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Synthesis, part of a Special Feature on New Methods for Adaptive Water Management

Linking Flow Regime and Water Quality in Rivers: a Challenge to Adaptive Catchment Management

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ABSTRACT. Water quality describes the physicochemical characteristics of the water body. These vary naturally with the weather and with the spatiotemporal variation of the water flow, i.e., the flow regime. Worldwide, biota have adapted to the variation in these variables. River channels and their riparian zones contain a rich selection of adapted species and have been able to offer goods and services for sustaining human civilizations. Many human impacts on natural riverine environments have been destructive and present opportunities for rehabilitation. It is a big challenge to satisfy the needs of both humans and nature, without sacrificing one or the other. New ways of thinking, new policies, and institutional commitment are needed to make improvements, both in the ways water flow is modified in rivers by dam operations and direct extractions, and in the ways runoff from adjacent land is affected by land-use practices. Originally, prescribed flows were relatively static, but precepts have been developed to encompass variation, specifically on how water could be shared over the year to become most useful to ecosystems and humans. A key aspect is how allocations of water interact with physicochemical variation of water. An important applied question is how waste releases and discharge can be managed to reduce ecological and sanitary problems that might arise from inappropriate combinations of flow variation and physicochemical characteristics of water. We review knowledge in this field, provide examples on how the flow regime and the water quality can impact ecosystem processes, and conclude that most problems are associated with low-flow conditions. Given that reduced flows represent an escalating problem in an increasing number of rivers worldwide, managers are facing enormous challenges.

Key Words: *catchment scale; ecosystem processes; environmental flows; flow regime; rivers; water quality*

INTRODUCTION

All living organisms are inherently dependent on access to water for their existence. During pre-human times, all accessible water in the world was used by natural ecosystems. After the entry of humans, increasing amounts of water have been subtracted for use in human societies and human-transformed systems, and this has degraded natural freshwater ecosystems. Access to safe water in sufficient quantities within acceptable distances is now recognized as a basic human right by many countries. It is even argued that “Right to Water” should be included in the UN Convention on Human Rights (Barlow 2006). The results from the latest review of the Millennium Development Goals (MDGs) of eradicating extreme poverty show that, even though the target to reduce extreme poverty by half can be reached in most parts of the world by the year 2015, some targets are unlikely to be met (United Nations (UN) 2007). The number of people without access to safe water and sanitation is still alarmingly high and inequalities in the developing world are rising, leaving the poorest of the poor with a smaller share of national consumption. In light of this, it is especially alarming that Goal 7 “Ensure environmental sustainability” is unlikely to be fulfilled (UN 2007). In fact, all the world’s ecosystems are deteriorating, but the freshwater ecosystems are the worst off (Millennium Ecosystem Assessment 2005) as a result of water extraction, flow regulation, and pollution. Jury and Vaux (2007) point to the fact that human use of freshwater and degradation of freshwater quality have now reached a point where shortage of safe water is likely to limit food production, ecosystem function, and systems of urban water supply. The primary reason for this shortage is population

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growth, which has increased at a faster rate than food production. The human population will include 2–4 billion more people by the middle of the 21st century, mostly in poor and water-short countries (Bengtsson et al. 2006). The poor people are those that will be most affected by increasing water scarcity, as they are often the ones most directly dependent for their subsistence on the goods and services provided by local ecosystems (e.g., Bordalo and Savva-Bordalo 2007). This review deals with the links between water quantity and water quality, and the challenge of balancing water requirements so that both humans and ecosystems can maintain acceptable standards.

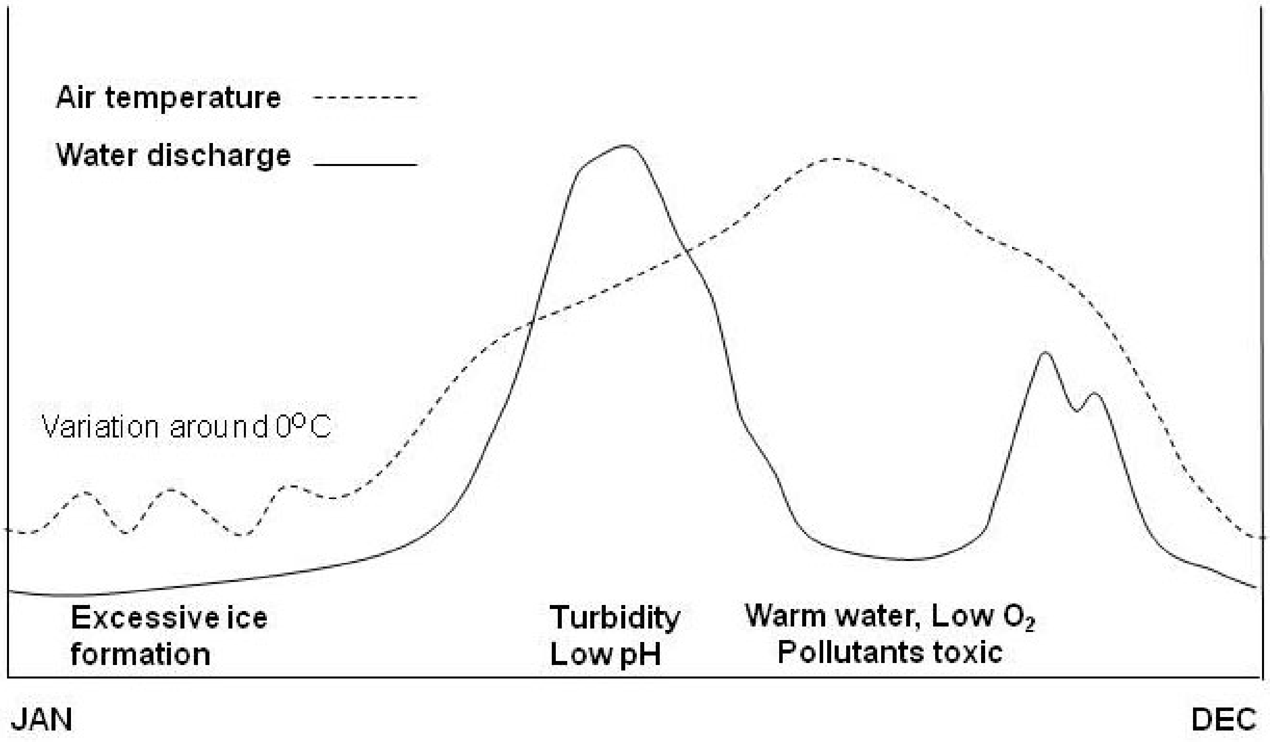
Quantity and quality of water are closely linked, yet these two aspects of water accessibility are often dealt with separately. The definition of “water quality” incorporates the concentration of different constituents in the water (such as oxygen, nutrients, toxicants, organic matter, and inorganic sediment) and also its temperature and state, i.e., whether it is frozen or not. The major processes governing water quality within a catchment are related to transport, retention, and processing (e.g., decomposition of organic matter). Specific concentrations of substances, water temperatures, and water states may have different impacts on these processes and associated ecosystem services during different times of the year (Fig. 1). The definition of “water quantity” often relates only to discharge and water mass, but equally important is the way water flow varies spatially and temporally. This variation in flow is as crucial to freshwater ecosystems as discharge and water mass, and has considerable impact on physical as well as chemical quality aspects of water.

