THE IMPORTANCE OF SURFACE WATER/ GROUNDWATER INTERACTIONS

ISSUE PAPER

FINAL
MARCH 30, 1999

(WITH MAY 19, 2000 EDITIONS)

KERIANNE M. GARDNER
Environmental Protection Agency
1998 EPA Intern Program Project
Office of Water/ Water Quality Unit

Region 10 EPA
1200 Sixth Avenue
Seattle, WA 98101
(206) 553-0268

Publication number: EPA 910-R-99-013

THE IMPORTANCE OF SURFACE WATER/ GROUNDWATER INTERACTIONS ISSUE PAPER

Publication number: EPA 910-R-99-013

ERRATA

THE MARCH 30, 1999 VERSION WAS EDITED ON MAY 19, 2000 TO REFLECT THE FOLLOWING MINOR CHANGES:

PAGE 7: The citation for Figure 9 did not show up due to the text box sizing. The text box was adjusted, and the reference was cited in the "Works Cited" section. Previously, the reference had been omitted from the "Works Cited." Instead, the individual chapters were cited, with the main text title included with those individual citations.

PAGE 8: The last sentence on the page, beginning "At a local scale...", was moved to immediately follow the sentence ending "...moving slightly uphill." Previously, the later sentence was located on the following line.

WHITE ET AL. 1998 was a misprint. The citation should read Winter et al. 1998. There were 2 instances of this occurring: P.5, Last paragraph and P.8, last paragraph.

KERIANNE M. GARDNER
Environmental Protection Agency
1998 EPA Intern Program Project
Office of Water/ Water Quality Unit

Region 10 EPA
1200 Sixth Avenue
Seattle, WA 98101
(206) 553-0268

Publication number: EPA 910-R-99-013

INTRODUCTION

Why is the connection between surface water and ground water relevant to the average citizen, the scientist, and the policy-maker alike? When ground water mixes with surface water, they impart their characteristics upon one another and unique gradients develop for each parameter. Since ground water and surface water are essentially one resource, there is potential for the surface water quality to affect ground water and vice versa (Naiman et al.1995; Squillace et al. 1993) . These interactions could affect quality of life for fish or drinking water for humans.

While ground water scientists have long studied the physical aspects of ground water/ surface water interactions, it has been in fairly recent times that these interactions have been looked at in relation to their ecological implications. With the coming of a more holistic approach to environmental protection, surface water/ ground water (SW/GW) interactions have been receiving heightened attention by ecologists and have begun to be looked at by policy makers and watershed managers. It is generally understood in conceptual form that ground water has the ability to enhance or detract from the surface water quality, yet little is known outside of specialized scientific realms about the processes by which these two entities interact. In the past, emphasis has been placed on studying the physical and chemical effects that ground water has on surface water quality, but it is also important to look at the ecological role surface water/ ground water interactions play. The study of surface water/ ground water interactions from an ecological perspective is slowly picking up momentum, with new fields of science being named to focus on these issues.

OBJECTIVE

The paper intends to enlighten a broad audience and nurture a general understanding of the interaction between surface water (SW) and ground water (GW). Scientists, non-scientists, community groups, programs within EPA, and other agencies all have many different viewpoints and access to a variety of resources. This paper hopes to capture the ideas presented in a number of previously published sources and establish a common language to discuss how the realms of surface water and ground water interact, what the importance of these interactions are, and what ecological functions are involved. The two target goals of this paper include:1) Make a case for the importance of understanding the ecological roles GW/SW interactions play, especially in relation to temperature and salmon; 2) Lay groundwork for future pilot projects to explore means of incorporating these interactions into water quality work. Ultimately, this paper aims to make the case for the importance of expanding our understanding of this connection and convince water quality managers of the need to explore ways to apply this understanding more directly in water quality work.

BACKGROUND

In current EPA programs, there is a general tendency to isolate each medium into its respective program (Naiman et al. 1995), thus ground water and surface water have been managed through separate programs. Though a slow transformation is under way to look at the "big ecological picture" via the "watershed protection approach", there is still some difficulty in comprehending how ground water and surface water connect programmatically. The "watershed protection approach" is described as a holistic way to address the complex and persistent problems in watersheds around the nation (Houghton 1993).

Nineteen ninety-three was a dynamic year for addressing surface water and ground water holistically . A prominent scientist in the field of ground water ecology, Jack Stanford, briefed Congress on the recent scientific findings and stressed the connectedness of ground water and surface water (Houghton 1993). In a watershed field workshop led by Jack Stanford, ecotone areas are described as "landscape hot spots of diversity" because of the diversity of habitat that tends to occur within transition areas. Since SW/ GW interactions link terrestrial and aquatic components, the processes involved in these interactions contribute to the overall diversity of habitat (Stanford et al. 1994). Carol Browner, EPA Administrator, spoke of treating ground water protection as an integral part of watershed management in the first series of hearings on the Clean Water Act reauthorization, but stopped short of calling for a national ground water protection goal (Houghton 1993). In the opinion of the *Groundwater Monitor's* contributing writer, EPA's recognition of the connections highlighted by Jack Stanford is a step in the right direction because the past Clean Water Act had ignored those connections (Houghton1993). Nevertheless, ground water is often viewed as a physically isolated resource in regulatory language (Job & Simons1994).

As mentioned before, the primary function of this issue paper is to focus attention on the need for and value of integrating the surface water/ ground water (SW/GW) interaction zone, or ecotone, into our water quality programs. We hope that this paper will lay the groundwork for pilot projects to explore means to better quantify this interaction and account for it in such programs as Total Maximum Daily Load (TMDL), Source Water Protection (SWP), Watershed Assessment, and Restoration. The focus is on making these concepts understandable to a broader audience of people which may include non-scientists, general scientists, policy writers, and watershed managers.

HOW GROUND WATER WORKS

The hydrologic cycle includes 4 main pools of water: oceans, ice, ground water, and atmosphere. Of these, ground water is the 2nd smallest but has great importance in terms of human use (*see figure 1 from Winter et al. 1998*). In ground water/ surface water interactions, the ground water component is much greater than the surface water, but has much less visibility, and thus attracts less public interest.

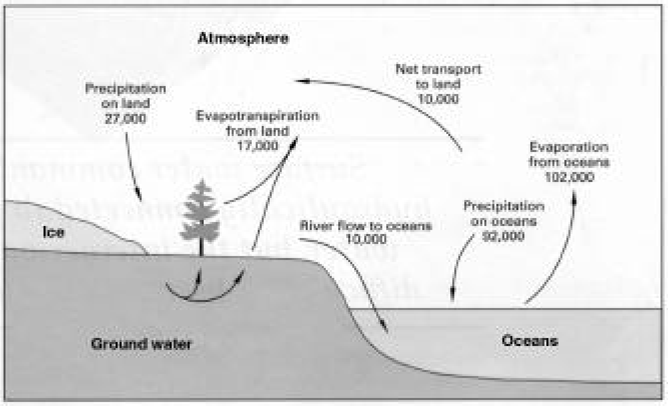


FIGURE 1: THE HYDROLOGIC CYCLE
(From Winter et al. 1998)

Because ground water is unable to been seen, water movement beneath the land surface is a difficult concept to visualize. Imagine a latticework below ground, with water flowing between the open spaces. At the time of formation, some rocks contain many spaces, or voids, while others are more solid. Usually rocks that are located near the earth's surface acquire more voids as they undergo physical and chemical weathering. This weathering breaks rocks down into various sized particles. These particles are deposited by gravity, wind, rain, or ice. Collections of these deposited particles are called sediments. During deposition of sediments, the variety of particle sizes allow openings, called pore spaces, to be left between the grains (Fetter 1994). It is through this latticework of pore spaces that ground water flows.

