior can be ignored when estimating hydrological responses to land use changes. For example, flow regimes at the outlet of a large basin (i.e., 10^2 to 10^3 km^2) may be estimated with reasonable accuracy using relationships between discharge records and some measure of basin characteristics (topography, relief, precipitation, etc.). These so-called lumped models, however, do not provide information on small-scale watershed responses, such as channel reach, that ecologists might be focusing on and do not incorporate information on the effects of continuous land use changes or the spatial distribution of these changes (e.g., riparian versus upland changes; Moglen and Beighley 2002). At larger scales, hydrologic response becomes increasingly dependent on stream channel characteristics, which can also be subject to human modifications (construction of dams, straightening and diking of channels). There is a similar suite of hydrodynamic or hydrologic routing models that relate channel characteristics with flow (reviewed in Bedient and Huber 1988). An examination of land use impacts, of course, must consider effects both to the land surface and to the channel, and thus consider both surface hydrology and channel routing.

Of the four disciplines considered here, hydrology is the most quantitative in an engineering sense, although general theories, such as variable source areas (Hewlett and Hibbert 1967), the geomorphic unit hydrograph (Rodriguez-Iturbe and Valdes 1979), and the hydrologic cycle provide important foundations for the field.

terns in larger, nonurbanized catchments, a topic of great interest to ecologists; however, accurate predictions are constrained by availability of data, which decreases with increasing watershed size (box 1).

Although geomorphology derived from geography and from mostly qualitative interpretations of landform evolution in the 18th and 19th centuries, aspects of the science of interest to ecologists (concerning erosion and sediment transport, for example) have origins in engineering, evolving from the need for quantitative prediction of natural hazards (landsliding) and the construction of canals for water conveyance (box 2). Nevertheless, predicting the effects of altered hydrology on sediment transport remains relatively imprecise (+/– 100 percent), even when using local data for calibrating models. This is because of temporal uncertainties in channel hydraulic geometry (width, depth, and slope) and sediment supply. Hence, channel morphology as represented in sediment transport models is typically treated as constant over time (box 2). This assumption defeats much of the purpose of predicting the movement of sediment in the first place with respect to ecological questions.

In contrast to the other two disciplines, the discipline of riverine ecology formed primarily after the mid-20th century during a period of heightened environmental awareness, and is closely aligned with general ecology, population and community ecological theory, biogeography, and biogeochemistry. Riverine ecology has focused largely on the recognition of ecological patterns, environmental problems, and phenomenology at scales much smaller than landscapes or basins (Fisher 1997). The comparative analysis of knowledge structures (figure 2; boxes 1–3) reveals that the scale and precision of analysis in hydrology and geomorphology do not match well with those of riverine ecology. Consequently, ecological responses to land use change are often couched in qualitative terms (box 3). For example, hydrologists can make relatively accurate predictions of changing peak flows in a watershed using new, spatially distributed models (Moglen and Beighley 2002). Using this information, geomorphologists can

