

## An Introduction to Rivers

*We are giving here an article that helps our understanding of Rivers. We are thankful to Devashis Chatterjee for drawing our attention to the source: AN INTRODUCTION TO RIVERS — THE CONCEPTUAL BASIS FOR THE MICHIGAN RIVERS INVENTORY (MRI) PROJECT, Dec 1997, Michigan Dept of Natural Resources, Michigan, USA. We have edited it to suit our requirements.*

What is a river? Most of us would agree that a river is a wonderful place. A soothing spot, with magically running waters. A home to swarming mayflies, fishes, herons, and otters. A place for commerce and industry, as well as recreation and relaxation. Most of us get to know rivers at particular sites: bridges, bends near the road, rapids, and the old swimming hole. Not surprisingly, the perspective of the river as “a place” is embedded in our popular culture and language. Stream, creek, river, brook, ditch, spring, run... we have a lexicon of names for what seem to us to be clearly different kinds of places. The technical literature on river management also largely comes from this perspective of the river as a place. Much of what we know today about the ecology of rivers we owe to biologists who have focused on certain populations of this or that species of fish, invertebrate, or plant; that live in specific habitats within rivers. In this context it has sometimes been useful to think of a whole river system as being essentially a large collection of unique places. Each with its own local properties (depth, velocity, substrate, water quality, etc.) and each potentially serving as a home to some unique set of discriminating organisms.

**Like the fable of the seven blind men who were each able only to touch and perceive one small part of the elephant, what we perceive at the river bank tends to be heavily biased by our limited vision.**

There is an alternate perspective, one perhaps more attuned to the ecological reality faced by modern river managers. It is that the river is not so much a place, as it is a thing. Like the fish that lives in it, the river itself is an entity with a unique structure and function, with a specific history, and capable of self-generated dynamic behavior. Protecting the many values of the river as place requires a thorough understanding of the nature of the river as a thing. What kind of thing is a river? We can recognize four fundamental characteristics which are essential to understanding the nature of river systems: A river is:

- ⇒ A landscape-scale system because of its immense physical extent.
- ⇒ A hydrologic system because it participates in regional water cycling.
- ⇒ A geomorphic system because it shapes the landscape it occurs on and its own channel.
- ⇒ An ecological system because it supports a diverse and highly adapted biota.

**Rivers as landscape-scale systems** In contrast to oceans and even lakes, people usually experience river channels as relatively small, intimate, geographic

features. This is likely a part of their inherent attractiveness to us. You can always see across a river; frequently you can wade across it, and many streams can be easily hopped over by a reasonably energetic adult. This small size, however, is an illusion. Our sensory capabilities are effective over only a very short radius; river systems, on the other hand, are immense but essentially linear objects. In fact, rivers are among the largest landscape elements known. Rivers operate at scales of hundreds to thousands of square miles.

This characteristically large scale by itself has important implications for river science and management. Most fundamental is the fact that rivers are always strongly influenced by both the regional composition of the landscape (e.g. geology) and by regional climatic characteristics. This means that every specific place on a

river is affected by two distinct sets of variables and processes.

Local (site-specific) variables include the characteristics of the site which can be observed and measured (potentially at least) at that place in the river. Large-scale regional processes and variables affect the site via the watershed (catchment) area which contributes water and material loads to that location. Determining the extent to which a problem of interest is a local (site management) issue or a systemic (watershed management) issue is necessarily one of the first steps in scientific river management. And since all rivers are by nature landscape-scale systems, even when the objective is narrowly defined as management for specific site characteristics, attention must be paid to larger landscape management issues.

Finally, the large size of river systems guarantees that every river presents a complex mosaic of interactions and relationships involving the many smaller landscape elements in its catchment. These include diverse terrestrial ecosystems as well as various human political and economic units. Indeed the primary challenges in managing rivers stem from the often competing, multiple values that these large systems offer (water supply, transportation, power, recreation) as they wind their way across great expanses of land. River management is therefore intrinsically a matter of ecosystem management. Resource scientists and managers are now recognizing the importance of developing larger-

scale, integrated strategies for managing natural resources. For river systems, there is no alternative. The scale, integration, and very nature of rivers require it.