The ability of ground water to flow through the lattice work is affected by a number of properties. Within sediments, there are pathways that connect the pore spaces and allow water to pass from one pore space to the next. First of all, the range of particle sizes will affect the amount of pore space, or porosity, present. Porosity can be measured as a percentage by dividing the volume of void space by the total volume of soil and void space. If there is a wide range of particle sizes, the smaller grains may fill the space between the larger grains (See Figure 2). This will decrease the porosity and thus reduce the amount of space for water to flow through.

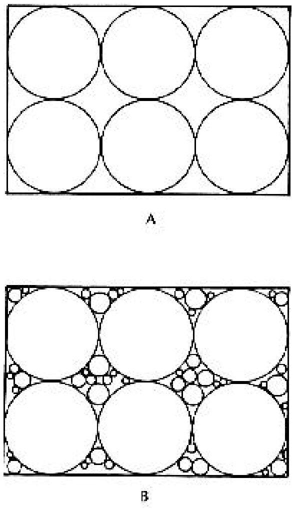


Figure 2: Interstitial spaces between particles
(From Fetter 1994)

Next, the shape of grain sizes will affect the amount of pore space available for water to travel through. Spherical shaped particles will be able to pack together tighter than oblong or irregular shaped particles. Lastly, the material composition and orientation of the particles will affect the porosity. Grain size is a property of material composition that will affect porosity. Clay particles tend to adhere to one another and form clumps of soil, called peds. These peds will act as larger sized particles and form abundant pore space. If the clay soil is compacted, the structure of the peds will be broken down, the particles will be smaller, and more closely packed. This change in composition will decrease the porosity of a soil.

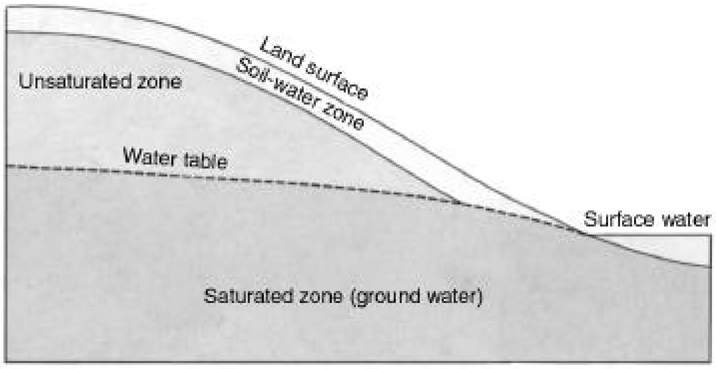


Figure 3: Saturated and Unsaturated Zones
(From Winter et al. 1998)

This water located below the land surface is grouped into two primary zones. The first zone is the *unsaturated zone*, where the voids and spaces between particles (sometimes termed "interstices") contain both air and water. The second is the *saturated zone*, where the voids are completely filled with water. The water table is a discreet line located at the uppermost surface of this zone, where the pore water pressure is equal to the atmospheric pressure (See figure 3). The water table generally follows the topography of the land surface.

A soil's ability to store water, along with its ability to transmit water make up the most important hydrologic properties. Hydraulic conductivity describes the rate at which water is able to move through the soil or other medium. It is determined by the size, shape, and connectedness of the pores, as well as the viscosity of the fluid. Temperature affects the viscosity of the water flowing through the latticework of pores. The colder the water, the more viscous, or "thick"it is.

An aquifer is a rock unit that is able to hold and transmit water at rates fast enough to supply reasonable amounts of water to wells. Aquifers may be near the land surface, with many continuous layers of materials with a high ability to allow water to permeate through. These types of aquifers are called "unconfined aquifers" or water table aquifers (Fetter 1994). (See Figure 4) A confining layer is a rock unit with very low, or no, ability to allow water to permeate through it. Aquifers which are overlain by a confining layer are called confined, or artesian, aquifers. Occasionally, a patch of material with a low ability to allow water to pass through it will be located above the water table. This layer will intercept the water moving through the unsaturated zone and form an area of saturated soil. This type of aquifer is called a perched aquifer (Fetter 1994). Seeps and springs arise where the water table or the perched aquifer intersect the surface topography, as in valleys or hillsides (Fetter 1994, McMastin 1996). (See Figure 5).

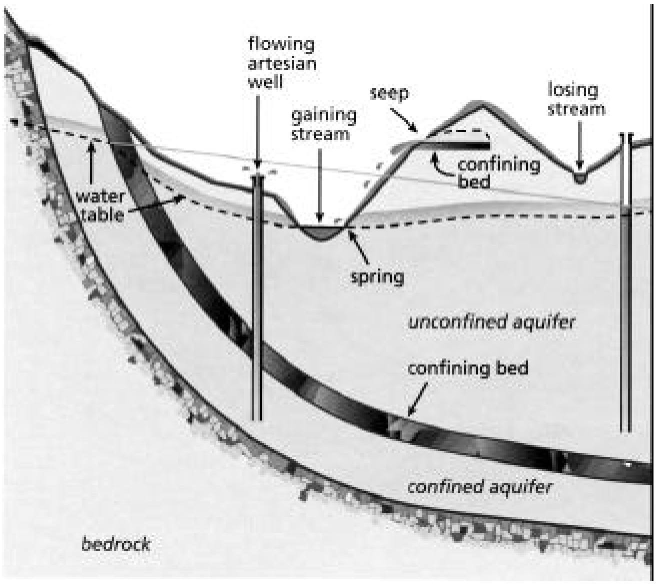


FIGURE 4: AQUIFER TYPES (FISRWG 1998)

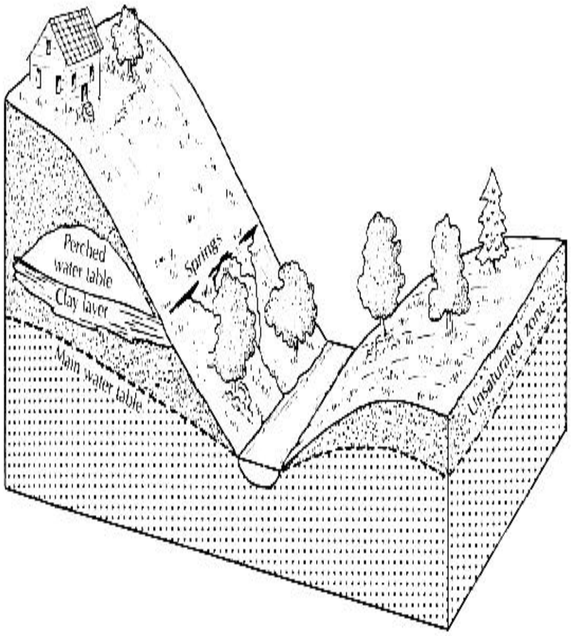


FIGURE 5: SPRING FORMATION DUE TO PERCHED AQUIFER (FROM FETTER 1994)

The ultimate source of ground water is precipitation, such as rain and (melted) snow, which infiltrates through the unsaturated zone and eventually recharges the underlying aquifer. Recharge is defined as "the accretion (or gradual growth in size due to external addition (Morris 1969)) of water to the upper surface of the saturated zone" (Winter et al. 1998). Aquifers may be recharged by water that has seeped through the unsaturated zone, by ground water that has moved laterally, or by water that has seeped upward from underlying sources. (See Figure 6). There is substantial variation in quantity, distribution, and timing of precipitation. Therefore, ground water recharge is a dynamic process, and the position of the water table varies seasonally and from year to year (Winter et al. 1998).