The definition of flow variation, usually termed “flow regime” (Poff et al. 1997), takes into account that flowing water affects ecosystems in different ways depending on the season and the level of discharge. For example, contrasting events such as floods and low flows relate to different combinations and magnitudes of environmental processes (including ecosystem services). Also, and especially in seasonal environments, specific discharges may vary considerably in importance depending on their timing. In other words, the “socioecological worth” of a drop of water in a catchment varies over the year. Another aspect related to this definition is that flowing water sustains different services depending on its current velocity. For example, turbulent and tranquil river reaches foster different kinds of ecological communities (Nilsson et al. 2002) and possess different roles in oxygen and carbon cycling (Zimmermann-Timm 2002). Irrespective of the specific nature of pristine spatial and temporal variation in water quality and quantity at different places, river biota have evolved to cope with this variation. Therefore, on a global scale, river channels and their riparian zones contain a rich selection of adapted species and have all been able to offer goods and services benefiting human civilizations. These benefits fall into three major groups: water for human needs (consumption and sanitation), goods other than water, such as food and fiber (e.g., fish and fuelwood), and nonextractive benefits such as recreation, transportation, self-purification, and energy (Postel and Carpenter 1997).

Following increasing human intervention, water conditions have become radically altered. Human societies have a long history of manipulating and redesigning channel structures and flows, and many of these impacts lead to changes also in physicochemical variables. In addition, a multitude of non-point- and point-source pollution types also affect the chemical characteristics of water, irrespective of flow. For example, compared with the assumed pristine situation, rivers and streams worldwide have doubled their content of nitrogen and phosphorus as a consequence of human activities (Camargo et al. 2004). In fact, many human impacts on natural riverine environments have resulted in more severe effects on ecosystems than would have been required for achieving desired goals. One example is the methane production that has followed from the creation of many water reservoirs (e.g., Kuznetsova and Dzyuban 2005, Guerin et al. 2006), due to flooding of uplands rich in organic matter. Release of methane is not a prerequisite for production of hydroelectric power. In addition, irrespective of intentions (e.g., UN 2007), many impacts on waters have become so serious that freshwater ecosystems are unable to sustain their ecological processes (Postel 2003). Therefore, new ways of thinking, and improved governance and management, including development of rehabilitation measures, are called for.

A growing scarcity of safe water threatens the persistence of ecosystems as well as progress in poverty suppression, public health, and food supply (Ward 2007). The challenge that meets managers of freshwater ecosystems is to find ways to satisfy the

Fig. 1. Annual variation in air temperature and discharge (hypothetical daily values) in a stream with a nival discharge regime. Three situations are highlighted during which discharge and water quality produce combinations that may impair biota. All these situations may occur under natural conditions, but human intrusion can worsen them and exacerbate their environmental impacts.



needs of both humans and nature, without sacrificing one or another. This compromise-oriented practice is centered around a concept called “environmental flows” (often simply “e-flows”) or related terms. Originally, this concept had its focus on more static hydrologic conditions, but it has successively been developed to encompass a dynamic view of water flow, specifically how a certain (minimum) mass of water could be shared out over the year to become most useful (Tharme 2003). An important aspect that has not been much dealt with until recently is how flow variation interacts with variation in the physicochemical characteristics of the water, especially when these are affected by waste discharge and non-point-source pollution (Palmer et al. 2005a). An associated applied question is how water extractions and releases can be designed to reduce ecological and sanitary problems that might arise from inappropriate combinations of flow dynamics and physicochemical characteristics of water. In a wider context, proper management of flows has to encompass the entire catchment to maintain a healthy river (e.g., Allan et al. 1997, Palmer et al. 2008). In other words, flows cannot be managed only, for instance, by specific release prescriptions from a water reservoir. The pertinent question here is whether certain changes in land-use patterns and restructuring of the river itself can assist in improving the flow regime and water quality. The similarly important question as to whether managers are disposed to adaptively shift between management options highlights the urgency of securing and institutionalizing advances in science and practice within new governance structures that integrate across disciplines and sectors.

