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Water Quality Degradation Effects on Freshwater Availability: *Impacts of Human Activities*

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Abstract: *The quality of freshwater at any point on the landscape reflects the combined effects of many processes along water pathways. Human activities on all spatial scales affect both water quality and quantity. Alteration of the landscape and associated vegetation has not only changed the water balance, but typically has altered processes that control water quality. Effects of human activities on a small scale are relevant to an entire drainage basin. Furthermore, local, regional, and global differences in climate and water flow are considerable, causing varying effects of human activities on land and water quality and quantity, depending on location within a watershed, geology, biology, physiographic characteristics, and climate. These natural characteristics also greatly control human activities, which will, in turn, modify (or affect) the natural composition of water. One of the most important issues for effective resource management is recognition of cyclical and cascading effects of human activities on the water quality and quantity along hydrologic pathways. The degradation of water quality in one part of a watershed can have negative effects on users downstream. Everyone lives downstream of the effects of some human activity. An extremely important factor is that substances added to the atmosphere, land, and water generally have relatively long time scales for removal or clean up. The nature of the substance, including its affinity for adhering to soil and its ability to be transformed, affects the mobility and the time scale for removal of the substance. Policy alone will not solve many of the degradation issues, but a combination of policy, education, scientific knowledge, planning, and enforcement of applicable laws can provide mechanisms for slowing the rate of degradation and provide human and environmental protection. Such an integrated approach is needed to effectively manage land and water resources.*

Keywords: *Hydrologic cycle, water pollution, watersheds, residence time, hydrologic pathways, downstream.*

Introduction

The continuing increase in global population is increasing the demand on freshwater supply. One important factor affecting freshwater availability is associated with socioeconomic development, and another factor is the general lack of sanitation and waste treatment facilities in high-population areas of developing countries. A principal cause of water scarcity is water quality degradation, which can critically reduce the amount of freshwater available for potable, agricultural, and industrial use, particularly in semi-arid and arid regions. Thus, the quantity of available freshwater is closely linked to the quality of the water, which may limit its use.

The major water quality issues resulting in degradation include water-borne pathogens and noxious and toxic pollutants. Despite efforts of United Nations organizations, international banks, and some national governments over the past several decades, human health is still at substantial risk due to water quality problems in many areas of the world (World Resources Institute, 1996). In 1990, 1.2 billion people, or 20 percent of the world population, did not have access to a safe supply of water, and about 50 percent of the world population had inadequate sanitation services (United Nations Commission for Sustainable Development, 1997). The continued rapid degradation of land and water resources due to water quality degradation may result in hydrocide for future populations (Lundqvist, 1998).

Hydrogeological and biophysical environments are directly affected by changes in land use and socioeconomic processes, which are largely controlled by human activities and resource management. A land management decision is a water resource decision, a fundamental concept for addressing and implementing integrated land and water resources management (Falkenmark et al., 1999). Land alteration and associated changes in vegetation have not only changed the water balance, but typically have altered processes that control water quality. One of the most important issues for effective resource management is the recognition of cyclical and cascading effects of human activities on the water quality and quantity along hydrologic pathways, particularly in a watershed context. Hydrologic pathways are routes along which water moves from the time it is received as precipitation (e.g., rain and snow) until it is delivered to the most downstream point in a watershed, the drainage area defined by the downstream point to which flow converges. The degradation of water quality in upstream parts of a watershed can have negative effects on downstream users, and because there generally is a continuum of users throughout a watershed, the degradation effects cascade through the watershed. Cyclical effects include the artificial movement of water upstream, such as groundwater abstraction for irrigated agriculture. Another cyclical effect is the increased leaching of nutrients to waterways. The increase in nutrient flux increases rates of growth of aquatic and riparian vegetation, which in turn increases the flow of water vapor to the atmosphere through increased evapotranspiration. The water quality crisis is more immediate and may be more serious than other phenomena, such as global climate change.

This paper (1) provides an overview of factors affecting water quality and its degradation, (2) presents a scope for water quality problems and issues, and (3) highlights interactions and linkages between water quality and water quantity as they affect sustainable water use within a drainage basin. Inherent to the discussion is the importance of the exploitation of land and water resources, which affect the quantity and quality of water flows, particularly in an upstream/downstream context germane to any drainage basin.

Evolution of Water Quality

The quality of surface water or groundwater at any point in a watershed reflects the combined effect of many physical, chemical, and biological processes that affect water as it moves along hydrologic pathways over, under, and through the land. The chemical composition of water varies depending on the nature of the solids, liquids, and gases that are either generated internally (*in situ*) or with which the water interacts. Furthermore, the chemical composition depends on the type of interaction. At the mostly pristine part of the hydrologic cycle, precipitation quality is derived from interactions with gases, aerosols, and particles in the atmosphere. Evaporation purifies water as vapor but concentrates the chemical content of the water from which it evaporated. Condensation begins the process of imparting chemical quality to atmospheric moisture by inclusion of chemical substances through the dissolution of condensation nuclei. The complexity of the water-material interaction increases as precipitation falls on the land.