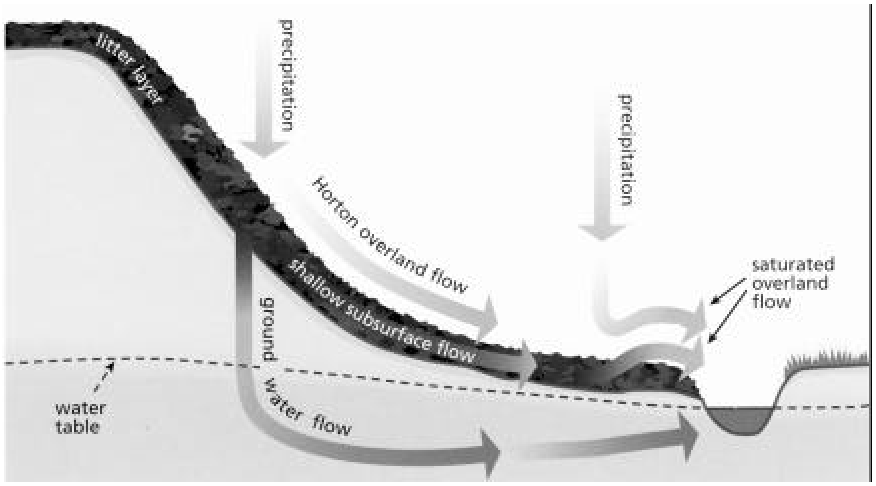


FIGURE 6: PRECIPITATION RECHARGING GROUND WATER (FISRWG 1998)

HOW FLOW SYSTEMS WORK

One may imagine that ground water flows much the same as surface water, from an area of higher elevation (source) to an area of lower elevation (mouth). In ground water ecosystems, this is not always the case. Unlike surface water, ground water flows down "gradient". Within the ground water environment, there are pressures and gradients which force ground water movement. The measurement of hydraulic head is used to document hydraulic gradient, which is calculated as a change in head per unit distance, within a ground water flow system (Fetter 1994). Hydraulic head may be measured by using a piezometer. "Head" is a measure of the amount of pressure that groundwater is subjected to. Water flows from an area of high pressure to an area of lower pressure at a given point within an aquifer. A piezometer is a small diameter well with a section of slotted pipe on the end (Fetter 1994). Further detail regarding methods of measurement will be discussed in a later section.

Within the saturated zone, there are 3 scales of flow systems within a flow network: a local flow system, which is the most near the surface; an intermediate flow system; and a regional flow system, which is the deepest and travels the greatest distance (Brunke and Gonser 1997, Winter et al 1998, Fetter 1994). The three scales of flow systems are differentiated by length and duration of the ground water's residence below ground before surfacing and interacting with surface water. (See figure 7).

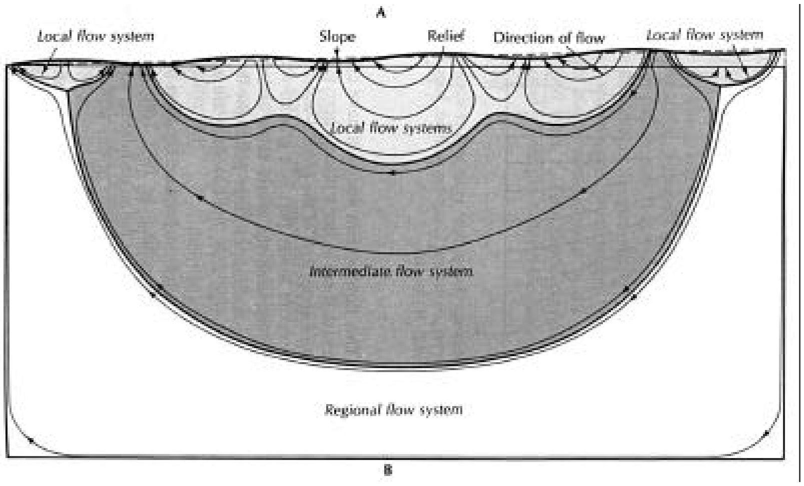


FIGURE 7: THREE GROUND WATER FLOW PATHWAYS: REGIONAL, INTERMEDIATE, AND LOCAL (FROM TOTH 1963, PRINTED IN APPLIED HYDROGEOLOGY FETTER 1994)

The largest is the regional/ continental scale. Flow at this scale is determined primarily by geographic features of the landscape, such as mountainous regions, coastal areas, and glacial till areas. At this scale, surface water would enter into the ground water system near the headwaters and would not reemerge until it reached the mouth of the regional system. These ground waters travel deep below the surface of the earth. The water moves very slowly through this scale, because it is traveling primarily through bedrock, which has a very low ability to transport water. It may take thousands of years for waters to move from recharge to discharge zone. This type of ground water is most resilient and least likely to be impacted by human actions. It would take a large scale geologic event, such as an earthquake, to cause change at this scale. Within this large scale, smaller scales are nested.

The intermediate scale is distinguished by topography within a region. Ground water flows at an intermediate depth and is in the system for an intermediate amount of time. It may take one to 100 years for the ground water to travel through this pathway, depending upon the distance the ground water travels before surfacing. In this pathway, precipitation is intercepted, infiltrates into the saturated zone, and flows down gradient as ground water. In this pathway, the ground water flows toward a stream or wetland area. This pathway is less resilient to changes than the deeper regional flow pathway, and thus more likely to be affected by human actions. Within each intermediate flow pathway, at least two local flow pathways are nested.

Local flow pathways are driven by more local topographic features, such as dips or depressions in the landscape. In local flow pathways, ground water flows most near the surface and resides within the flow path for the shortest duration of time, relative to the above flowpaths. Usually, ground water is present in this flow path for less than a year. This pathway is most susceptible to changes and is most likely to be impacted by human activities.

In the intermediate and local flow pathways, flow between ground water and surface water may occur in either direction. Influent is where surface water moves into ground water. Other terms that describe this net flow of surface water to ground water include down-welling, stream-fed aquifer, aquifer recharge, and infiltration. Effluent is where ground water moves into surface water. Other terms that describe this type of net flow include upwelling, aquifer-fed stream, aquifer discharge, and exfiltration (Brunke & Gonser 1997).