Developing the concept of prescribed flow allocations from reservoirs, and catchment management that increases water retention in uplands, are adaptive processes that require institutional commitment and collaboration among land and water managers and scientists. Also, introduction of new legislation and adjustments to policy and institutional structures are needed to allow implementation of flow-related management regimes (Arthington and Pusey 2003, Richter et al. 2006). In Europe, the Water Framework Directive (2000/60/EC) has rationalized and updated existing water legislation by setting common EU-wide objectives for water. By including a timetable stating when restoration and preservation of water resources in different river basins need to be accomplished, the Directive has stimulated a concerted occupation with river basin management plans. The purpose of the present paper is to provide an overview of links between flow regime and water quality, with a special focus on the challenge of balancing the water needs of both humans and ecosystems. We begin by giving examples on how flow regimes can harm water quality and linked ecosystem processes, and conclude by discussing a set of options managers can use to avoid or reduce episodes of disadvantageous water quality.

THE INTERACTION OF FLOW REGIME AND WATER QUALITY

Water quality is naturally variable both in space and time. Water quality varies along the course of a river and is influenced by natural features such as altitude, geology, instream physical habitat complexity, streamside wetlands and riparian areas, and by connectivity with the floodplain (e.g., Vannote et al. 1980, Newbold et al. 1982). Water quality also varies in the same location over time due to changes in climate and the flow regime, the so called “flood pulse” concept (Junk et al. 1989). The flood pulse concept predicts that the nutrient status of the floodplain is dependent on the quality and amount of dissolved and suspended solids of the parent river. It also incorporates the idea that floodplain processes and nutrient transfer mechanisms between terrestrial and aquatic environments influence nutrient cycles, primary and secondary production, and decomposition. The transport of an atom of a nutrient species can spiral through biological uptake (organic state) and mineralization (inorganic state) many times on its way from the headwaters to the coast, and it can move between the river channel, the riparian zone, and upland areas ruled by flow variation and hyporheic zones. Phosphorus is transported mainly through this spiraling, but nitrogen can to a certain extent also be transported from the water to the air through nitrification–denitrification processes (Pinay et al. 2007). Human interactions such as modifications of drainage basin, alterations of channel structures and water flows, and pollution have disturbed links between flow regime and water quality, and caused shifts in water quality above natural variability. Such changes started early, but their effects have become especially profound since the industrial era (cf. Norris et al. 2007).

The flow regime is determined primarily by combinations of its magnitude, duration, frequency, timing, and rate of change (Poff et al. 1997). Water quality, on the other hand, refers solely to the physicochemical characteristics of water (such as temperature, state, and substance contents). From an ecosystem perspective, deviations from the “norm” (in this case, the pre-industrial situation) in any of these variables are considered to reduce ecosystem status because organisms are usually not adapted to new conditions that are more or less artificial (Bunn and Arthington 2002). As humans, however, we necessarily judge whether changes are beneficial or detrimental using human values. In many cases, direct and indirect human manipulation of flows and effects on water quality are ancient. In addition, many features of riverine landscapes have been reformed and non-native species have been introduced. Humans have often come to enjoy the perennial wetlands established where once the wetlands were seasonal. Some reservoirs are good places to fish and swim, and irrigation canals support water birds in arid landscapes although they are far from pristine. In other words, some highly impacted river systems can support humans with valued goods and services. Therefore, the “natural flows paradigm,” which assumes that all departures from natural flows will reduce the status of a river system, may apply to the natural ecosystem components, but is unlikely to be universally acknowledged when human views are considered.

By having physicochemical (water-quality related) requirements as well as habitat needs that relate to specific flow standards, aquatic and riparian organisms possess an indicator role for assessing water status. For example, a key issue for optimizing water quality management is identifying the flow situations when water quality variables become limiting to ecosystem processes (Palmer et al. 2005b). Such limits depend on numerous co-varying factors and also differ among and within river systems and with seasons (Fig. 1). Many aspects of water quality and flow regime are interlinked. For instance, a certain amount of pollutants in a stream can vary in importance depending on the actual discharge and on how much it becomes diluted. Below and in Table 1, we provide examples of such associations and their connections to ecosystem processes from a hydrograph perspective. However, it is not only the hydrograph and the land–water interactions that influence water quality, but also the way different river and stream reaches tie together, i.e., their longitudinal connectivity. In response, examples of such links are also provided in the paragraph on connectivity.

Flood Events

Major floods cause considerable addition of organic and inorganic matter to the water. For example, Carroll et al. (2004) showed that a single major flood was responsible for nearly 87% of the total mass eroded from the banks of investigated reaches in the Carson River in west-central Nevada over 6 years. Although organic matter is important for maintaining biological production (e.g., Padial and Thomaz 2006), it also increases turbidity and eventually sedimentation, reducing primary production (Vervuren et al. 2003) and jeopardizing survival of juvenile fish (Korstrom and Birtwell 2006). High flows are also vital for reducing levels of various elements in rivers, by downstream transport, retention, or emission, e.g., denitrification that requires inundation of soils and oxygen depletion to occur (e.g., Forshay and Stanley 2005, Pinay et al. 2007). Periods of extreme (and non-natural) high flows, however, imply increased hazards for water quality because various pollutants can be washed into the river from otherwise unflooded ground. If high flows are caused by heavy rains, effluents may be collected from yet larger areas (Chang and Carlson 2005). In most cases, because of dilution, effects on water quality are insignificant. However, in 2002, when the Elbe River in central Europe experienced its highest flow ever recorded, chemical production sites were flooded and high levels of, e.g., insecticides and their metabolites were embedded in sediments, which made them ecotoxic (Grote et al. 2005). Another example of floods causing reduced water quality is the decline in pH associated with meltwater events in boreal rivers and streams during spring floods. Although this pH reduction is largely naturally driven, in Sweden it has been interpreted as being caused by anthropogenic acid deposition. It has been viewed as a threat to fish production, and it has triggered a large liming program (e.g., Laudon et al. 2004). Yet another example is when prolonged flooding causes extended periods of anoxia in riparian soils, especially in tranquil reaches, which may lead to plant death (Renöfält et al. 2007). It is also well known (e.g., Kelly et al. 1997, Hylander et al. 2006) that artificial flooding caused by dams may cause buildup of benthic anoxic water layers, which mobilize enough mercury in to the food chain that fish become too toxic for humans to eat.