The physical characteristics and mineralogical composition of soil and bedrock, topography, and biology substantially affect water quality. Most freshwater is a mixture of water derived from several hydrologic pathways. For example, streamwater may be composed of varying mixtures of shallow and deep groundwater, precipitation, snowmelt, throughfall, overland flow, lateral flow, or throughflow in the soil. Furthermore, the streamwater composition may change *in situ* due to biological reactions or due to the interactions with the streambed and adjacent riparian zone. Even the groundwater component of streamwater is a mixture of water derived from different hydrologic pathways that vary in their composition due to the residence time of the water, the length of the hydrologic pathway, biological reactions, and the nature of the materials with which the water interacts. Temperature is another important variable that affects physical characteristics (e.g., transfer of gases), state changes (vapor, water, and ice), and chemical and biological reaction rates of the water.

Water is a solvent and a medium for transfers of mass and heat. Perhaps most important, water is necessary to sustain life. As water travels along a hydrologic pathway, such as groundwater moving from a recharge area to a spring, a variety of interactions occur that are associated with the type of geologic media and with the biota. The interaction causes some chemical elements to dissolve and precipitate, while others transform, such as the oxidation of iron and the change of one nutrient species to another. Particles not only interact with the water, but can be transported by the water depending on the mass, size, and shape of the particle, the water velocity, and the material through or over which the water flows. Living organisms, particularly microorganisms such as phytoplankton and bacteria, affect water quality genesis through several mechanisms. For example, the biota can use and release nutrients and other elements that are commonly specific to particular plants and geographic regions or generate other products, including gases.

Natural water quality varies markedly and is affected by the geology, biology, and hydroclimatic characteristics of an area (Hem, 1985). Even under natural conditions, water may be toxic or otherwise unfit for human consumption. The occurrence of high and toxic metal concentrations is not uncommon and can be attributed to weathering of naturally occurring ore deposits. Although generally non-toxic, the solute concentrations of "pure" bottled spring water can vary by several orders of magnitude worldwide. However, the concept of pollution is relative, in that it reflects a change from some reference value to a value that causes problems for human use (Meybeck, 1996). A worldwide reference value is difficult to establish because insufficient monitoring has occurred prior to changes in water quality due to human activities. Furthermore, there is no universal reference of natural water quality because of the high variability in the chemical quality of natural waters (Meybeck, 1996).

Natural water quality variations occur over a wide range of time scales (Meybeck, 1996). Long-term changes in water quality can occur over geologic time due to factors such as soil evolution, glaciation, mountain building, and mass wasting (downslope gravitational movement of soil and rock). Intermediate changes can occur due to successional changes in vegetation, forest fires, floods, and droughts. Seasonal and shorter-term variations in stream and river water quality are partly explained by variations in the mixture of contributing waters (water partitioning), each of which has different compositions due to transit time and contact with materials and the growth cycle of vegetation. Rapid changes in water quality can occur over relatively short spatial distances. The ability to change water quality rapidly is an important control of water quality deterioration, such as the mobilization of toxic substances due to a rapid change in the oxidation and reduction characteristics of groundwater discharging through contaminated streambed sediments. In contrast, these rapid changes also are an important control of water quality improvement, such as the removal of nutrients by wetlands and other riparian zone vegetation.

Natural disasters, such as hurricanes, floods, tsunamis, earthquakes, volcanic eruptions, and landslides, also have major effects on water quality and water quantity. The time scale of the perturbation varies with the size of the disaster. Over the short-term, relatively more precipitation from a specific event falls directly on the surface water without passing through the soil. This contribution to the surface water has a relatively short transit time, which has a greater effect on catchments with a large proportion of open water (lakes and reservoirs) than on catchments dominated by groundwater. Consequently, changes in precipitation chemistry such as decreasing pH can rapidly affect surface water chemistry. Also, where rainfall intensities exceed soil infiltration capacities and large amounts of surface runoff occur, water quality can change due to the erosion and dissolution of substances from eroded soil particles. The time scale can vary depending on the source of the soil particles and whether or not they have been either contaminated or enriched with respect to some substance.

Human Effects on Water Quality and Quantity

Human influences have had a direct effect on the hydrologic cycle by altering the land in ways that change its physical, chemical, and biological characteristics (Lundqvist, 1998; Hem, 1985; Meybeck and Helmer, 1989). Physical alterations such as urbanization, transportation, farming (irrigation), deforestation and forestation, land drainage, channelization and damming, and mining alter hydrologic pathways and may change the water quality characteristics by modifying the materials with which the water interacts (see Figure 1). For example, the impervious surfaces created by urbanization produces overland flow and high amounts of runoff even at moderate rainfall intensities (Arnold and Gibbons, 1996). In addition, these human activities alter water quality not only by changing hydrologic pathways, but by the addition of substances and wastes to the landscape. These activities include application of pesticides, herbicides, and fertilizer, and leaching to groundwater and surface water from landfills, mine tailings, and irrigated farmland. Figure 2 shows a schematic cross section of the landscape showing some biogeochemical cycles under natural or pre-development conditions and under modern day influenced human conditions activities.