HOW RIVERS WORK: GROUND WATER IN A RIVERINE CONTEXT

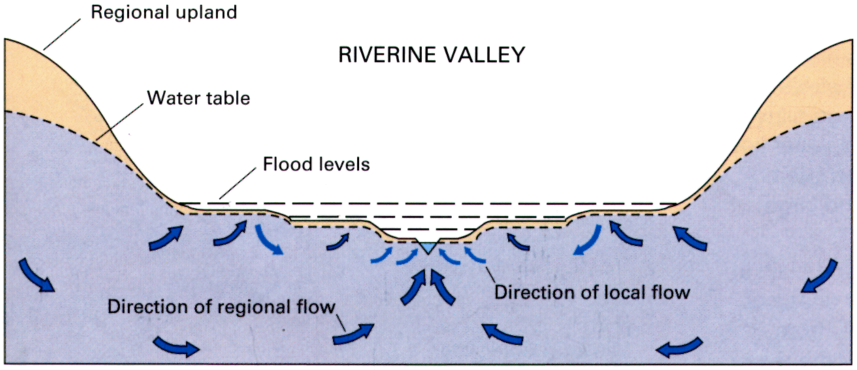


FIGURE 8: GROUND WATER IN A RIVERINE CONTEXT (WINTER ET AL 1998)

The previous section outlined the classic view of how ground water flows. This section aims to superimpose the classic way ground water flows upon the morphology of a riverine system to see how ground water works in this setting (See figures 8 and 9).

At the large scale, surface water would enter into the ground water system near the headwaters and would not reemerge until it reached the mouth of the regional system. Imagine a basin area, from the headwaters to the outwash plain (See figure 9). The basin morphology determines the large scale regional flow pathway, ground water would flow below ground, without surfacing, from mountains to the outwash plain. This scale is not easily influenced by human activities, nor does it have a profound or direct ecological impact upon the surface waters of the riverine system, therefore it will not be focused on in this paper.

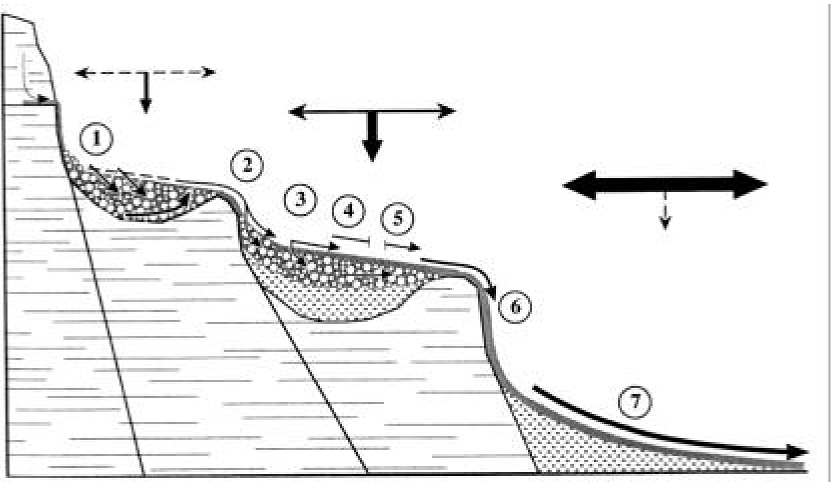


FIGURE 9: A CROSS-SECTION VIEW OF FLOW SYSTEM FROM HEADWATER TO OUTWASH PLAIN. Surface and interstitial flows indicated by horizontal and vertical arrows, respectively. Thickness of the arrow represents volume of overland flow. Numbers refer to segments in river continuum: 1. headwaters, 2. transition, 3. montane floodplain, 4. transition, 5. valley floodplain, 6. transition, 7. Coastal plain (Gibert et al 1994)

In a riverine system, the intermediate scale is distinguished by floodplain morphology within a region. Ground water flows at an intermediate depth and is in the system for an intermediate amount of time. Imagine a stream reach located in a canyon riverine system with alluvial valleys. There would be alternating narrow canyons composed of bedrock and wider alluvial valley floodplains composed of gravel. Ground water enters the intermediate pathway at the top of an alluvial gravel floodplain and reemerges at the opposite end of the floodplain, where the channel is again constricted by a bedrock canyon. Each episode of surface water exiting the narrow canyon, infiltrating into the alluvial gravels as ground water, then reemerging as surface water at the next constriction would constitute an intermediate flow pathway. It may take one to 100 years for the ground water to travel through this pathway, depending upon the size of the floodplain, the hydraulic conductivity, the depth of the gravels within the floodplain, and the number of bends, or sinuosity, in the channel. This pathway is less resilient to changes and more likely to be affected by human actions than the large scale pathway. Within each intermediate flow pathway, at least two local flow pathways are nested (Gibert et al 1997, Fetter 1994). (See figure 10)

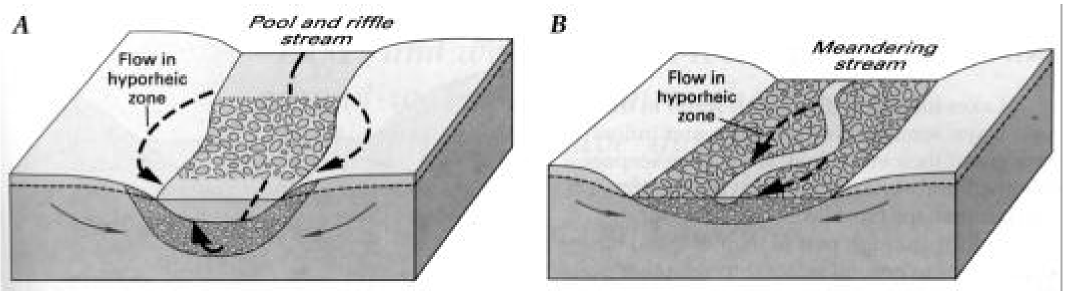


FIGURE 10: A) Local interaction due to bed morphology (pool and riffle).
B) Intermediate interaction due to channel morphology. (From Winter et al. 1998)

Local flow pathways in a riverine system are driven by stream bed morphology, such as pool riffle sequences. Within a channel, the bed is composed of alternating pools and riffles formed by the presence of sediment bars or large woody debris. Each episode of surface water entering into the stream bed from a pool, traveling towards a riffle, and then exiting out of the stream bed into the next pool would constitute a local flow pathway (Brunke & Gonser 1997, Winter et al 1998, Pacific Rivers Council 1995).

Whether the stream is gaining or losing surface water to the ground water realm depends upon the head in the aquifer relative to the elevation of the stream surface (See figure 4 in previous section). In order for ground water to contribute to surface water, the head in the water table must be higher than the elevation of the stream surface. For surface water to enter into ground water, the converse must be true (Winter et al. 1998, Weston 1998). Therefore, at an intermediate scale, water surface elevation is low during times of low flow, so ground water tends to flow towards surface water, even if it must move slightly uphill. At a local scale, pressure that builds in a deep pool behind a riffle will tend to push surface water into the interstitial space of the gravel, thus causing the surface water to move into ground water (Weston 1998).