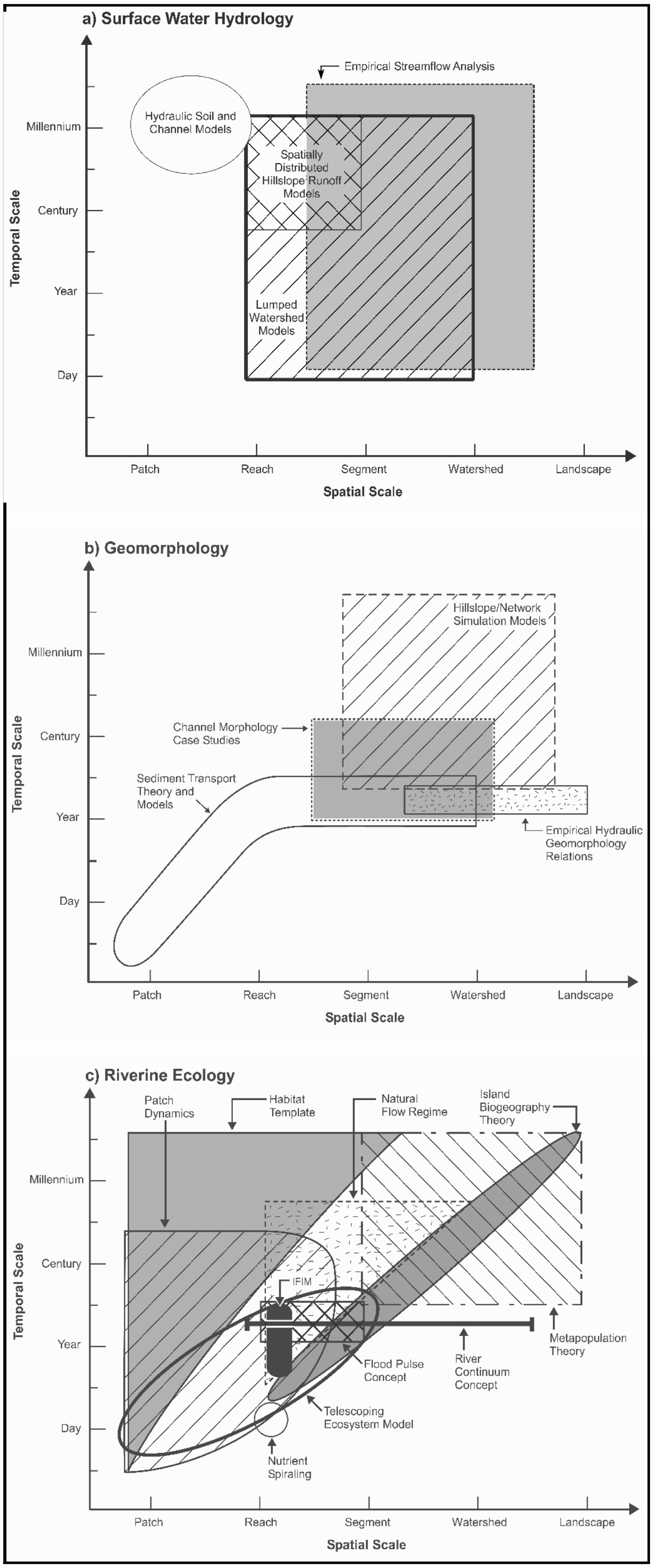

Figure 2. An approximate mapping of disciplinary knowledge according to the spatial and temporal scales addressed by the various scientific concepts, theories, or empirical databases in each of the three disciplines that are applicable to our riverine ecosystem problem. (See boxes 1, 2, and 3 for more detail.)

make only relatively inaccurate predictions of sediment transport and cannot say anything definitive regarding bed scour or changes in channel form (the latter two attributes of great interest to ecologists). As a result, ecologists may say that certain taxa are at risk, but quantitatively defining that risk in terms of changes in abundance of individual species or the change in community diversity is not generally feasible.

Our illustrative analysis of knowledge structures indicates a trend across the three disciplines. Hydrology, with the fewest parameters, makes relatively accurate quantitative predictions at small scales. Geomorphology, with a larger number of parameters or free coefficients, makes relatively inaccurate quantitative predictions and hence is pressed to make qualitative predictions. Finally, riverine ecology makes predictions mostly in qualitative or conceptual terms. The trend of increasing quantitative uncertainty with increasing number of parameters (and associated temporal and spatial scales; see figure 2) across the three disciplines represents a challenge in this type of interdisciplinary collaboration. Of course, other scientific disciplines are also limited in their ability to make accurate predictions, because of the limits imposed by scale, historical contingency, and local conditions (see, for example, Ulanowicz 1997).

Constructing solvable problems

In their analysis of scientific practice, Clark and Fujimura (1992) concluded that, in addition to the theoretical basis for scientific work, the everyday work of science involves "constructing doable problems" given a wide range of practical considerations. Our proposed method is designed to help identify solvable problems and, if necessary, reject or modify preexisting questions. We identified five potential difficulties during the comparative analysis of knowledge structures: (1) absence of scientific knowledge; (2) knowledge available at the wrong dimensional scales; (3) unequal precision (i.e., unequal quantitative abilities across all disciplines); (4) low accuracy; and (5) absence of field data for system description, calibration, and testing (including the inability to measure predicted change) (table 1). Once recognized, the potential difficulties can be used to identify strategies for constructing solvable problems or, if necessary, to change preexisting questions. Strategies could include modifying precision, modifying the dimensional scale of analysis, eliminating or bypassing a discipline, performing a coarse-grain analysis, and conducting new research. The first four of these strategies are discussed below in the context of real-life examples of their application, using our illustrative case problem.