The chemical alteration associated with human activity is, in part, related to the physical alteration, but oc-

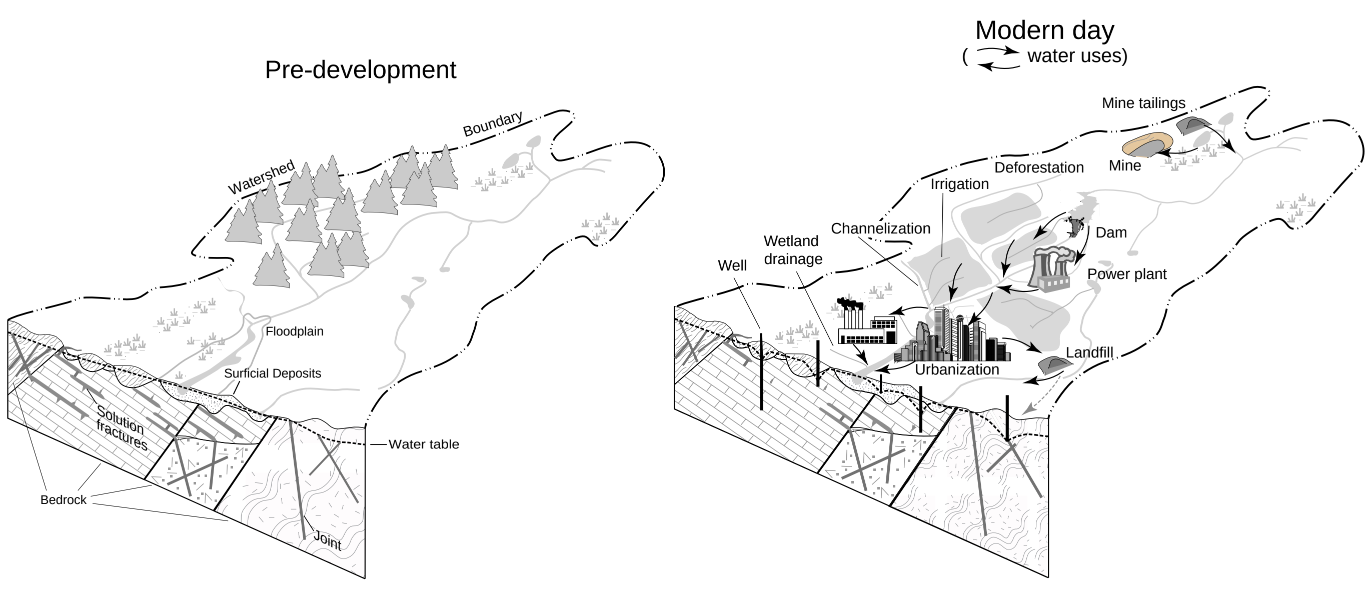

Figure 1. Examples of some alterations of natural hydrological pathways by human activities.

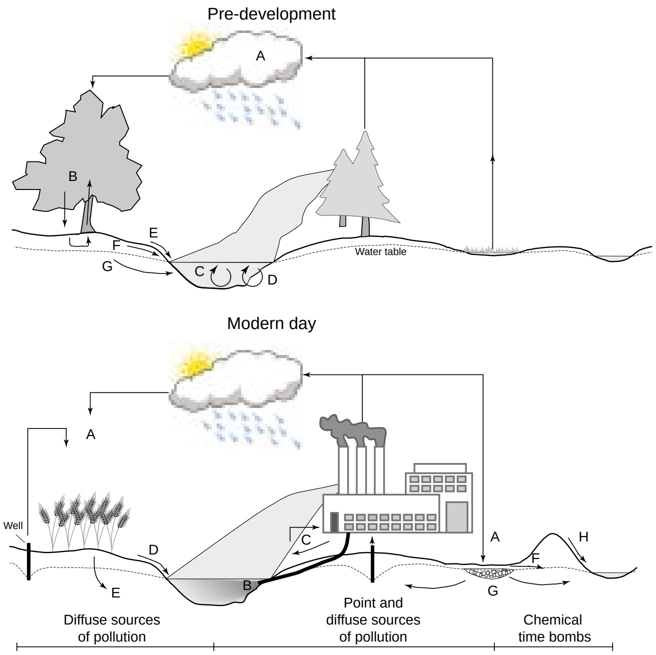

Figure 2. Biogeochemical cycles under pre-development and modern day conditions. Top – pre-development cycles: (A) atmospheric emissions and deposition; (B) cycling within vegetation and soil; (C) cycling within water bodies; (D) cycling within a ripareian zone and floodplain; (E) overland flow; (F) lateral flow; and (G) groundwater discharge. Bottom – modern day cycles: (A) pollutant emissions and atmospheric deposition; (B) wastewater collector; (C) diffuse or stored urban runoff; (D) agricultural runoff; (E) groundwater contamination from pesticides and fertilizer; (F) leaching of polluted soils; (G) leakage of contaminants from waste dumps; and (H) leaching of mine tailings.