Low Flows

Periods of low flows are integral parts of the hydrograph for many rivers (Smakhtin 2001), and necessary for many processes in riverine ecosystem functioning (Postel and Richter 2003). For example, low flow periods in summer represent the major growing period for riparian plants provided that there is sufficient precipitation to support growth (Williams et al. 2006). If the low-flow situation is prolonged or water quantity reaches extremely (and unnaturally) low levels, however, ecological communities are impaired. Low-flow situations are often particularly sensitive to water quality stressors. For example, concentrations of substances that are more or less continuously added, but in low doses (e.g., from sewage treatment plants), will increase and might reach levels toxic to organisms (see examples below), or concentrations might exceed bathing and recreational water directives (such as for fecal bacteria, e.g., Garcia-Armisen et al. 2005). During warm weather, water becomes warmer, boosting primary production and leading to eutrophication and various secondary effects. Lindqvist et al. (2005) assessed the environmental risk of drug residues in running waters by the ratio of measured environmental concentration and predicted no-effect concentration. Not surprisingly, they found that, during dry seasons and malfunctioning of sewage treatment plants, concentrations increased and some compounds could be associated with a

Table 1. Examples of situations when combinations of water quality variables and extreme discharge conditions can produce environmental problems.

Water quality variables	Low flows	High flows
Pollutants	Concentrations can reach toxic levels	Can be washed out from adjacent, otherwise unflooded uplands; dilution reduces but does not eliminate risk for toxicity
Drugs	PPCP:s (Pharmaceuticals and Personal Care Products) can become toxic; natural estrogens can feminize fish	
Nutrients	Can lead to eutrophication and acidification; N levels can become toxic	Removed from watercourse by downstream transport, uptake by riparian vegetation and denitrification
Salts	Can lead to acidification, mobilization of toxic metals and invasion of salt-tolerant species	
Organic matter and sediments		Considerable addition that increases turbidity, which reduces primary productivity and may increase acidity and threaten fish production Organic matter can reduce pH Sedimentation of transported inorganic matter restructures channel
High temperature	Lowers oxygen content, makes contaminants more toxic, lowers productivity	
Low temperature	Surface ice cover leads to reduced oxygen Open water and low air temperatures can foster excessive formation of frazil ice and anchor ice that damage aquatic biota Open water and temperatures rising from below to above 0°C lead to melting anchor ice that can jam up and produce local floods and upland ice that damage riparian and upland biota	If high flows occur during periods with low temperatures and surface ice, water can be forced on top of the ice, often leading to floods, or the ice cover may break up and run the risk of jamming

risk in small water systems. In cold winter climates where rivers become ice-covered (Fig. 2), oxygen will be depleted during winter, sometimes to levels known to impair biological activity (Prowse 1994). Low-water situations in turbulent reaches may foster excessive ice formation (Fig. 2), including ice jams, and disturbance to (and rejuvenation of) riparian and upland ecosystems. Such ice disturbance, which starts with abundant formation of frazil ice (Shen and Liu 2003), will ultimately affect water chemistry, especially in nutrient-poor regions where abundant ice formation can in fact increase the nutrient load brought to the river because vegetation and soil are eroded by ice and washed into the river (Moore and Landrigan 1999, Prowse and Culp 2003).

Drugs

One type of contaminant that reaches surface waters worldwide at an increasing rate consists of pharmaceuticals and personal care products (PPCPs) and natural estrogens (Ternes 1998, Heberer 2002). These PPCPs represent a large group of compounds that include non-prescription and prescription pharmaceuticals for human and veterinary use, and the active and inert ingredients in personal care products (Lishman et al. 2006). Many of these chemicals are released from sewage treatment plants, but effluents from livestock feedlots and kraft pulp mills can also be important sources (Parks et al. 2001, Soto et al. 2004). In most cases, the concentrations found in surface waters are too low to have a biological effect. However, some compounds, e.g., estrogens, bioaccumulate in fish tissue and are likely to feminize wild fish (Gibson et al. 2005). There are also indications that PPCPs could harm liver cells in fish (Gagné et al. 2006). The risks these contaminants exert on other aquatic organisms and possibly human health are poorly understood. In response, precautionary management actions for reducing their release in the environment have been presented (Doerr-MacEwen and Haight 2006), however, without including any flow-related prescriptions.