ECOLOGICAL IMPORTANCE AND VALUE OF GROUND WATER/ SURFACE WATER CONNECTION

The surface water/ ground water ecotone forms a varied habitat that is important to both aquatic and wildlife communities. Ecotone is a term used to describe the transition zone between different habitat types (or "eco types"). Prior to the First International Workshop of Land/Water Ecotone in 1988, ecotone was used as term to describe a terrestrial community transition, such as shrubland to forest (Gibert et al. 1997). In the context of surface water and ground water transition zone, the term "ecotone" encompasses water flow and living and non-living components of surface water/ ground water interactions. In the ecotone concept, the Hyporheic zone is contained within the land/ water ecotone and is comprised of upwelling and downwelling ecotones. In literal terms, Hyporheic can be broken down into its Greek base words "Hypo" and "rhe", which mean below and flow, respectively (Borror 1960). It is defined by the presence of ground water that originated as surface water in the river. The hyporheic zone is functionally a composite of both riverine and ground water ecosystems. (See figure 11).

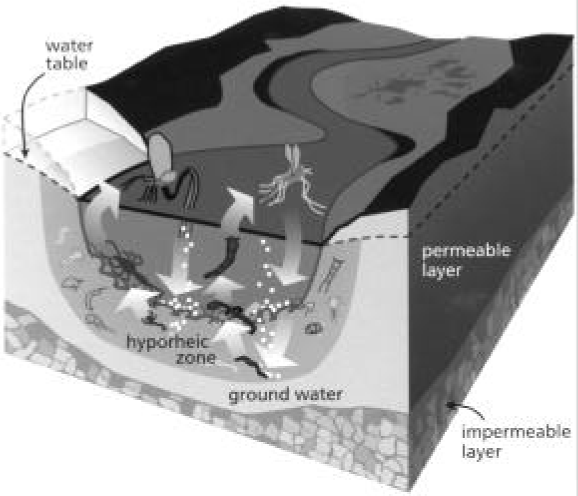


FIGURE 11: THE HYPORHEIC ZONE
(from FISRWG 1998)

The Hyporheic zone provides a number of ecologically important services, including thermal, temporal, and chemical buffering, "food service", habitat, flow augmentation, and refugia.

PROVIDES BUFFERING CAPABILITIES (Chemical, Temporal, and Thermal)

< CHEMICAL BUFFERING/ CLEANING CAPACITY : When surface water recharges ground water, there is opportunity for organic pollutants and detritus to become trapped in the sediment. While trapped, sediment bacteria may catalyze reactions that could change the chemicals into a less toxic form or could transform the chemicals into available nutrients. In contaminated aquifers, many bacterial micro-organisms residing in ground water and sediment interstices can carry out some degradation and denitrification (Gibert et al.1997).

< TEMPORAL (Reduce potential for flooding) The riverine aquifer that underlies the riparian zone on a floodplain, commonly referred to as "Bank storage", provides a vital buffer

during periods of rapidly rising water levels. Bank storage may be a slightly misleading term in that one may think that water enters into the stream bank, is stored, and then the same water is released at times of low flow. Water that enters into a bank or other landform, such as a mid-channel gravel bar, will flow below ground and may reemerge at a different location and time (Refer to the previous section "How Rivers Work"). With a rapid rise of water level within the stream, water is forced to move from the stream into the stream bank. (See Figure 12). These rises in water levels are usually caused by storm precipitation, rapid snow melt, or release of water from an upstream reservoir. In a situation where water rises above its bank, instead of simply running overland and downstream, much of the precipitation may percolate into the ground to recharge aquifers. These diversions allow the onslaught of water into streams to be delayed by days, weeks, or months and thus mitigate the effects of flood peaks (Winter et al 1998, McMastin 1996, Brunke & Gonser 1997).

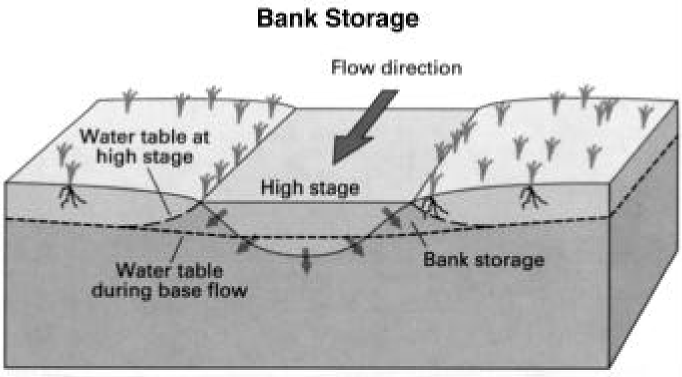


FIGURE 12: "BANK STORAGE", or recharge of the riverine aquifer that underlies the riparian floodplain.
(From Winter et al. 1998)

- THERMAL: Since ground water temperatures remain relatively constant, the water that discharges into surface water tends to be cooler relative to surface water in the summer, and warmer relative to surface water in the winter.

The influx of ground water into surface water plays an important role in the maintenance of essential fish habitat for many salmonid species. (Winter et al. 1998, Williamson et al. 1998, NMFS et al. 1998, Stanford 1994).

FORMATION AND MAINTENANCE OF HABITAT:

The Hyporheic zone creates valuable habitat for micro-organisms, macro-invertebrates, fish, and wildlife. For example, surface water areas where ground water upwells is the common denominator in spawning habitats chosen by adult chum salmon. They rely on the characteristics of the Hyporheic zone, such as an adequate supply of dissolved oxygen and warmer winter temperatures, to incubate their eggs (NMFS et al. 1998).

- Deposition of gravels within a floodplain form a hydraulically connected network of voids as described in the section "How Ground Water Works". These structures within the Hyporheic zone creates an environment which hosts rich and diversified faunal populations (Brunke & Gonser 1997; Gibert et al. 1997; Stanford 1994).

< The influx of surface water into the ground water environment often brings oxygen rich water to a system that is often limited by oxygen availability. This allows a unique and biologically diverse set of organisms to thrive in the surface water/ ground water interaction zone (Naiman et al. 1995).

< These organisms range from microbiotic organisms to macro-invertebrate species. Some surface dwelling organisms, such as specialized stoneflies and certain species of fish, spend at least a portion of their life cycle in the Hyporheic zone (Brunke & Gonser 1997, Stanford 1994; Houghton 1993).

< Interstices between gravel coupled with relatively warmer ground water flowing into the surface water system form ideal habitat conditions for fish to spawn in and for the eggs to incubate in. The influx of relatively warmer ground water prevents smaller tributaries and side sloughs from freezing during the winter (Brunke & Gonser 1997; Stanford 1994). Relatively cooler ground water flowing into surface water during summer provides the necessary lower temperatures required by some salmonid species for rearing and spawning (Pacific Rivers Council 1995; Brunke & Gonser 1997).

< The combination of diverse organisms and warmer ground water flowing into surface waters provide ideal winter feeding grounds for juvenile salmonid species (Pacific Rivers Council 1995). The influx of warmer water prevents smaller tributaries and side sloughs from freezing and the diversity of organisms in the Hyporheic zone provide adequate nutrition. More detail into the food web relationships will be discussed in the “Food Service” section.