curs mainly through the addition of wastes (gases, liquids, and solids) and other substances to the land. These additions include waste disposal on the land or in waterways and the application of substances to control the environment, such as fertilizers for crop production, herbicides for weed control, and pesticides for disease control. Atmospheric transport and deposition is a major hydrologic pathway of substances directly to surface water or indirectly to groundwater by infiltration through the soil. Some human-derived substances, including pesticides, microorganic pollutants, nitric acid, and sulfuric acid from fossil fuel combustion, have been found in virtually every remote area, and the occurrence and distribution of many of these is due to long-range transport in the atmosphere (e.g., pesticides, Majewski and Capel, 1995). For example, the pesticide atrazine has been found in lakes and rain in Switzerland (Buser, 1990) and organochlorine compounds have been found in the Arctic (Lockerbie and Clair, 1988) and the Antarctic (Tanabe et al., 1983). Other types of wastes may be concentrated in one area or, in the case of liquid wastes, discharged to surface water from a pipe and therefore are referred to as point sources. In contrast, wastes distributed over larger areas, such as fertilizer application to cropland and the emission of gases and aerosols from industry, are referred to as non-point or diffuse sources. Diffuse sources also include several smaller point sources distributed over a large area, such as residential septic tank effluent from multiple dwellings and multiple building construction sites in a developing area. The erosion and transport of soils from agricultural lands during intense rainstorms can rapidly mobilize bioavailable phosphorus (Sharpley, 1993; Sharpley et al., 1998), which affects the freshwater trophic status (Ryding and Rast, 1989; Correll, 1999; Smith et al., 1999). Surface mining also alters the land, which affects hydrologic pathways. Water interactions with mine tailings and, in some cases, discarded chemicals used for ore processing can leach undesirable and toxic substances to receiving waters. Biological alterations include forest management, agriculture, and the import of exotic species.

Human requirements for water also directly affect hydrologic pathways by providing water of a specified quality for different activities to sustain human existence (e.g., agriculture, potable supplies, power generation, power plant cooling, and industry). The water quality from urban areas is complex due to the myriad of sources and pathways (Driver and Troutman, 1989). In urban areas, not only are there multiple sources of individual substances, but the natural hydrologic pathways are replaced with artificial drainage channels, wet and dry storage basins, sewers, and water distribution systems, all of which affect the spatial and temporal quantity and quality of urban runoff. The management of the delivery of untreated waste (point source) directly to surface water has received considerable attention in developed countries, and recently, more emphasis has been placed on controlling diffuse sources (Line et al., 1999).

Human activity is now one of the most important factors affecting hydrology and water quality. Humans use large amounts of resources to sustain various standards of living, although measures of sustainability are highly variable depending on how sustainability is defined (Moldan et al., 1997). Nevertheless, the land must be altered to produce these resources. Irrigated agriculture alone is responsible for about 75 percent of the total water withdrawn from "surface water and groundwater sources," and more than 90 percent of this water is consumed and delivered to the atmosphere by evaporation (United Nations Commission for Sustainable Development, 1997). In addition to placing a demand on the quantity of water, which is diverted for food production, the quality of water flowing through a typical agricultural area is markedly degraded. Degradation depends on several factors including the climatic characteristics (amount and timing of rainfall and associated potential evapotranspiration) and the various agrochemicals applied to increase yields. Consequently, headwater agricultural development affects the water flows and associated downstream water quality. Conversely, the resource demands of downstream users may result in the diversion of water, which may have been used for headwater agriculture, from basin headwaters. In some cases, land conversion to agriculture may ultimately cause soil salinization, which effectively poisons the land (Ghassemi et al., 1995). Similarly, conversion to irrigated agriculture can increase evaportranspiration from crops and alter the regional climate (Pielke and Avissar, 1990; Stohlgren et al., 1998).

Historically, the development of water resources focused on modifying the hydrologic pathways of the natural system to provide water for human activities. Over time, the efficiency of some water uses has improved, but the water needs of an ever-increasing population have increased the importance of the quality of the water, particularly in areas of water scarcity. However, the effects of concentrated toxic wastes on human and environmental health generally are not known, despite efforts in disease geography and environmental toxicology. The number of new chemical substances that are released into the environment far exceeds those that are monitored or researched to determine their fate, transformation, transport, and environmental or human effects. An emerging issue is the manufacture of pharmaceutical chemicals, their release into the environment, and the effect of the chemicals on biota. The difficulties in understanding the toxicity are compounded by the environmental complexity added by human activities such as urbanization. Furthermore, current research of toxicity effects cannot keep pace with the numbers of compounds and the complex interactions of natural settings. Current research on toxicity relies primarily on exposure of biota to various types of runoff (Marsalek et al., 1999) and less on a systematic assessment of mixtures of compounds that may have symbiotic effects on biota.

Process knowledge about the fate, transformation, and transport of contaminants is not complete, but it is sufficient to provide some technical solutions to many water quality degradation problems. This knowledge alone, however, will not lead to effective controls on the cascading effects of water quality degradation. A social and political will to initiate improvements also is needed, particularly in developing countries where economic resources are limited. Policy alone will not solve many of the degradation issues, but a combination of education, policy, scientific knowledge, planning, and enforcement of associated laws can provide mechanisms for slowing the rate of degradation and provide human and environmental protection. Such an integrated approach is needed to effectively manage land and water resources.