Salts

Although salinization is often associated with arid and semi-arid regions, it is not restricted to such areas. Elevated chloride concentration in streams due to urbanization is likely similar in most urbanized regions of the world. Chloride contamination comes from road salts, industrial wastes, failing septic systems, and certain agricultural chemicals (e.g., potash). A study made in the northeastern USA showed that chloride concentration in rivers and streams increased at a rate that threatens the availability of freshwater (Kaushal et al. 2005). In wintertime, chloride concentration in freshwater amounted to 25% of the concentration in seawater (i.e., ca. 5 g/L), and in summertime, it still remained 100 times higher in streams located in urban and sub-urban catchments compared with streams in unimpacted forest streams. Elevated chloride concentration in streams and rivers leads to acidification and mobilization of toxic metals through facilitated ion exchange (Kaushal et al. 2005). This in turn can cause changes in the rate of mortality and reproduction of aquatic plants and animals (Sarma et al. 2005) and alter the structure of riparian and wetland plant communities and their nutrient cycling (Baldwin et al. 2006). It can also facilitate the invasion of saltwater species into freshwater ecosystems. Apart from threatening ecosystems, it also affects local supplies of drinking water. Variation in salinity of running waters is strongly related to variation in flow. For example, Chang and Carlson (2005) found that chloride concentration was negatively correlated with discharge of Spring Creek in Pennsylvania, suggesting the worst effects occurred during low flows and were diluted at higher discharges. In other words, a flush of chloride from land during rain storms is less important. The Amu Darya River in Central Asia shows a similar pattern. River water is used for land washing—a means to reduce soil salinity—and irrigation of surrounding crop land. During low flows, the return of this water to the river increases water salinity. During high flows, however, water from snow and glacier melting in the headwaters promotes dilution of dissolved salts (Crosa et al. 2006). In the lower reaches, this dilution period, representing <5 months on average, is the only one offering palatable freshwater (Crosa et al. 2006).

Temperature

The concept of “thermal pollution” is widely used for cases when water quality is impaired through temperature increase, usually following the use of water as a coolant, especially in power plants. Provided that the quantity of water used as coolant is more or less constant, warming is most influential during low-water periods because of the reduced buffering capacity of the receiving water mass. Warming reduces the solubility of gases, e.g.,

Fig. 2. Stream in which the bottom is covered by anchor ice, and the water is running on top of this ice, thus raising water levels. Such seasonal events may hamper biota in aquatic as well as riparian habitats and can serve as population bottlenecks for many species. Photo courtesy of Johanna Engström.

oxygen, which can have serious consequences for aquatic life (e.g., Najjar et al. 2000, Ficke et al. 2007). There are also combined effects of thermal discharge and the toxicity of many contaminants, which are shown to increase with temperature (Langford 1990). Extensive water extraction for irrigation or hydropower production also creates low-flow situations that make rivers and streams vulnerable to temperature fluctuations. Small streams are especially vulnerable due to low thermal capacity (Caissie 2006), and even more so if they have lost riparian shade through deforestation of streamside buffers or extensive grazing. Thermal pollution also affects stream productivity, for example, through influences on spawning, survival, and growth of fish (Todd et al. 2005). Warm waters can also increase fish mortality, for example, due to viral infections (Hara et al. 2006), and restrict fish distribution (Madej et al. 2006).

Nutrients

Human activities such as fossil-fuel-derived atmospheric deposition, fertilizer use, and sewage/

industrial effluents have increased nutrient levels in aquatic systems (Conley 2000, Boyer et al. 2006). Low-flow situations with high nutrient concentration are especially damaging if they occur at a time when organisms are biologically active, like spring or summer (Jarvie et al. 2006). Ecosystem responses to eutrophication are most studied in standing waters, but nutrient addition also enhances primary production in streams, predominantly of benthic algae (Lawrence and Gresens 2004, Torrecilla et al. 2005), but can also enhance growth of pelagic algae (Smith et al. 1999). Eutrophication of running waters may lead to reduction of water clarity, taste and odor problems, blockage of intake screens and filters, restriction of swimming and other water-based recreation, harmful diel fluctuations in pH and in dissolved oxygen concentrations, reduction of habitat quality for macroinvertebrates and fish spawning, and an increase in the probability of fish kills (Nijboer and Verdonschot 2004). Apart from causing eutrophication, enhanced deposition of inorganic nitrogen can also increase the concentration of hydrogen ions in freshwater ecosystems with low acid-neutralizing capacity, resulting in acidification of those systems (Camargo and Alonso 2006). Nitrogen can even become toxic and impair the ability of aquatic animals to survive, grow, and reproduce. At elevated concentrations, ammonia, nitrite, and nitrate are all toxic to aquatic animals (Camargo et al. 2005). Inorganic nitrogen pollution of ground and surface waters can also induce adverse effects on human health and economy. Ingested nitrites and nitrates can induce methemoglobinemia (particularly in infants) and have a potential role in developing various cancers and birth defects. They can also play a role in the etiology of insulin-dependent diabetes mellitus and in the development of thyroid hypertrophy, or cause spontaneous abortions and respiratory tract infections. Indirect health hazards can occur as a consequence of algal toxins, with symptoms ranging from nausea to severe poisoning syndromes (Camargo and Alonso 2006).

Frequency, Timing, and Rate of Change of Flow Events

Worldwide, there are examples of streams naturally varying from stable to highly variable flows (Puckridge et al. 1998) with subsequent changes in water quality. For example, sudden drops in flow, resulting from naturally occurring dry spells, or human-caused fill-up of reservoirs or water extraction, will leave water-saturated sediments exposed, thus increasing the risk for mud slides and turbid water. Similarly, sudden increases in flow will also increase sediment discharge. For example, Old et al. (2005) describe natural jökulhlaups (glacier outburst floods) in the Skaftá River in Iceland in which discharge increased from 120 to 572 m^3/s over 53.5 hours, and sediment concentration increased 5.4 times. Furthermore, sudden increases in flow in ice-covered rivers can cause ice jams (e.g., Shen and Liu 2003), leading to flooding and potential nutrient enrichment of the river water (Prowse and Culp 2003; cf. above). Effects on water quality can also result when extreme flow events deviate from the norm in their timing. For example, it is well known from impounded rivers that long-term flooding, especially during the growing season, will destroy plant cover and erode soil, thus increasing the nutrient content of water but also its concentration of metals such as methyl mercury (St. Louis et al. 2004). This “damming effect,” which often leads to a rapid increase in, e.g., fish production, reaches a peak during the years following the erection of a dam, slowly disappearing thereafter (e.g., Stockner et al. 2000, Gunkel et al. 2003). Gentle fertilization of such reservoirs has been suggested as a means of maintaining fish production (and fishing tourism) at a more sustainable level (e.g., Persson et al. 2008). Howitt et al. (2007) developed a model to predict unfavorable water quality associated with flooding in the Barmah-Millewa Forests on the River Murray, Australia and found that pooled floods and those in the warmest months of the year were substantially more likely to result in blackwater events (high levels of dissolved organic matter associated with low levels of dissolved oxygen) than floods in cooler times of the year and involving more water exchange between the river channel and the floodplain.