**Rivers as hydrologic systems** Rivers carry water across the landscape, participating in the larger regional cycling of water between the oceans, the atmosphere, and the landscape. A river's hydrologic properties are inseparably intertwined with its geomorphic, chemical, and biological characteristics. The amount and timing of water transport through a river channel network is the end result of a complex interaction between landscape elements and the climate. To understand the hydrologic behavior of a river, we have to understand the key hydrologic processes that generate stream flow and govern its distribution in time and space. These processes include: precipitation, evaporation, transpiration, depression storage, infiltration, overland flow, and groundwater flow. Together these hydrologic processes link the river to the larger landscape it is a part of. The catchment area is the basic landscape unit in river hydrology. Every site on a river network has a unique catchment area, that is, an area of the landscape that contributes water to the flow at that site.

Because water is chemically conservative, in every watershed there is an approximate balance (called a water balance) between inputs, outputs, and storage of water in the landscape per unit time. Balance equations are useful summarizations that help us think about the relationship between river discharge and various hydrologic processes on the landscape.

Writing out the balance equation, we get a statement about how hydrologic processes on the landscape are related to flows observed in the river (Q).

$$Q = P - [ET + \Delta GW + (\Delta S_s + \Delta S_{sm} + \Delta S_{gw})]$$

EQ 1

Precipitation (P) and evapotranspiration (ET) depend on climate patterns and vegetation cover. The term ( $\Delta GW$ ) represents net groundwater flux in the catchment basin and is principally a feature of the geology. The term ( $\Delta S_s + \Delta S_{sm} + \Delta S_{gw}$ ) represents change in water storage on and in the landscape and depends primarily upon the topography and soil characteristics. It is then clear that ultimately three primary factors control the catchment water balance and therefore river flow (Q): landscape, climate, and geology.

**In most watersheds the path water takes to the channel controls the way that stream flow responds to precipitation in the watershed.**

**Runoff reaches the channel rapidly, throughflow reaches the channel after a moderate (hours to days) lag time, and groundwater flow after a long (months to years) lag time.**

**Sources of streamflow** When it rains there are three possible pathways precipitation can take to get to a river channel.

**Runoff**—rain arriving at the soil surface infiltrates at a rate set by capillary action and permeability. When (1) precipitation rate exceeds infiltration rate or (2) the soil surface becomes saturated because of lateral throughflow, water accumulates at the surface and flows overland and down slope.

**Throughflow**—water that infiltrates the soil surface must percolate vertically through lower layers of soils. If there are differences in the percolation rates of these

layers, water can accumulate at horizon interfaces and generate sub-surface flows down slope.

**Groundwater flow**—water that infiltrates may eventually reach the local water table (a zone of more or less permanently water-saturated soils). This groundwater [GW] also moves down slope albeit at very low rates. Groundwater can eventually reach the river channel by several means including (1) channel incision of the water table, (2) seepage and/or artesian flows to spring and wetlands that drain to the channel, and (3) artesian feeds to drainage lakes. The extent to which groundwater contributes to the flow of a given river depends heavily on the geology of the catchment (particularly infiltration characteristics) and the rate at which groundwater can flow down slope.

Groundwater velocities can vary by 5-8 orders of magnitude depending on geological composition of the saturated layers and the hydrostatic pressures involved. Hydraulic conductivity (K) is related to porosity and, together with hydraulic slope (usually water table slope  $DH$ ) and flow length (l), governs groundwater flow velocity ( $V_{gw}$ ) according to Darcy's Law:

$$V_{gw} = K * (DH / l) \quad \text{EQ 2}$$

Darcy's Law is also sometimes expressed as a function of the area of a particular aquifer (A), with the dependent variable being groundwater volume discharge ( $Q_{gw}$ ):

$$Q_{gw} = K * (DH / l) * A \quad \text{EQ 3}$$

Practically speaking Darcy's Law indicates that watersheds with extensive areas of porous (eg. sand or gravel) substrates and large elevation changes (hills) are most likely to have high rates of groundwater input to river channels. Rivers draining flat terrains and/or with

finer soils are least likely to have substantial groundwater supply.