Alteration of the Land and Time Scales of Recovery

As discussed previously, most freshwater is a mixture of water derived from several hydrologic pathways. Consequently, alteration of hydrologic pathways or changes to water quality along a pathway may affect the composition of water with which it mixes. This concept is important to consider in evaluating or assessing resources. We all are aware of the consequences of inadequate storage of radioactive waste, yet the same principles apply. The concept of human intervention in the landscape and the disposal of substances have created chemical time bombs. Our understanding of transport through basin materials evolved as our attention focused on major human health issues associated with the disposal of toxic substances in the landscape (Young, 1999). This concept of chemical time bombs has emerged in the past few decades through environmental toxicology investigations and results of environmental remediation. Our perceptions of the risk associated with exposures to toxic substances has likewise evolved (Howe, 1988).

Effective management of land and water resources requires an understanding of spatial and temporal effects of human activities on these resources. For example, transport time through the soil is a crucial parameter for the transport and retention of various substances, and thus, the composition of water flowing through the soil. Knowledge of transport time and retention characteristics is needed to determine the susceptibility of the land to water quality degradation by waste disposal. Important natural and human-influenced characteristics of water quality genesis, including spatial and temporal constraints on water quality evolution, are listed in Table 1. For many water quality issues, the spatial scale is linked to the temporal scale in that short hydrologic pathways can deliver substances to surface waters faster than long pathways

For example, the mobilization of nitrogen (N) fertilizer to cropland may not have an immediate effect on the tropic status of an adjacent stream or lake. The fertilizer rapidly dissolves and is transported vertically through the soil to groundwater, which moves more slowly than overland flow to a stream. However, the fertilizer applied to the land closest to the stream has the best chance of being mobilized rapidly to the stream. But eventually, even the enriched groundwater, which is the longer hydrologic pathway, will discharge to the surface water and also affect the aquatic biology. The scientific understanding of nutrient transport processes is far from complete, but it has led to an effective management practice, which is to provide buffer zones in riparian areas to *trap* the N before it reaches the stream. In contrast to the rapid mobility of N, phosphorus (P) applied in fertilizer has a much higher affinity for adsorption on soil and other basin material. The dominant mechanism for mobilizing the adsorbed P is soil erosion during rainstorms or snowmelt. Because the P adsorption varies depending on the characteristics of the materials, dissolution of the P fertilizer will depend on the type of fertilizer, and the P mobilization will depend on the soil characteristics and water flux (Haygarth and Jarvis, 1999). For example, P is retained

Table 1. Spatial and Temporal Constraints on Water Quality Evolution

Major Causes/Issues	*Major Related Issues*[1]	*Space Scale*	*Time Scale*		*Major Controlling Factors*	
			Contamination[2]	*Clean-up*[3]	*Biophysical*	*Human*
Population	Pathogens	Local	<1 yr.	<1 yr.		Density & treatment
	Eutrophication*	Regional	<1–10 yr.	1–100 yr.		Treatment
	Micro-pollutants	Regional	<1–10 yr.	1–100 yr.		Various
Water Management[4]	Eutrophication*	Regional	<1 yr.	10->100 yr.	Hydrodynamics	Flow
	Salinization	Regional	10–100 yr.	10->100 yr.		Water Balance
	Parasites	Regional	1–10 yr.	>100 yr.		Hydrology
Land Management	Pesticides	Local-regional	<1 yr.	1–100 yr.		Agrochemicals
	Nutrients (NO_3^-)	Local-regional	10–100 yr.	>10 yr.		Fertilizer
	Suspended Solids*	Local-regional	<1–10 yr.	10–100 yr.		Construction/clearing
	Physical Changes	Local	<1–10 yr	>100 yr		Cultivation, Mining
						Construction & Clearing
Atmospheric Transport	Acidification*	Regional	>10 yr.	10 yr.		Cities, melting & fossil-fuel emissions
	Micropollutants	Regional	>10 yr.	1–100 yr.		
	Radionuclides	Regional-global	<1 yr.	>>100 yr.		Industry
Concentrated Pollutant Sources:						
Mega Cities	Pathogens	Local	<1 yr.			Population & treatment
	Micropollutants	Local-regional	<1 yr.			
Mines	Salinization	Local-regional	10–100 yr.			Types of mines
	Metals	Local-regional	<1 yr.			
Nuclear Industry	Radionuclides	Local-global	<1 yr			Waste management
Global Climate Change	Salinization	Global	>10 yr.	>100 yr.	Temperature & precipitation	Fossil-fuel emissions & Greenhouse gases
Natural Ecological Conditions	Parasites*	Regional	Permanent	Permanent	Climate & hydrology	
Natural Geochemical Conditions	Salts	Regional	Permanent	Permanent	Climate & lithology	
	Fluoride**	Local-regional				
	Arsenic**, Metals**	Local-regional			Lithology	

[1] * is relevant primarily to surface water and ** is relevant primarily to groundwater

[2] space scales: local — <10,000 km^2; regional — 10^5 to 10^6 km^2; and global — 10^7 to 10^8 km^2

[3] lag between cause and effect

[4] longest time scale is for groundwater, followed by lakes, and shortest for rivers and streams

in clay soil and mobilized in sandy soil. Even if fertilizer applications were stopped today, the nutrient content of the receiving surface water may increase for several decades as the nutrient-enriched soil is eroded and groundwater slowly moves to the receiving surface water (Bohlke et al., 1995; Haygarth and Jarvis, 1999).