Modifying precision. Land uses such as dams, dikes, urbanization, and logging are known to affect the hydrologic cycle, in part by altering flow regimes. Hence, a question might take this form: What are the effects of urbanization on the abundance and species diversity of aquatic invertebrates? Since the impact of changes in flow regimes on aquatic invertebrates is often mediated by changes in sediment char-

Table 1. Relationship among the components of a knowledge structure, the potential problems it may reveal, and strategies for constructing solvable problems.

Components of a knowledge structure	Potential difficulties	Strategies for constructing solvable problems
Disciplinary history and available forms of knowledge	Absence of scientific knowledge	Eliminate or bypass a discipline (includes black box analyses)
Spatial and temporal scales at which knowledge is applied	Knowledge available at the wrong dimensional scales	Modify scale of analysis, scale up or scale down
Precision: quantitative versus qualitative nature of understanding across scales	Unequal precision across all disciplines	Modify precision of analysis
Accuracy in predictions	Low accuracy	Coarse-grain analysis
Availability of data to construct, calibrate, and test models	Absence of field data for system description, calibration, and testing (includes inability to measure predicted changes)	Hybrid approaches and/ or new research

acteristics (see, for example, Poff and Ward 1990, Townsend and Hildrew 1994), this question requires knowledge from each of the three disciplines. However, the analysis of knowledge structures (figure 2; boxes 1–3) identified important constraints regarding this question. First, although hydrologic models may make reasonably accurate predictions of changes in flow regime, there are no widely applicable geomorphic models for predicting channel bed scour as a function of changes in flow over the range of scales that affect aquatic habitat. (These scales range from reach [up to 100 m] to network and from individual storms to a series of storms over years.) The lack of applicable models is related to the complex interactions between sediment supply, sediment transport, and channel scour (DeVries 2000). In the face of this problem, precision can be reduced to circumvent the limits in quantitative understanding. Instead of asking how many centimeters (cm) of channel bed scour will result from a 20% increase in peak flows, researchers might ask: Will the forecasted increase in peak flows lead to small (< 10 cm), moderate (10–50 cm), or large (> 50 cm) changes in channel morphology? Are gravel beds or cobble bed channels more susceptible to change? Similarly, how will invertebrate populations or communities respond to qualitative, directional changes in habitat?

Formally recognizing the absence of quantitative scientific knowledge or the low precision of understanding can impart legitimacy to questions that generate qualitative and contextual answers (see O'Brien 2000). For example, a persistent question involves the synergistic effects of logging and overfishing on regional anadromous fish stocks over the last 50 years in the Pacific Northwest (Meehan 1991). This environmental dilemma has recently been cast in terms of questions with qualitative, contextual answers, because it cannot be addressed at high precision (Jensen et al. 2000). The difficulties in obtaining quantitative predictions involving complex environmental situations have fueled a call for applying qualitative, low-precision forms of knowledge as a basis for adaptively managing and solving complex environmental problems (Walters and Korman 1999).

Modifying dimensional scales. Eggs of many stream fishes are known to be highly sensitive to increases in the proportion of fine sediment in the interstices of gravel beds (Everest et al. 1987). In many watersheds, increased erosion has resulted from land use practices. To assess the impacts of fisheries, scientists may be asked such questions as these: How has the intrusion of fine sediment in gravel beds changed over the last several decades of watershed disturbance? And by what amount will a predicted increase in erosion in a watershed change the proportion of fine sediments in river channels? Our analysis of knowledge structures indicates that these questions contain one problem of data availability and two problems of scale. First, information on channel substrate composition spanning decades, or even shorter periods, is not available for virtually any river in the world. Second, it is very difficult to make accurate predictions of erosion over even short time scales such as years, because of the stochastic nature of erosion and channel sediment supply (Benda 1995, Dunne 1998). Third, sediment transport theory and models cannot make accurate predictions about changing proportion of sands in bed substrate because of uncertainty regarding the physics of sediment transport (box 2).

When researchers face limitations in knowledge (for example, because of an absence of scientific theory, technology, or empiricism), the question can be scaled up or scaled down. The purpose of this strategy is usually to increase precision, accuracy, or both. For example, instead of focusing on the condition of small-scale channel morphology (the amount of fine sediment in channel beds) as an indicator of environmental degradation, containing a problem of both data availability and scale, the question could be scaled up to valley floor morphology. Floodplains have been shown to be a key landform in properly functioning riverine ecosystems (Stanford and Ward 1993), and their overall condition has been used as a proxy to estimate the ecological condition of river systems, including fish populations (Sedell and Froggatt 1984). Moreover, because of the general availability of historical aerial photography and of topographic and other survey maps, the history of channel changes and