*Why hydrologic source is important* Runoff reaches the channel rapidly, throughflow reaches the channel after a moderate (hours to days) lag time, and groundwater flow after a long (months to years) lag time. Storage (surface or sub-surface) can also create substantial lags in delivery time.

The more complex the flow path is, the longer a pulse of precipitation takes to reach the channel, the more attenuated its peak becomes, and the more its effects on flow are spread out in time.

As a result the flow characteristics of a river depend to a large extent on the nature of its hydrologic source.

Rivers supplied primarily by runoff respond dramatically to rain, rapidly generating high peak discharges and quickly passing water downstream. In between rain events these rivers experience rapid & severe declines in discharge since most excess water in the basin has already been transported away. These rivers are sometimes referred to as being hydrologically "flashy".

Rivers supplied primarily by groundwater respond weakly to precipitation events. Discharge increases just a little because most precipitation is captured by infiltration.

This water slowly makes its way to the channel, and the resultant lag time ensures an ample and continuous supply of groundwater to the river between rain events. Groundwater Rivers are hydrologically-stable systems, with lower peak flows but higher base flows than in runoff-driven rivers of comparable size.

Most rivers receive some water from runoff, throughflow, and groundwater sources. As might be expected, rivers with a relatively balanced mix of sources have intermediate hydrologic properties. Their specific flow characteristics vary substantially depending on their particular position along the continuum between predominantly runoff and predominantly groundwater sources. Other factors, including the size and shape of the stream network, and the amount of hydrologic storage available in floodplains and reservoirs, can also have significant influences on delivery times and attenuation of discharge peaks. For example round, funnel-shaped basins deliver water more rapidly than long, narrow basins. Likewise, well-developed drainage networks deliver larger volumes of water more rapidly than low-density networks.

**Rivers as geomorphic systems** As naturally as river channels carry water across the landscape, they also carry sediment and dissolved materials, transforming this landscape by erosion, dissolution, and deposition. This landscape-shaping function of rivers has been a key focus of geologists interested in geomorphology for at least a century (geomorphology, from the Greek, geo = earth, morph = form). Building on the foundation of the Davis (1899) model of landscape evolution, geologists have played a leading role in studying rivers from a whole-system perspective. Davis (1899) considered the observed landscape to be the result of cycles of geologic uplift and erosion. Rivers were viewed as the principle agent of continental erosion, and between episodic uplifts continually reduce landform elevations towards a base level set by the elevation of the river mouth.

A simplified but useful model of the overall geomorphic structure of a river divides the fluvial system into three major zones. Each zone is distinctive in terms of material processing. The upper river network comprises the zone of production where most of the sediment, dissolved mineral and nutrient, and water loads of the system are acquired. The zone of transfer consists of the middle to lower reaches of the river system in which transport and channel building processes dominate. Finally, the zone of deposition is found near and at the mouth where loads are deposited or delivered to the receiving

system. This viewpoint clearly emphasises the geomorphological function of rivers: moving material across the landscape.

The amount of power available for geomorphic work is proportional to both the amount (mass) of water being moved in the channel (and therefore to river flow,  $Q$ ) and to the slope of the channel. High slopes and/or large  $Q$  result in high-power rivers with massive potential for erosive work and channel building. Small  $Q$  and/or mild slopes generate little power and produce a reduced capacity for erosive work and material transport.

Since power is proportional to  $Q$ , the geomorphic potential of a river is intimately bound up with its hydrologic character. Runoff Rivers, with their flashy and high peak flows, do geomorphic work in short, extremely powerful bursts. Groundwater Rivers seldom have as powerful peak flows, but maintain more powerful base flows and can accomplish lighter geomorphic work for most of the year. Slope (which helps determine stream power) is a characteristic of both the landscape and of the river channel itself. The Davis model implies that catchment slope varies over time as erosion of the

**As geomorphic systems, rivers employ energy (generated by moving large masses of water down slope to accomplish the work of erosion, sediment transport, and channel building. This is the same power we use to generate electricity from the artificially-steep gradients engineered into spillways of hydropower facilities.**

landscape progresses. This is, of course, a very long-term process that typically occurs in a geological time frame of thousands to millions of years. The slope of channel, however, can be adjusted by the river itself (within the constraints of the catchment slope by) in a much shorter time frame (years to decades) by meandering and altering channel length.