As another example, the concentrations of DDT, an insecticide that was banned in 1972 from further production and use in the U.S., remains high in agricultural soils, streamwater, suspended and streambed sediment, and in fish in the Yakima River basin, Washington (Rinella et al., 1993; Rinella et al., 1999). The Yakima River basin drains about 16,000 km^2 and contains 250,000 people. Irrigated agriculture in the downstream part of the basin, where the DDT was applied, dominates the economy. DDT is persistent in the environment, affects wildlife reproduction, and is toxic to wildlife and humans. Despite declining DDT concentrations in streamwater, which is an integrator of the catchment transport, some of the 1990 streamwater DDT concentrations exceeded 0.1 mg/L which is ten times higher than the chronic-toxicity criterion for the protection of freshwater aquatic life established by the U.S. Environmental Protection Agency. An important result of research conducted in the basin is that despite the application and persistence of DDT in the lower part of the basin, DDT has been detected in fish throughout the basin, even in pristine headwater areas. Consistent with the results of the Yakima River basin, more than

97 percent of the DDT loading to the Great Lakes has been attributed to atmospheric transport and deposition of the insecticide during its widespread use in the 1960s and early 1970s (Strachan and Eisenreich, 1990).

Most compounds interact with basin materials to some extent, and therefore, are retained to varying degrees. Consequently, the time that water resides in the landscape, referred to as the water residence time, typically is shorter, in some cases much shorter, than the residence time of a particular substance or contaminant. The location of the contaminant relative to receiving waters (groundwater and surface water) is important for determining the time scale of pollutant effects on the receiving water. The mobility of a substance is slowed relative to the water due to interaction of the substance with the basin materials and imperfect mixing of the waters along hydrologic pathways. Several decades may elapse in small (~10 km^2) watersheds before a substance applied to the land surface is transported to surface water and some surficial aquifers, and the time scale for removal may be several hundred years in very large basins (100,000 km^2) and confined aquifers. Consequently, the clean-up time or duration of removal for substances added to the landscape generally is on the order of human generations.

In addition to listing several major water quality issues, we have put into perspective the concept of residence time for these issues by providing spatial and temporal scales for the problem and a temporal scale for the recovery (Table 1). Although there is some scientific basis for these numbers, the scales are inexact and are intended primarily to provide a sense of the relative importance of time and space for water quality problem resolution. Recall that for some water quality issues, the time scale for either contamination or clean up is linked to the spatial scale. Many water quality problems are on small spatial scales but occur over large areas, and in some cases have a global scope.

Nutrient Loading and Estuarine and Marine Water Quality Degradation

Human alterations and additions to the landscape affect not only freshwaters — the oceans are the ultimate recipients of this alteration, most rapidly through transport of degraded water in rivers and more slowly through groundwater transport directly to the coastal zone and through long-term contributions to rivers. The increased river flux of nutrients has resulted in an increase in estuarine eutrophication (Hodgkin and Hamilton, 1993; Jorgensen and Richardson, 1996). The frequency and spatial extent of hypoxia and related degradation, particularly the loss of marine life, has been increasing and may be attributed to increased biological oxygen demand accompanying increased inputs of agricultural nutrients (Jorgensen and Richardson, 1996). Hypoxia is a condition where water has an extremely low dissolved oxygen content (< 2 mg/L), which is typically insufficient to support life that inhabited the area prior to the loss of the oxygen (Burnett, 1997). The increasing area of hypoxia in the Gulf of Mexico and the role of agriculture and the transport of nitrogen fertilizer in the Mississippi-Atchafalaya River basin is an example of the effect of human activities on marine biota (Goolsby et al., 1999). Average riverine N fluxes were about 500 kg/km^2 (1980-1996), but were about three times greater in 1999 than in 1969. Some of the increase was attributed to an increase in precipitation and runoff. However, 9 percent of the basin area, which consists of intensive agriculture (Iowa and Illinois), contributed as much as 35 percent of the N flux in years of average rainfall, and 90 percent of the N flux was from diffuse or non-point sources. These contributions were even greater during flood years, such as in 1993 when Iowa (4.5 percent of the drainage basin area) contributed about 35 percent of the N flux. Hypoxia also occurs in fresh waters and has likewise been attributed to excess nutrient transport to lakes or reservoirs (Ryding and Rast, 1989; Rast and Thornton, 1996).

Conclusions

Human activities in the landscape result in alterations of hydrologic pathways by physically altering the land, by changing the vegetation, and by artificially routing water to where humans want it. In addition, human activities have affected water quality by adding substances (gas, liquid, and solid). Human requirements for sustainability, cultural characteristics of the population, socioeconomic situations, and the biophysical and climatic settings of an area determine the level of interaction, and consequently, the rate of land and water degradation. Although downstream and large-scale effects occur, human interactions with land and water resources occur on small scales, where decisions are made by individuals interacting with the landscape. Consequently, human interactions with the land and with the water should be addressed (and managed) at small spatial scales (yard, garden plot, field). Effects of human activities on the small scale are relevant to the entire drainage basin. Such analyses, therefore, are not only of interest for the status of a particular landscape, but also to downstream users who are impacted by management decisions in the upstream area. Local, regional, and global differences in wetness and water flow are considerable, causing varying effects of human activities on land and water quantity and water quality, depending on the location within the watershed, the geology, biology, and physiographic characteristics of the watershed, and the climate of the area. These natural characteristics also greatly control the human activities that will, in turn, modify (or affect) the natural composition of the water. In addition, the most important characteristic of water flows (and chemistry) is the extreme variability of flows over time and space, particularly in semi-arid areas.