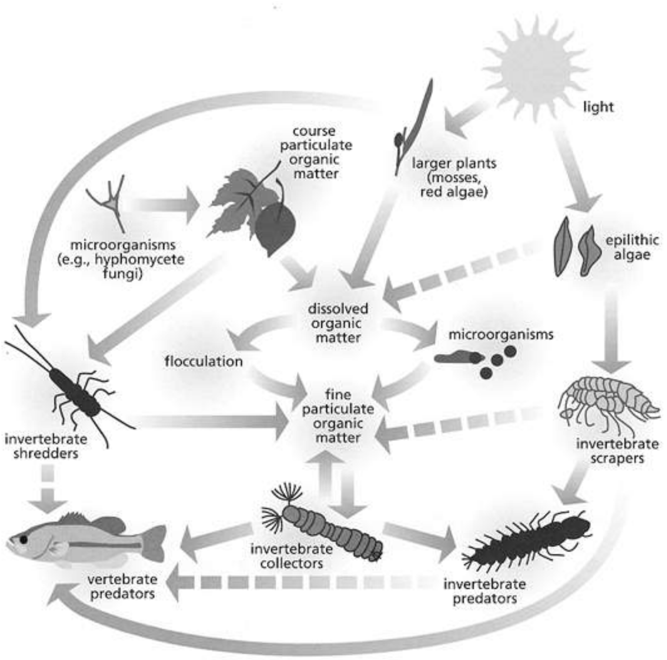
< Riparian habitat: Ground water’s role in sustaining bank vegetation provides an indirect effect on surface water quality by enhancing bank stability against erosive forces and providing shade (Brunke & Gonser 1997; Williamson et al. 1998). Surface water/ ground water interactions are also key components in wetland habitat formation (Gibert et al. 1994).

< A number of wildlife species rely on habitats associated with surface water/ ground water interactions due to the higher productivity of those areas. The influx of warm ground water, relative to cold surface water, temperatures during the early spring provide an important food source for wildlife. The influx of ground water prevents the freezing of smaller tributaries, sloughs, and wetlands, thus allowing vegetation to green up earlier, sustaining fish populations, and providing water fowl habitat (USFWS 1998).

“FOOD SERVICE”

The surface water/ ground water interaction zone plays a vital role in the aquatic food web. (See figure 13). The macro invertebrates, termed benthic organisms, that reside in the Hyporheic zone for all or a portion of their life cycle provide an important food source for fish species. The fish may browse along the gravel interstices to access the macro invertebrates or they may wait for the organisms to become dislodged from their interstitial habitat. The fish catch the macro organisms as they drift downstream (FISRWG 1998).

FIGURE 13: FOOD RELATIONSHIPS FOUND IN STREAMS. Note the "Benthic organisms", or those invertebrates that live in the hyporheic zone for a portion of or all of their life cycle. These organisms provide an important food source for many fish species. Thee fish may browse directly on these species, or they may catch them as they are dislodged and move downstream (FISRWG 1998).



< Surface water flowing into the Hyporheic provides the basic food source (organic matter) for microbial activity in ground water ecosystems. Sediment interstices act as an effective retention site for particulate organic matter (Gibert et al 1994). Organic matter that has been deposited onto the sediment layers is carried into the Hyporheic zone by surface water that is moving into ground water (Stanford 1994). Decomposition of organic matter, or detritus, by microbial organisms provides bioavailable nutrients for macro invertebrates and other organisms who spend a portion of their life cycle in the Hyporheic zone, such as specialized stone flies. Macro-invertebrates and stone flies emerging from the Hyporheic zone will be an available food source for salmon and other aquatic organisms (Stanford & Ward 1994, Gibert et al. 1997).

< Surface water moving into ground water is one of the ways in which microorganisms may colonize ground water environments. Microorganisms migrate actively or passively via percolation from surface, lateral migration from recharge areas, and introduction into sediments during deposition (Gibert et al. 1997).

Aside from permanent and seasonal habitat, the surface water/ ground water interaction zones provide temporary refugia.

REFUGIA:

With increased fragmentation and degradation of habitat, there are only a few healthy and productive patches scattered throughout each stream system. Theses healthy spots are called "Refugia", because they offer refuge for endangered aquatic species (Pacific Rivers Council

1995). Hyporheic zones, areas of ground water input, and micro-habitats within flood plains, such as pools, are locations associated with refugia (Berman 1998).

- Interstitial area provides temporary shelter from high discharge areas, desiccation, and extreme temperatures. They also provide protection from predation for immobile life stages of insects and fish, such as pupae and eggs, respectively. (Brunke and Gonser 1997).

- Locations where cooler ground water flows into surface water streams offer localized areas of cool temperatures for fish to take refuge from warmer surface water temperatures (Pacific Rivers Council 1994).

AUGMENT FLOW :

- "Base flow" is ground water that discharges into surface water channels and maintains flow through times of low flow (USEPA 1993; Stanford 1994). Stream flow, as well as base flow varies with season, physiography and climate (Winter et al. 1998). According to Paul Jehn, associate director of Idaho's Water Resources Institute, "nearly 100 percent of the water (in the Snake River) comes from the ground...If you took ground water away, there would be no river" (Houghton 1993).

PROBLEMS OF NOT ACKNOWLEDGING THE INTERCONNECTEDNESS OF GW AND SW

While streams and ground water are not always well connected, when they are, the interaction zone may be extensive. Current research has suggested that surface water/ ground water interactions may potentially occur up to 2 kilometers from the stream channel (Stanford 1994, Gibert et al 1997). Certain species spend all or a portion of their life cycle in the Hyporheic zone. If a pollutant load becomes too high for ground water organisms to tolerate, the number, diversity, and population viability may decline. Since ground water invertebrates and micro-organisms are an important food source for fish, their decline could affect the viability of native fish populations (Duncan & Fuentes, 1998). The presence or absence of certain ground water species may indicate the location of surface water/ ground water interaction zones and a decline in the diversity of ground water species may indicate a decline in water quality (Stanford et al. 1994, Gibert et al. 1997).

The discovery that surface water and ground water has the potential to interact at such a distance from the stream channel may present some potential problems with current regulations. Taking this discovery into consideration, waste sites or lagoons located a mile away from the stream channel have the potential to rapidly contaminate ground and river water. If the ground water joins surface water bodies rapidly, as is common in hyporheic zones, there may be great potential for water quality problems to develop (Duncan & Fuentes 1998). An example of this was given by Paul Jehn: In an attempt to follow Best Management Practices (BMPs) to control nonpoint source pollution, efforts intended to hold water in a lagoon and thus prevent nutrients from running off into a stream actually allowed time for these nutrients to seep into the soil. The irony of this is that the same nutrients that infiltrated into the ground water would discharge into the stream via a spring source a few miles away. This is an instance where regulations intended to protect surface water quality could inadvertently affect ground water quality, and in turn affect surface water quality (Houghton 1993).

Often when contaminated ground water discharges into surface water, the current is fast, and the pollutants are rapidly washed down stream and diluted beyond traceable measures. If they are volatile chemicals, they may vaporize into the atmosphere. However, if the pollutants have heavier components, such as metals, the pollutant may accumulate in the sediments. Without precise sediment bioassays performed at the exact discharge areas, these pollutants may not be able to be measured. That is not to say that they wouldn't have any effect on incubating salmon eggs or invertebrate ground water organisms (Duncan & Fuentes 1998). Surface water contamination may also occur during periods of low flow, when polluted ground water provides significant stream flow (USEPA 1993). Since ground water may not be protected to the extent that surface water is, the regulations for surface water may fail at times of low flow as a result of under-protected ground water (Gibert et al 1997, Squillace et al. 1993).