The balance between hydrologic driving variables, available power, and channel morphology (e.g. width, depth, slope, shape, and sinuosity) has been a central focus of river geomorphologists. From their perspective the resulting "fluvial system" is a physical, landscape-scale system that tends over time to move toward a dynamic equilibrium where available stream power and sediment load are balanced against channel resistance, and sediment transport and deposition. That is to say, within constraints imposed by local landscape features, the river continuously builds and shapes its own channel to accommodate the water and sediment loads generated by its watershed. A river that approaches this dynamic equilibrium is said to be "in grade". This dynamic behavior of a fluvial system can be thought of as being both (1) self-generating (endogenous) and (2) directional (moving towards an equilibrium balance of power and work).

**Rivers as ecological systems** In addition to being fascinating physical systems, rivers are full of interesting biology. Modern rivers contain myriad species of plants, animals, and micro-organisms that have evolved over the last 2.5 billion years to make their living and find a home in fluvial systems. Continental rivers pre-date the evolution of life on this planet, and were undoubtedly among the first habitats on the continental land masses penetrated by an originally marine biota. Since that time numerous lineages have colonized rivers both from the sea and from the land. Given millions of years and the periodic hydrologic isolation of distinct river basins, evolution has produced numerous species highly adapted to specific fluvial environments.

The biota found in any given place in a river today reflects the balance between two important zoogeographic processes: (1) additions of species

(immigration) from the pool of populations available in the region, which have had an opportunity to colonize a particular river segment; and (2) losses of species (local extinctions) through ecological processes like competition, predation, or excessive environmental disturbance (including pollution). In modern times humans have increased the rate of introduction of new species to specific river environments, homogenizing the biological communities of the world's rivers to a greater and greater extent. We have also increased the severity of environmental stresses and disturbances in most river ecosystems. The unfortunate result has generally been a significant increase in the rate of local extinctions and the loss of many unique populations. The ecological richness of natural river systems is in danger of being replaced with a significantly less-diverse array of biological forms more tolerant of the physical changes we impose on river systems.

*Structure and function of river ecosystems* Fluvial ecosystems share with all ecosystems the property of being both physically and biologically controlled in terms of energy and nutrient cycling. As in other ecosystems, the presence of complex biological communities comprised of interacting populations can give rise to new and additional elements of dynamical behavior at the ecosystem level. Biological dynamics arise from specific interactions between competitors, predators and prey, pathogens and hosts, etc. These interactions in turn can have important consequences for the chemical and even physical organization of river environments.

On the other hand, there are several important ways in which rivers are distinct from most other more familiar, and well-studied, ecosystems. Key differences include:

⇒ Rivers have a large-scale directional organization (upstream-downstream).

⇒ Rivers are dominated by active rather than diffusive material transport.

⇒ rivers have exceptionally high rates of energy and material throughput

⇒ rivers always 'contain' many other imbedded ecosystems (both terrestrial and aquatic)

Attempts by stream ecologists to explicitly recognize this

**Human modifications of water or sediment loads, or of local channel constraints create conditions requiring a new equilibrium relationship. A river will tend to respond to such modifications by adjusting its channel through erosional or depositional processes. Practical management and planning with respect to rivers is impossible without a basic appreciation for this intrinsic behavior of fluvial systems.**

**The hierarchically-nested nature of river networks, coupled with the directional flow of water (down-slope), leads to accumulating water and material loads as rivers flow downstream. As a result rivers develop a large-scale upstream-downstream pattern in the organization of both ecological processes and biological communities.**

*longitudinal structuring* has led to several distinct theoretical paradigms over the past century including longitudinal zonation schemes, the river-continuum concept, and various modifications and derivatives. Biologists have long recognized that communities in rivers change progressively in a downstream direction.