Human activities on all spatial scales affect water quantity and quality. Furthermore, the results of these human activities affect users downstream; at some point, everyone lives downstream, and everyone experiences the consequences of human effects on the hydrologic cycle. The scientific understanding of the effects of human activities on the hydrologic cycle and water quality, in particular, is far from complete, but we see most effects as being cyclical, with strong upstream and downstream linkages within watersheds. For example, the water transport from headwater areas to lower parts of a watershed for irrigation purposes results in cycling most of the water back to the atmosphere through evapotranspiration. Atmospheric emissions of gases and aerosols from a variety of activities ranging from agriculture (application of fertilizers and pesticides) to industry (petrochemical production and fossil fuel combustion) first concentrate the substance from various sources and then emit some of the substance or a derivative into the atmosphere. Other effects are cascading and moving downstream, such as the addition of fertilizers that are leached to surface water and groundwater, which in turn is used downstream for irrigation or potable water supply.

Another important factor is that substances added to the atmosphere, land, and water generally have relatively long time scales for removal or clean up. The nature of the substance, including its affinity for adhering to soil and its ability to be transformed, affect the mobility and the time scale for removal of the substance along hydrologic pathways. Contaminants in groundwater, which eventually either discharges to some receiving surface water or is abstracted for some use, will take much longer to be removed than contaminants added to the land in an area dominated by shallow and short hydrologic pathways, such as a riparian zone in a small watershed. Even in a best-case scenario of a short hydrologic pathway, some retention of the contaminant by the soil matrix requires continual flushing of the soil for some time to completely remove the contaminant.

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References

Arnold, C.L.J. and C.J. Gibbons. 1996. "Impervious Surface Coverage - The Emergence of a Key Environmental Indicator." *Journal American Planning Association* 62: 243–256.

Bohlke, J.K. and J.M. Denver. 1995. "Combined Use of Groundwater Dating, Chemical, and Isotopic Analyses to Resolve the History and Fate of Nitrate Contamination in Two Agricultural Watersheds, Atlantic Coastal Plain, Maryland." *Water Resources Research* 31, No. 9: 2319–2339.

Burnett, L.E. 1997. "The Challenges of Living in Hypoxic and Hypercapnic Aquatic Environments." *American Zoologist* 37, No. 6: 633–640.

Buser, H-R. 1990. "Atrazine and Other s-triazine Herbicides in Lakes and in Rain in Switzerland." *Environmental Science and Technology* 24: 1049–1058.

Correll, D.L. 1999. "Phosphorus: A Rate Limiting Nutrient in Surface Waters." *Poultry Science* 78, No. 5: 674–682.

Driver, N.E. and B.M. Troutman. 1989. "Regression Models for Estimating Urban Storm-Runoff Quality and Quantity in the United States." *Journal of Hydrology* 109, No. 3/4: 221–236.

Falkenmark, M. L. Andersson, R. Castensson, and K. Sundblad, eds. 1999. *Water, A Reflection of Land Use – Options for Counteracting Land and Water Mismanagement*. NFR, Swedish Natural Science Research Council, Stockholm, Sweden: 128 pages.

Ghassemi, F., A.J. Jakeman, and H.A. Nix. 1995. *Salinisation of Land and Water Resources; Human Causes, Extent, Management and Case Studies*. Australian National University, Centre for Resource and Environmental Studies, Canberra, Australia: 526 pages.

Goolsby, D.A., W.A. Battaglin, G.B. Lawrence, R.S. Artz, B.T. Aulenbach, R.P. Hooper, D.R. Keeney, and G.J. Stensland. 1999. "Flux and Sources of Nutrients in the Mississippi-Atchafalaya River Basin — Topic 3 Report for the Integrated Assessment on Hypoxia in the Gulf of Mexico." NOAA Coastal Ocean Program Decision Analysis Series No. 17. NOAA Coastal Ocean Office, Silver Spring, Maryland, USA: 129 pages. http://wwwrcolka.cr.usgs.gov/midconherb/ hypoxia.html

Haygarth, P.M. and S.C. Jarvis. 1999. "Transfer of Phosphorus from Agricultural Soils." *Advances in Agronomy* 66: 195–249.

Hem, J.D. 1985. "Study and Interpretation of the Chemical Characteristics of Natural Water." *U.S. Geological Survey Water-Supply Paper* 2254: 263 pages.

Hodgkin, E.P. and B.H. Hamilton. 1993. "Fertilizers and Eutrophication in Southwestern Australia—Setting the Scene." *Fertilizer Research* 36: 95–103.

Howe, H.L. 1988. "A Comparison of Actual and Perceived Residential Proximity to Toxic Waste Sites." *Archives of Environmental Health* 43, No. 6: 415–419.