Box 2. Geomorphology

Geomorphology is primarily concerned with how the surface of the earth forms, a field that spans hillslope erosion, chemical denudation, river sediment transport and deposition, and channel-forming processes. The discipline of geomorphology originated in qualitative theories of landscape evolution proposed by physical geographers in the 18th, 19th, and early 20th centuries. In the mid- to late 20th century, geomorphologists began to emphasize quantitative predictions of landform evolution using field estimates of erosion and deposition, mathematical models, and remote-sensed imagery. Like other areas of geology, geomorphology examines systems that span very large time and space scales (regional landscapes over millennia), where current environmental conditions are strongly contingent on past events (geologic and climatic history) (figure 2b). As a result, geomorphic predictions are often imprecise, qualitative, and relatively inaccurate compared to predictions in hydrology, which are generally applied quantitatively over smaller temporal and spatial scales. Moreover, experimental manipulations and opportunities for repeating observations and falsifying hypotheses are few because each geomorphic situation (watersheds or channel networks) is unique (Schumm 1991).

Engineering has also made major contributions to quantitative approaches in geomorphology by addressing problems related to sediment transport in canals (DuBoys 1879) and landsliding in hazard prediction (Terzaghi and Peck 1967). Sediment transport theory provides a quantitative foundation for addressing issues related to the entrainment, movement, and deposition of individual sediment grains, representing the smallest spatial and temporal scales addressed by fluvial geomorphology in the context of land use change (figure 2b). Nevertheless, the accuracy of predictions generally declines with increasing scale and the number of model parameters. For example, sediment transport, an area of great relevance to riverine ecologists, cannot be predicted accurately even at reach scales (10^1 to 10^2 meters of channel length) because of unresolved variability in channel geometry, in streambed particle sizes, and in watershed-scale sediment supply (Gomez and Church 1989). Moreover, accurate predictions are infeasible because large-scale processes constrain local geomorphic conditions. One such process is basin erosion, which affects the availability of sediment to be transported. Hence, with respect to questions about river responses to land use practices, it is difficult to make accurate quantitative predictions about altered sediment transport regimes and their effect on channel morphology, including substrate size and hydraulic geometry (width and depth).

The channel cross section represents the next largest scale of analysis. Many studies have attempted to explain the width, depth, and slope of rivers either empirically using hydraulic geometry relationships (e.g., Leopold et al. 1964) or theoretically using principles of sediment transport mechanics (ASCE 1998). Because temporal variability in flow regimes and channel form is not included in any of these approaches, it cannot readily be used to study the evolution of channel form following changes in land use.

Case studies documenting changes in basin erosion regimes using sediment budgeting can often provide rough quantitative estimates of land use effects (Reid and Dunne 1996). Although some studies have forensically linked basin sediment budgets with channel response, developing predictive relations between hillslope erosion and small-scale channel changes relevant to stream ecology is generally beyond the quantitative capabilities of geomorphology. In addition, simulation models have been constructed to examine geomorphological changes over large spatial and temporal scales (e.g., 10^1 to 10^3 years, 10^1 to 10^3 km^2). However, such models require simplified descriptions of key processes (Benda and Dunne 1997), and hence their ability to predict changes due to land use impacts is limited.

floodplain activity, including diking, can often be reconstructed (Reid and Dunne 1996). Therefore, a question about channel morphology can be scaled up from the reach to the floodplain, and much can be learned about the history of riverine degradation and opportunities for river restoration that may enhance fish habitat.

The scale of an analysis can also be changed for biota. In considering the effects of bed scour on aquatic invertebrates, species-level identification of invertebrates is generally infeasible and information on species persistence and diversity as a function of flow regime and sediment characteristics is not available (Palmer 1997). Hence, solvable problems might address more robust indicators of environmental response, such as functional guilds or higher-order taxonomic descriptions (e.g., families). Even then, however, scientists lack a detailed understanding of how invertebrate communities might respond to particular magnitudes, frequencies, and timing of floods (see Poff et al. 1997, Bunn and Arthington 2002). The focus might be scaled up even further from invertebrates to fish, for which a better species-level understanding exists (e.g., Gehrke and Harris 2001).