Attempts to provide a functional explanation for this zonation gave rise to the River Continuum Concept which suggested that longitudinal changes in community structure reflects longitudinal changes in the availability of various forms of organic carbon during its transport through the channel system. For example, headwater

streams in forested areas are likely to transport large amount of leaf material and may be expected to have a fauna adapted to feeding on decaying leaf material (leaf *shredders* in the ecologists' lingo). In large downstream segments of rivers fine particulate carbon will be deposited and the RCC predicts an abundance of animals that feed by collecting small organic particles (*collector-gatherers*).

The physical power inherent in a river leads to an ecosystem in which active transport of materials predominates. This is true not only of the transport of sediment (of interest to the geomorphologists) but also of almost all biologically-relevant materials including particulate organic carbon, nutrients, dissolved gases, pollutants, and even organisms themselves. In rivers rates of material flux are predictably high and directional. This is in contrast to most other aquatic and terrestrial ecosystems in which multi-directional, slow, diffusion or diffusion-like transport processes prevail. One of many interesting results is the so-called *physiological richness* of river habitats which allows organisms to access nutrients and other essential inputs like oxygen, and even food, with relatively lower energy investments than would be required in still-water or terrestrial environments. In a sense organisms allow the river to subsidize their energy needs. Evolutionarily, many river organisms have a reduced ability do certain things themselves (e.g. find food or ventilate gills). This is one reason that river animals (for example trout) are frequently dependent upon a relatively narrow range of habitat conditions.

Rivers are also unique in that they are relatively small-volume, but open, ecosystems with high rates of energy throughput. As a result, turnover rates of biologically-

relevant materials are extraordinarily high. This leads on the one hand to an enhanced sensitivity to changes in inputs. At the same time, the high turnover rates of rivers give them an extraordinary resilience, recovering rapidly to pre-disturbance configurations when inputs are returned to normal. Making use of the self-cleansing

ability of rivers is a conscious feature of our society's waste-water handling systems (termed *assimilation capacity* by civil engineers). Our long history of polluting and degrading rivers is eloquent testimony to the sensitivity of these ecosystems to changes in nutrient, carbon, and sediment loading. The fact that many (if not most) rivers are today (or till recently

were) in reasonably-good shape biologically, despite a legacy of abuse, is a testimony to their ecological resilience.

Functionally, river ecosystems contain many other smaller types of ecosystems, including many that do not lie within the open-water channel. Upland catchment areas that recharge groundwater; or provide overland flow, nutrients, and sediments, are important parts of the fluvial system. So also are riparian ecosystems, such as floodplain forests and crenel wetlands, especially in the zones of production and deposition. These, and other hydrologically-linked wetlands lie at the land-water interface and influence the deliveries of water, sediment, nutrients, organic matter, and solar energy to the channel system; they also place important structural constraints on channel development and provide habitat for many species. The interface zone (between surface water and groundwater ecosystems) has a characteristic biota that responds to thermal and oxygen gradients driven by flow patterns in both the overlaying river and in the local groundwater table. It is often an important processing location for fluvial dissolved carbon and nutrients.

*River fishes* The fish fauna of river systems provides a convenient and useful basis for generalizing about the biological communities of

fluvial ecosystems. Each kind of fish requires a specific set of hydraulic, thermal and nutritional conditions to flourish. River fishes, like the systems they inhabit, can travel considerable distances during their life cycles. The spawning, feeding and growing, and winter refuge habitat requirements of a species may be met at very different locations within the river system it inhabits. Anadromous (river-spawning ocean species) and catadromous (ocean spawning river species) are

**Likewise many species rely on the downstream transport of young fishes and the upstream movements of juveniles and adults, to "re-seed" potential habitats recovering from local spates or other disturbances. This is one reason that the fragmentation of river systems by dams and impoundments is seen to be such a threat to natural fish populations.**

**Our society has a long history of both commercial and recreational exploitation of riverine fisheries, and fish remain the central focus of much of our current investment in river management.**

extreme examples of this large-scale mobility of riverine fishes. Most river fish populations do utilize in some way the large-scale nature of the rivers they inhabit. The ability to freely transit the river network allows many species to succeed in what is often naturally a very physically demanding & unpredictable environment. For example, many river fishes extend spawning habitats by migrating into temporarily useful tributary systems during the spring.