Another problem associated with sediment is in relation to agricultural practices. Large alluvial gravel filled valleys are effective ground water transport and storage areas that frequently interact with surface water (Brunke & Gonser 1997, Winter et al. 1998, Pacific Rivers Council 1995). They are often desirable areas for grazing and agriculture. While these areas have the ability to introduce the cooling effects of ground water to a surface water system, they are also easily degraded by mismanagement practices. Active bank erosion as result of excessive trampling of stream banks by grazing ungulates may compact soil, which decreases interstitial spaces between soil particles, thereby diminishing the amount of water stored or transported in the stream bank. Compaction of soil particles could force ground water to prematurely rise to the surface, which would allow solar radiation to warm the water, and would prevent it from passing its cooling effects onto the stream (Gibert et al. 1994).

In association with the loss of bank structure and stability, ground water pathways become impaired, and a disconnection between the ground water zone and the surface water zone results. Since ground water has potential to add to the flow volume of the stream, flow may decrease. With a decrease in flow, the amount of sediment load that the water body will be able to carry will also decrease. This decreased carrying capacity coupled with an increase in sediment load has the potential to widen the channel, clog the gravel interstices, and cause channelization, or the formation of multiple channels where only one had existed previously. This widening and/ or division of the waterbody will expose more surface area of the water to the warming radiation of the sun. The increase in temperatures could be detrimental to the ability of fish species to maintain a sustainable population. The clogged interstial spaces between gravel in the Hyporheic zone could suffocate salmonid spawning beds and hinder food availability.

The placement of wells could also be affected by surface water ground water interactions. If a well is installed relatively close to a stream, and pumps at a moderate rate, some of the ground water that usually discharges to the stream will be diverted up into the well. If the pumping rate is increased, there is a possibility that the flow of ground water may be reversed and instead the well may pull up surface water, thus risking contaminating ground water and drinking water (Winter et al. 1998). Aside from the risk of surface water contaminating ground water, surface water volumes could be reduced. As described above, decreased flow volumes could cause problems related to increased sediment deposition.

As exemplified in the above paragraphs, there are a number of potential problems that may arise as result of interaction between surface water and ground water. An important concern in the future will be to determine adequate policies to address these issues.

SW/ GW INTERACTIONS IN POLICY

There tends to be an "Out of sight, out of mind" view of ground water in regard to surface water quality which is made evident in that there is no "Clean Ground water Act". While ground water is protected in relation to drinking water, in areas where drinking water is not an issue, ground water quality is not monitored. According to LaJuana Wilcher, former EPA Assistant Administrator for Water, "the line between surface water protection and ground water protection has been drawn in people's minds...in spite of the fact that up to 40 percent of U.S. surface water comes from ground water" (Ground water Monitor May 5, 1992).

At the first Ground water Ecology Conference in 1992, Jack Stanford suggested that the reauthorization of the Clean Water Act should redefine ground water as "a continuum of hydrologic units that contain differing and dynamic food webs that in many, many ways determine the quality of this country's surface water" (Ground Water Monitor May 5, 1992). From providing an important food source to fish and aquatic life to playing a large role in metals loading in sediment layers, the contribution of ground water has the potential to do great good or to do great harm to surface water quality. There is a need to look at how these interaction will be managed from a policy standpoint in the future.

While there have been a few court cases regarding surface water/ ground water interactions, there is still a long road ahead of policy makers. The fact that ground water ecology is such a young science and many of the theories relating to this subject are still being studied will slow the implementation of policy. Nevertheless, the study of surface water/ ground water interactions has potential to greatly improve the current methods of evaluating surface water quality.

MEASURING INTERACTION

Ground water scientists have conducted and continue to conduct extensive research in the development of technical tools to measure and predict the presence of surface water/ ground water connections. While progress has been made, the methods of measurement are extremely complex, require extensive technical knowledge, and are resource intensive. Having said that, I do not wish to scare off interest in this subject area, but consider this a forewarning as to the complexities of this issue. Currently, there is not one simple, agreed upon way to measure the connections, and there are many theories as to the best methods out there. The scope of this paper is not at the depth necessary to adequately describe the methods involved in performing the actual measurements. However, it can steer you in the right direction, by naming some current tools, methods, and resources where more information may be found.

Tools for identification range from inexpensive to outrageously resource intensive. The tools themselves may be moderate to highly complex to use. It is the associated method, location of measurements, and quantity of data that will increase resource needs. First, a topographic map & aerial photo, where braided channels, ancient stream channels, and dense vegetation may indicate a surface water/ ground water interaction zone. Next, vegetation type, where species such as cottonwood and the presence of algae along shallow edges of waterways, may point to a surface water/ ground water ecotone (Williamson et al 1998; Keeland et al.1997).

Various probes may be used to measure changes within the channel, which may indicate the points of surface water/ ground water interaction. Temperature probes may be used to determine change in temperature, which indicate influence of ground water on surface water. Hyporheic probes may be used to measure interstitial flow rates and change in gradient, and a piezometer may be used to measure change in hydraulic head, which indicate the potential for ground and surface water to interact (Lee & Cherry 1978; USEPA 1993; Brunke & Gonser 1997; Duncan & Fuentes 1998; Weston 1998).

Research is currently being conducted to test the feasibility of using specific micro- and macro-organisms to indicate the distinction between the surface water/ ground water and true ground water (Stanford et al. 1994).

RESEARCH NEEDS

By better understanding and accounting for surface water/ ground water interactions and the ecological function that those interactions serve in the watershed, we may enhance the effectiveness of our programs to protect and restore water quality.

The importance of conserving, restoring, or protecting the Hyporheic zone is driven by the potential destruction of important biological communities and ecological processes due to pollution and by human demand for potable water sources (Naiman et al. 1995). The steps necessary to turn around the downward trend of water quality will require more than just focusing on improving the polluted reach. Instead, focus should first be on understanding how specific freshwater ecosystems work.

The research area of primary priority should be devoted to providing sound scientific information with emphasis on ecological restoration and rehabilitation. In order to successfully restore a stream, an understanding of how freshwater ecosystems function, what the causes of disturbance are, and how specific freshwater respond to and recover from disturbances will be needed (Naiman et al. 1995). At this time, there are a number of ongoing research projects and a few published papers that cover restoration of a natural flow regime as a means of restoring Hyporheic flow. One method currently being researched, the Hydrogeomorphic (HGM) Wetland Classification System, advocates identifying wetlands based on their position in the landscape (Hashisaki 1996). By determining site specific ranges of values for individual functional indicators, land managers and policy makers may eventually be able to answer questions such as "Is the system working? Is it clean enough? Is it sustainable?" (Naiman et al. 1995).

Further research in the development of a range of scientifically based tools and techniques will help to increase success of restoration efforts (Stanford et al. 1996). Research will also help identify bioindicators of water quality, such as stoneflies, and other ecological indicators which may be used to delineate ecotone boundaries, to predict the base flow quality of the stream, and to monitor the progress of restoration (Job & Simons 1994; Naiman 1992). Supporting further research in this area may lead to a more feasible way to quantify the effects of base flow on stream temperatures, and thus better methods to monitor restoration efforts.

These research ideas presented are not brand new concepts, but build on existing concepts. The research should complement existing programs and encourage a broader ecological perspective on water quality issues.