CONNECTIVITY

There is also a landscape ecological component involved in the relationship between the flow regime and the resultant water quality. Connectivity in rivers is maintained by interactions between river channels and surrounding landscapes and by natural hydrographs in unfragmented channels. Although connectivity is essential for upholding ecosystem processes of a river (e.g., Ward et al. 1999), including transport of materials, it also facilitates transport of unwanted substances such as anthropogenic pollutants within the catchment. On average, humans have increased connectivity between uplands and rivers (clearcuts, impervious land, trenching networks), but decreased connectivity in rivers (dams and reservoirs), although with large variation between extremes (heavily channelized stretches vs. cascades of dams and reservoirs). Impounded rivers may retain major fractions of waterborne substances in reservoirs (e.g., Humborg et al. 2006), but the importance of this retention for nutrient cycling of a river is under debate (Teodoru and Wehrli 2005). Dams also change water quality at various distances downstream from the dams (e. g., Stanford et al. 1996). For example, after damming of the Alta River in northern Norway, water temperature in the river downstream of the dam decreased in early summer and increased in late summer and autumn, but effects on fish growth were considered negligible (Jensen 2003). In warmer climates, however, hypolimnic water release from reservoirs can cause considerable reduction of water temperature downstream from the dam, reduce metabolic rates and breakdown of organic matter, and disrupt spawning of native fish (Preece and Jones 2002).

Connectivity is important to consider when managing flows for good water quality (Kondolf et al. 2006). Pollutants stem from point as well as non-point sources and affect a river system differently depending on the location within a catchment. River reaches located in the middle and lower parts of catchments are subjected to the cumulative effects of human alterations to the flow regime and the water quality (Pringle 2000). Location relative to predominant climates, such as ruling wind direction, is also an important factor for reach sensitivity. For example, a river reach that receives pollutants from atmospheric deposition can be more sensitive to riverborne pollutants than a reach without such inputs. The connectivity between river water and groundwater, mediated by the hyporheic flow (flow in the exchange zone between river and groundwater) is also an important factor in management of water quality. The behavior of solute transport is highly affected by the hyporheic pathways as these affect the degree of transient storage in the river (Kazezyilmaz-Alhan and Medina 2006). The hyporheic zone also affects water quality. Harner and Stanford (2003) compared cottonwood growth between a gaining (upwelling) and a losing (downwelling) reach on the Nyack Floodplain, Flathead River, Montana, USA, and found that trees in the gaining reach grew fastest. They associated this difference with a greater availability of growth-promoting resources in the gaining reach, such as improved hydration and fertilization due to microbial activity in the hyporheic zone. The greater availability of nutrients was reflected in lower C:N ratios in the leaves of the trees in the gaining reach. Upwelling hyporheic water can also serve as thermal refugia for fish, in situations with low flow and high water temperatures (Ebersole et al. 2001).

MANAGING RIVERS FOR WATER QUALITY

Our review has presented a number of examples in which human interference with the water system has reduced its ability to produce ecosystem services. Such services include products such as food, fuel, and fiber; regulating services such as climate regulation and disease control; and nonmaterial benefits such as spiritual or aesthetic benefits (Millennium Ecosystem Assessment 2005). For example, a wet, forested floodplain can regulate local climate by cooling the ambient temperature by as much as 20°C at noon compared with a drained field with row crop monoculture (Pokorný 2001), encouraging local rainfall. Our review also indicates that most problems are associated with reduced flows in rivers. To maintain a water system that can be supportive of both natural ecosystems and human societies, competent and innovative management is required. The successful management of rivers for water quality requires scientific knowledge presented as well-grounded ecological principles in a format that is easily accessible and usable by water managers, linked to a political agenda and funding for their implementation. The nursing and sustaining of political commitment usually necessitate increased communication and education across disciplines and spatial scales, and between scientists, managers, and stakeholders to facilitate an integrated view of freshwater resources (Johnstone and Horan 1996, Baron et al. 2002, Macleod et al. 2007). Teaching students to manage aquatic ecosystems at the catchment level is also important (Chaubey and Matlock 2007). This participatory river-basin management is called “social learning” and is alleged to be a useful strategy, yet with many obstacles (Mostert et al. 2007). The required management actions would fall into three categories (Fig. 3): (1) changed land-use patterns in the catchment, (2) restructuring of river morphology, and (3) modified discharge patterns.

The first two categories imply a more long-term transformation of the river and its catchment, whereas the last one can be used to correct short-term needs if necessary infrastructure such as dams and locks are in place.