Similarly, a problem involving behavior of natural river channels that cannot be tackled because of complexity may be scaled down to the level of a flume experiment in which many environmental conditions can be controlled. For example, flumes have been used to study many aspects of the transport of both sediment (Lisle et al. 2001) and biota (e.g., Merritt and Wohl 2002), including the intrusion of sand into river gravels and its impacts on incubating fish eggs (Phillips et al. 1975). Much knowledge has been gained from these experiments. The quantitative results from these scaled-down studies, however, are often difficult to extrapolate to real channel environments because of unresolved variability in sediment supply, flows, and channel geometry, all of which may vary naturally hour by hour in a natural channel during floods. Nonetheless, if the limitations in small-scale studies are recognized, their results can contribute to improved qualitative assessments of the relationship between land use, sediment transport, and fish reproduction.

Eliminating a discipline or constructing a "black box." In pursuit of solutions to difficult problems, another generally involve a large range of temporal and spatial scales (figure 2). Because of the absence of long-term data, however, simulation models may be needed to study complex ecosystem behavior. Ideally, large-scale numerical models would be developed using a quantitative understanding of all relevant interdisciplinary processes. However, there are theoretical and technical impediments to developing large-scale environmental models based on predicting smaller-scale processes (Weinberg 1975, Allen and Starr 1982). To circumvent these limitations, models can be constructed whereby some small-scale processes are ignored, or are subsumed within larger-scale representations of processes, a strategy commonly applied by physicists and referred to as "coarse graining" (Gell-Mann 1994). In practice, in the watershed sciences, this often requires combining empirical knowledge and theoretical reasoning available at smaller scales, by means of mathematical synthesis and computer simulation, to produce new understanding at larger scales. The objective of this approach is not to generate precise predictions about exact future states at individual sites, but rather to develop new, testable hypotheses on large-scale interactions of watershed processes (e.g., climate, topography, and vegetation) and riverine biota. This approach has a history in the study of certain hydrological and geomorphological problems at large scales (Rodriguez-Iturbe and Valdes 1979, Benda and Dunne 1997), and it may be helpful for addressing certain ecological questions (Benda et al. 1998). The description of large-scale patterns of behavior, even in the absence of mechanistic understanding for all of the observed processes, is a hallmark of the study of complex systems (Gell-Mann 1994).

Conclusions

Constructing solvable scientific problems is a primary operational mandate of many scientists. Given the constraints of acceptable scientific practice, there is only a finite set of strategies for overcoming limitations in scientific understanding. Recognizing knowledge structures and scientific limitations may be difficult during interdisciplinary collaborations because numerous disciplines, models, parameters, and human personalities converge. The discovery of scientific limitations and the development of strategies for overcoming them are often made post hoc and perhaps haphazardly. Even when successful interdisciplinary collaborations take place, the justification for pursuing certain strategies, including simplifying certain difficulties (e.g., modifying questions), is often not made transparent.

Our goal is to make the process of conducting successful interdisciplinary collaborations and constructing solvable problems more transparent, efficient, and rigorous. By putting into place a formal process and paper trail for what basically constitutes an epistemological analysis, the processes of altering questions, shifting from quantitative to qualitative forms of knowledge, and employing new types of knowledge can promote an increased legitimacy to the scientific method, particularly among nonscientists such as policymakers, stakeholders, and the public.

There are dangers if science teams, or mixed science–policy teams, ignore the knowledge structure of individual disciplines. For instance, where collaborative teams fail to recognize that contributing disciplines approach problem solving with differing forms of knowledge, additional studies may be commissioned with little chance of success, delaying policy and management decisions. Similarly, science can be used as a "litmus test" in which a question (typically a quantitative one) is forced upon a science team or policy group, with no expectation of a precise answer, to justify a particular ideological doctrine. Questions to science teams requiring knowledge that is not available, or that will not be forthcoming in the near future, should not be placed in a pivotal and referee position.

Conducting an epistemological analysis of the scientific disciplines involved with environmental problems can help establish realistic expectations about the role of science, the adequacy of information, and the effectiveness of management policies in dealing with particular problems. By recognizing limits and identifying commensurate scales of analysis, scientists can help guide and direct debates surrounding the appropriate use of scientific knowledge in environmental risk assessment and in setting management policy (O'Brien 2000). For example, the increasing recognition that the accuracy of global climate model predictions is limited to coarse scales (continental regions over decades) has led to better acceptance that local predictions with fine-grained temporal resolution remain out of reach, despite the great social need for such information (Ledley et al. 1999). Similar admissions of scientific uncertainty and the means to circumvent limitations in the scientific disciplines dealing with other interdisciplinary problems, such as those covered in this article, are needed (see Sarewitz et al. 2000).

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