The same basic hydrologic processes that shape the river channels and water budgets also control specific habitat conditions relevant to fishes at various points in the life cycle. Spawning and hatching success for many riverine fishes are related to the occurrence of moderate flows during specific time windows. Fall and spring spates can frequently and unpredictably disturb important periods of reproduction. Stable-flow Rivers, on the other hand, are relatively free of such disturbances. The nature of a river's summer growing environment is very closely tied to hydrology. A river's channel dimensions of width and depth are usually set to accommodate annual peak flows.

*Characteristics of runoff-fed rivers* In summer, runoff rivers are wide and shallow (small low flows filling wide and incised channels), as a result water velocities are low (at the extreme, some rivers are reduced to a series of barely-connected pools). These low velocities allow the accumulation of fine silt and sand substrates. Water temperatures in such channels are strongly influenced by ambient air temperatures, typically very warm during the day but cool at night. Similarly, winter water temperatures make for harsh winter conditions and often substantial mortalities. Hydrologic sources also help define both the natural productivity of a river and its response to human additions of pollutants. Storm water moving overland carries nutrients, and other dissolved materials derived at the ground surface, directly to the river channel. Nutrient deliveries are high from impermeable, nutrient-rich clayey and loamy soils (and alternatively, very low from nutrient poor bedrock landscapes). In agricultural and urban areas, storm flows carry high amounts of nutrients and frequently toxic pollutants to rivers.

Fishes of flashy, runoff rivers are diverse, but specially adapted to warm, slow water, and harsh, variable conditions. They are habitat generalists, with tolerances

for a relatively wide range of temperature and oxygen conditions. Reproduction of any given species is unpredictable and poor in many years. Fish populations in such systems tend to have a "boom-bust" quality about them.

*Characteristics of groundwater-fed rivers* In contrast, groundwater-fed rivers have deeper channels and faster flows during the summer. Substrates are coarser.

Through flow and groundwater temperatures, modified by the temperature of the soils through which they pass, help keep streams temperatures cool and fairly constant. Stable groundwater temperatures also help warm these rivers during winter. Fishes of stable, Groundwater Rivers (e.g. trouts and sculpins) are habitat specialists, adapted

to a rather narrowly-defined constant, cold, swift-water environment. Reproduction is predictably high each year.

*Characteristics of mixed-source rivers* In these systems, not surprisingly, the fish fauna can be quite mixed with differing combinations of warm-water, cool-water, and cold-water species reflecting the relative importance of the three main hydrologic sources of stream flow as it varies from location to location within in the river network.

**Understanding river ecosystems is clearly a challenging and complicated task. Fluvial ecology is an appropriate name for this enterprise. However, it is important to recognize that the study of rivers has historically been fragmented into a number of distinct disciplines, each of which carry on relatively isolated discussions and generate publications in separate, disciplinary journals.**

**The proper study of rivers is then an authentically *inter-disciplinary* experience. Perhaps *supra-disciplinary* is an even more appropriate term since what is essential is a basic grasp of the perspectives of a number of disciplines.**

**Studying rivers** Understanding river ecosystems is clearly a challenging and complicated task. Fluvial ecology is an appropriate name for this enterprise. However, it is important to recognize that

the study of rivers has historically been fragmented into a number of distinct disciplines, each of which carry on relatively isolated discussions and generate publications in separate, disciplinary journals. Biologists studying rivers have variously organized themselves under rubrics that include Stream Ecology, Limnology (in the broad sense), Fisheries Science, Aquatic Entomology, Benthic Ecology, Aquatic Toxicology, and most recently Landscape Ecology. Relevant physical disciplines are likewise numerous and include Fluvial Geomorphology, Quaternary Geology, Civil Engineering, Hydrology, Hydrodynamics, and Hydraulics. Some of this scientific infrastructure is a logistical necessity but much is an historical artifact of the way various groups of people became interested in rivers. For the student of rivers an awareness of this plethora of heritages is a necessary evil, since much terminology and many useful models are still associated with specific disciplines. ~~