Changes in Land Use

Reduction and deceleration of polluted surface runoff

Management of river catchments can be tailored to "reduce rapid surface runoff during rains," thus also reducing the risk that various pollutants become washed out of the landscape to accumulate excessively in rivers. Lane et al. (2006) provided an example of this for the location of new roads. If roads are sited so that runoff water may travel overland for considerable distances and infiltrate, connectivity between road runoff sources and stream networks will become limited. Another example was given by Bekele et al. (2006) who reported from an area at the North Bosque River in Texas, where during a 4-year period, 500 000 metric tons of dairy manure was hauled from the catchment to composting facilities, thereby preventing nutrients from being washed into the river. At the sites with the highest amounts of manure being removed per cow and per catchment area, phosphorus levels in the water decreased significantly. Jia et al. (2006) considered both these approaches—to remove nutrients from the catchment or to let them travel (aboveground and belowground) and eventually reach the water—and concluded that proper "scheduling of wastewater addition" (as fertilizer) to agricultural fields and proper timing of irrigation were more efficient than remedial measures such as "development of vegetative buffers." Liljaniemi et al. (2003) also evaluated the efficiency of vegetated buffers in cleaning effluents from forested and drained, fertilized peatlands in Finland and found that 2–10 m wide buffers did not succeed in retaining nutrients and metals. They concluded that considerably wider buffer strips would be needed. This may be true for upland buffers, but other factors than width are also important. Riparian buffers can be effective in reducing nutrients even in rather narrow states (Schoonover et al. 2005, McKergow et al. 2006) but their efficiency increases with width, forest cover, and longitudinal continuity (Scarsbrook and Halliday 1999, Nieminen et al. 2005, Harding et al. 2006). Verhoeven et al. (2006) reviewed measurements from different regions around the world and concluded that 2–7% of the catchment area needs to be wetland habitat in order to provide efficient water quality improvement. They also stressed the importance of keeping nutrient loads to wetland habitats under a critical threshold level to avoid biodiversity loss and structural changes in the wetland ecosystem. Also loadings could surpass a critical level where the wetland no longer performs nutrient retention, but instead releases additional nutrients or emits N_2O (a greenhouse gas).

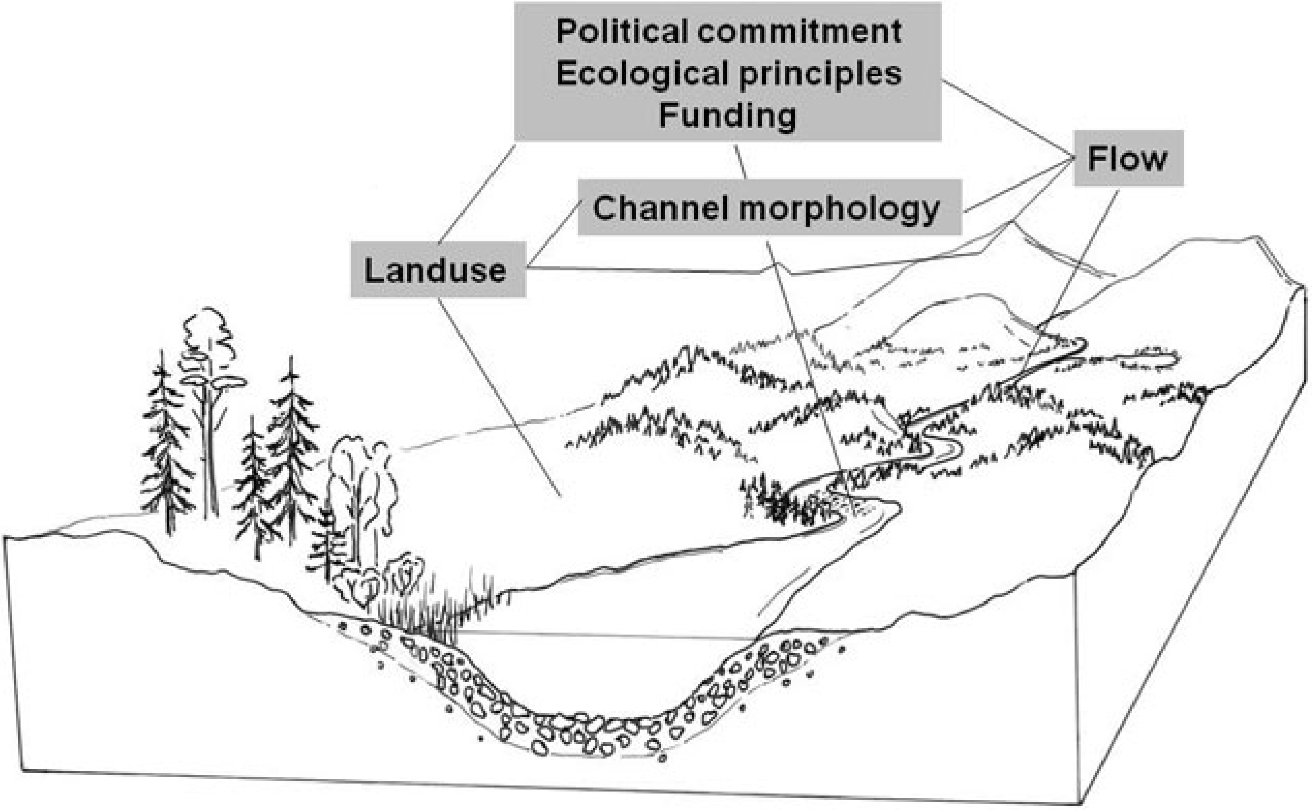
Modification of wastewater releases

Another change in land use is "modifying releases of pollutants." Chen et al. (2006), working on polluted rivers in Taiwan, described an approach to first identify sources of pollution and second make an effort to reduce pollution discharge. Their management framework is based on collaboration between environment, society, economy, and various institutions, and on the principles of sustainable development. In an attempt to optimize a river's ability to accommodate various wastewater discharge concentrations, Ng et al. (2006) developed a discharge program by using variation in flow conditions and seasons. They concluded that, as the river has high assimilative capacity in winter compared with summer, less efficient (implying release of small but acceptable amounts of chemicals) wastewater treatment can be allowed during winter because of the high dilution capacity in the river. Under some circumstances, removal of wastewater effluents can even reduce water quality of a river. Farber et al. (2005) described such a case for the Jordan River, the water of which is composed of saline groundwater and non-saline surface water. Reducing the wastewater effluents, which is part of the Israel–Jordan peace treaty, would significantly reduce the river's flow and increase the relative proportion of saline groundwater flux into the river. This, in turn, would probably cause river desiccation during summer months.