Jorgensen, B.B. and K. Richardson, eds. 1996. "Eutrophication in Coastal Marine Ecosystems." In American Geophysical Union, Washington, DC, USA. *Coastal and Estuarine Studies* 52: 272.

Line, D.E., G.D. Jennings, R.A. McLaughlin, D.L. Osmond, W.A. Harman, L.A. Lombardo, K.L. Tweedy, and J. Spooner. 1999. "Nonpoint Sources." *Water Environment Research* 71, No. 5: 1054–1069.

Lockerbie, D.M. and T.A. Clair. 1988. "Organic Contaminants in Isolated Lakes of Southern Labrador, Canada." *Bulletin of Environmental Contamination and Toxicology* 41: 625–632.

Lundqvist, J. 1998. "Avert Looming Hydrocide." *Ambio* 27, No. 6: 428–433.

Majewski, M.S. and P.D. Capel. 1995. "Pesticides in the Atmosphere: Distribution, Trends, and Governing Factors." In R.J. Gilliom, ed. *Pesticides in the Hydrologic System*. Chelsea, Michigan, USA: Ann Arbor Press: 214 pages.

Marsalek, J., Q. Rochfort, B. Brownlee, T. Mayer, and M. Servos. 1999. "An Exploratory Study of Urban Runoff Toxicity." *Water Science and Technology* 39, No. 12: 33–39.

Meybeck, M. 1996. "River Water Quality: Global Ranges, Time and Space Variabilities, Proposal for Some Redefinitions." *Internationale Vereinigung für Theoretische und Angewandte Limnologie, Verhandlungen* 26: 81–96.

Meybeck, M. and R. Helmer. 1989. "The Quality of Rivers: from Pristine Stage to Global Pollution." *Palaeogeography, Palaeoclimatology, Palaeoecology* 75: 283–309.

Moldan, B., S. Billharz, and R. Matrazers, eds. 1997. *Sustainabillity Indicators*. SCOPE 58, Paris, France.

Munn, T.E., A. Whyte, and P. Timmerman. 1999. "Emerging Environmental Issues: a Global Perspective of SCOPE." *Ambio* 28: 464–471.

Pielke, R.A. and R. Avissar. 1990. "Influence of Landscape Structure on Local and Regional Climate." *Landscape Ecology* 4, No. 2/3: 133–155.

Rast, W. and J.A. Thornton. 1996. "Trends in Eutrophication Research and Control." *Hydrological Processes* 10: 295–313.

Rinella, J.F., P.A. Hamilton, and S.W. McKenzie. 1993. "Persistence of the DDT Pesticide in the Yakima River Basin, Washington." *U.S. Geological Survey Circular* 1090: 24 pages.

Rinella, J.F., S.W. McKenzie, J.K. Crawford, W.T. Foreman, G.J. Fuhrer, J.L. Morace, and G.R. Aiken. 1999. "Surface Water Quality Assessment of the Yakima River Basin, Washington; Distribution of Pesticides and Other Organic Compounds in Water, Sediment, and Aquatic Biota, 1987–91." *U. S. Geological Survey Water-Supply Paper* W 2354-B: 180 pages.

Ryding, S.O. and W. Rast, eds. 1989. "The Control of Eutrophication of Lakes and Reservoirs." *Man and The Biosphere*, Vol 1. UNESCO.

Sharpley, A.N. 1993. "Assessing Phosphorus Bioavailability in Agricultural Soils and Runoff." *Fertilizer Research* 36, No. 3: 259–272.

Sharpley A.N., W. Gburek, and A.L. Heathwaite. 1998. Agricultural Phosphorus and Water Quality: Sources, Transport and Management. *Agricultural and Food Science in Finland* 7, No. 2: 297–314.

Smith, V.H., G.D. Tilman, and J.C. Nekola. 1999. "Eutrophication: Impacts of Excess Nutrient Inputs on Freshwater, Marine, and Terrestrial Ecosystems." *Environmental Pollution* 100, No.1–3: 179–196.

Stohlgren, T.J., T.N. Chase, R.A. Pielke, Sr., T.G.F. Kittel, and J.S. Baron. 1998. "Evidence That Local Land Use Practices Influence Regional Climate, Vegetation, and Stream Flow Patterns in Adjacent Natural Areas." *Global Change Biology* 4, No. 5: 495–504.

Strachan, W.H.J. and S.J. Eisenreich. 1990. "Mass Balance Accounting of Chemicals in the Great Lakes." In D.A. Durtz, ed. *Long Range Transport of Pesticides*. Chelsea, Michigan, USA: Lewis Publishers: 291–301.

Tanabe, S., H. Hidaka, R. Tatsukawa. 1983. "PCBs and Chlorinated Hydrocarbon Pesticides in Antarctic Atmosphere and Hydrosphere." *Chemosphere* 12: 277–288.

United Nations Commission for Sustainable Development. 1997. *Comprehensive Assessment of the Fresh Water Resources of the World*. Geneva, Switzerland: World Meteorological Organization.

World Resources Institute. 1996. *World Resources 1996-97*. New York, New York, USA: Oxford University Press: 365 pages.

Young, A.L. 1999. "Burying Love Canal." *Environmental Regulation and Permitting* 8, No. 3: 5–14.