Restructuring of River Morphology

Changes in land use can also imply restoration. For example, Mitsch et al. (2005) proposed the "construction of riparian wetlands to clean polluted river water" before it reaches the ocean. They estimated that 22 000 km^2 of wetland creation and restoration could remove 40% of the nitrogen

Fig. 3. Major management actions required to reduce the risk for unfavorable water quality situations fall into three major categories at the catchment scale. If political incentive, knowledge, and funding are available, management should focus primarily on modifying land use, channel morphology, and flow.



estimated to discharge from the Mississippi River into the Gulf of Mexico. Mitsch et al. (2005) found this solution economically preferable to reducing fertilizer use in agriculture. Stone et al. (2003) proposed a similar solution, but for very small streams. The idea of wetlands for pollution retention is by no means new, but usually they are used to treat water before it reaches a river (e.g., Poe et al. 2003). To remove nitrate, a general management strategy could be to increase the complexity of riverine systems, because nitrate levels in water are reduced by water retentive structures, not only by aquatic vegetation but also by coarse woody debris and baffles (Ensign and Doyle 2005). It is also important to realize that natural variations in discharge (and river width) affect the capacity of rivers to process nutrients. Riparian wetlands are not only functional in reducing nutrient loading into rivers but are also valuable for flood protection. Within the Rhine basin, it is now recognized that the best protection against flooding is to make space for the river to flood certain areas to protect others from being flooded (Scholz 2007). Setting aside certain areas for flooding could thus be a means of both protecting valuable land and reducing the risk of pollutants being washed out in the water.

Modification of Discharge

Securing enough water at the right time to uphold regulating ecosystem services such as water and habitat quality control to sustain riverine ecosystems and people dependent on them is essential to allow for a sustainable use of water resources. So far, the vast majority of work on environmental flows has concentrated on the magnitude of flow and its variation (Tharme 2003) and direct links between flow and ecosystem responses; indirect links between flow, water quality aspects, and ecosystem responses are less studied. The South African National Water Act (NWA) of 1998 is probably the most advanced act so far in defining integrated management of the flow regime and the water quality (Scherman et al. 2003, Palmer et al. 2005a). It has recognized that to sustain the goods and services that are provided by rivers it is essential to safeguard the entire riverine ecosystem (Department of Water Affairs and Forestry (DWAF) 1999, Malan and Day 2003). The NWA provides the term “ecological reserve” for the quantity and quality of water necessary for sustainable protection of aquatic ecosystems while still allowing human use of the resource. The NWA calls for a system of classification of water resources and has stimulated research on how water quantity and water quality can be inter-related (e.g., Malan et al. 2003). The scientific understanding of these relationships and the resulting effects on ecosystems are limited. Hence, the integration of water quantity and water quality variables in protecting water resource management is still in its infancy (Palmer et al. 2005a).

CONCLUSIONS

Increasing human manipulation of stream flows and increasing pollution have led to many environmental problems that require attention. We have provided a number of examples of changes that could balance water quantity and quality and improve environmental conditions, such as reduction of surface runoff, timing of wastewater release, regulation of flows, and development of habitats for water cleaning. Flow schemes designed to avoid extended periods of low water will be especially important. The need for action is reflected in the fact that water management schemes have developed substantially over the last decade in many countries, and further development can be expected following the increasing societal demands for water. Water development schemes are usually complex and present many challenges, such as maintenance of biodiversity, ecological functions, and ecosystem services in a context where human beliefs, actions, and values play a central role. In essence, coordinated, holistic water management that takes in all water users in nature and society is needed. One such example is Integrated Water Resource Management (IWRM), which promotes sector integration in development and management of water resources to ensure that water is allocated between different users in a fair way, maximizing economic and social welfare without compromising the sustainability of vital ecosystems (Jonker 2007). One limitation of such management systems is that economically and politically powerful users can easily quantify and argue their needs. It is harder to define the economic value of ecosystem services and, therefore, the ecosystems and people most dependent on them for their subsistence become voiceless and often neglected users. Therefore, integrated approaches should make sure that stakeholders and sectors involved will reflect the true complexity and diversity of interests and livelihoods and provide an opportunity for more coordinated and effective policies and programs within and between sectors (Nunan 2007).

Such participatory approaches will hopefully also reveal constraints such as uncertainty, data heterogeneity (Hannerz and Langaas 2007), technology shortcomings, and insufficiencies in legislation and institutions. Another constraint is when advanced, best-practice policy directives stress the importance of cross-sectoral integration (e.g., EU’s Water Framework Directive), but do not translate at regional levels into legislation and planning that is effective in this regard (e.g., Furhacker 2008). Many problems with impaired water quality are associated with highly unnatural episodes of low flow, and the stress imposed on the ecosystem varies between seasons. Many rivers only have a fraction of their natural flow remaining within the channel, and an increasing number of formerly perennial rivers never reach the sea (Brown 2006). The uncertainties of future changes to the global climate and the long-term implications of management actions add extra complexity to water management (cf. Lehner et al. 2006, Palmer et al. 2008). These uncertainties echo the call for a transition from currently prevailing, more sector-specific regimes of river basin water management to more integrated, adaptive approaches that are flexible and responsive to change (cf. Bouwer 2002).

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol13/iss2/art18/responses/

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