TOTAL MAXIMUM DAILY LOAD (TMDL) PROGRAM AND SW/ GW INTERACTIONS

The investment made to support the research needs highlighted above will promote a greater understanding of surface water/ ground water interactions in an ecological context and will result in more effective scientific tools and methods. These tools and increased knowledge will play a large role in the development of long-term comprehensive water quality management plans (or Total Maximum Daily Loads- TMDLs).

Taking surface water/ ground water interactions into account can greatly help in the development of sustainable restoration plans for waters that are not currently meeting Water Quality Standards. With a broader ecological perspective, the focus will be on restoring the system to properly functioning conditions, which will save money in the long run, since there will not be the high maintenance costs associated with temporary solutions.

There are current research programs that show that the addition of the ground water component has the potential to cool the stream or provide refugia for fish, and thus mitigate the effects of increasing temperatures. A study evaluated subsurface flow patterns adjacent to a beaver dam and pond. That study found that water would enter the subsurface flow pathways at a relatively high temperature, and after flowing slowly through the subsurface, it emerged on the other side of the dam at considerably lower temperatures. The water was tracked by it's thermal pattern through wells, and it was determined that it took 2-3 months for the water to move from the pool, through the subsurface, and back into the surface water on the other side of the dam. There was a marked temperature decrease from this single subsurface interaction. It may be possible that the cooling effects could be cumulative, and thus provide an even greater decline in temperature (Lowry & Bescheta 1994).

The ability to quantify ground water temperature impacts may provide incentive for stakeholders to implement protective measures around healthy riparian corridors and restore impaired riparian corridors. Restoration efforts to return streams and river systems to Properly Functioning Conditions (PFC), where channels are reconnected to the floodplain and allowed to reach a post-disturbance equilibrium, could benefit from the ability to quantify the interaction of ground water with surface water (FISTWG 1998).

With a better understanding of surface water/ ground water interactions, reasoning behind management actions may be presented in a more clear manner to stakeholders and with better tools, progress could be tracked. With the ability to efficiently quantify the effect of surface water/ ground water interaction, recommendations for stream restoration made in the development of Total Maximum Daily Loads(TMDLs) may be monitored for effectiveness.   Eventually, research of this concept could lead to the ability to predict the effectiveness of regulation criteria (Naiman et al. 1995).

CONCLUSION

This paper draws from a number of previously published sources to illustrate how ground water flows, how ground water works within a riverine system, and what the ecological importance of the surface water/ ground water interaction is within the environment. It also discusses the problems that arise when we fail to acknowledge the interconnectedness of surface and ground water. While the subject of surface water/ ground water interaction from an ecological viewpoint is a relatively young science, one can see that it has great implications within our ecological and programmatic systems. There is much to be learned still, as the measurement and interpretation of interaction areas are complex. However, with attention and perseverance, developing our understanding of surface water/ ground water interactions has the ability to enhance our efforts to protect watersheds and improve conditions for the lives dependant upon healthy watersheds.

Works Cited

"Ist Ground Water Ecology Conference Says Feds, Scientists Have Long Road." Ground Water Monitor. 5 May, 1992. Page 80-82.

Berman, Cara. 1998. Oregon Temperature Standard Review. EPA Region 10.

Blomquist, William A. 1991. Coordinating Water Resources in the Federal System: The Groundwater/ Surface Water Connection. USGS Report # A-118. pp.17-19, 105-125.

Borror, Donald J. 1988. Dictionary of Word Roots and Combining Forms. Mayfield Publishing, Mountainview, C alifornia.

Brunke, Matthias and Tom Gonser. 1997. The Ecological Significance of Exchange Process Between Rivers & Groundwater. Freshwater Biology, Vol. 37. Page 1-33.

Drever, James I. 1982. The Geochemistry of Natural Waters. Prentice Hall Englewood Cliffs, NJ. P.6.

Duncan, Bruce and Fuentes, Rene. 1998. Relevance of Groundwater Fluxes of VOCs to Ecotoxicology Concerns, or, A Conceptual Model of Hyporheic Ecosystems and VOCs: "Try Clean" or "Dry Clean"? University Solvents In-Ground Water Research Program Fall Progress Meeting. Oregon Graduate Institute. Oct. 6-8, 1998.

Federal Interagency Stream Restoration Working Group (FISRWG). 1998. Stream Corridor Restoration: Principles, Processes, and Practices. October 1998.

Fetter, C.W. 1994. Applied Hydrogeology. Prentice Hall Englewood Cliffs, NJ.

Freeze, R. Allan and John A. Cherry. 1979. Groundwater. Prentice Hall Englewood Cliffs, NJ. Pp. 196.

Gibert, Janine, Dan Danielopol, Jack A. Stanford, eds. 1994. Ground Water Ecology. Academic Press. 571 pp.

Gibert, Janine; Mathieu, J.; Fournier, F., eds. 1997. Groundwater/ Surface Water Ecotones: Biological and Hydrological Interactions & Management Options. Cambridge University Press.

Goodman, Iris. 1993. Ground Water/ Surface Water Interactions. Aquatic and Subsurface Monitoring Branch Program Goal Statement for a new research program. Contact information: Iris Goodman US EPA Environmental Monitoring Systems Laboratory P.O. Box 93478 Las Vegas, NV 89193-3478 (702) 798-2623 or (702)798-2692

GW Ecology Gaining Importance in How Regulators Do Business. Ground Water Monitor. February 23, 1995. Page 33.

Hashisaki, Sono. 1996. Functional Wetland Restoration: An Ecosystem Approach. *Northwest Science.* Vol 70, no. 4.

Houghton, Mary (Ed). 1993. Research Illuminates Intricate Play Between Ground and Surface Waters; EPA Chief Urges Watershed Protection at Senate Clean Water Act Hearing. Ground Water Bulletin: Summer 1993.

Job, C.A. and J.J. Simons. 1994. Ecological Basis for Management of Groundwater in the United States: Statutes, Regulations, and a Strategic Plan. From the text Groundwater Ecology. Pp.523-540.

Keeland, B.D.; J.F. Dowd; W.S. Hardegree. 1997. Use of Inexpensive Pressure Transducers for Messuring Water Levels in Wells. Wetland Ecology and Management 5: 121-129. Kluwer Academic Publishers.

Keenan, Dru. 1995. Notes from Ground and Surface Water Interaction Zones: A Watershed Field Workshop, Sept. 6-9, 1995. Flathead Lake Biological Station. Sponsored by U.S. EPA, NPS, and The University of Montana. Workshop leaders: Jack Stanford, John Simons, Bill Hanson.

Lee, David R. and Cherry, John A. 1978. A field Exercise on Groundwater Flow Using Seepage Meters and Mini-piezometers. Journal of Geological Education, vol. 27. Pp. 6-10.

Lowland, M.M., and R.L. Bescheta. 1994. Effect of a beaver pond on groundwater elevations and temperatures in a recovering stream system. Proceedings of American Water Resources Association 1994 Annual Meeting. July 1994. Jackson Hole, WY.

M.C. Mastin. 1996. Surface Water Hydrology and Runoff Simulations for Three Basins in Pierce County, Washington. USGS Water Resources Investigations Report 95-4068.

Morris, William (ed.). 1969. The American Heritage Dictionary: New College Edition. Houghton Mifflin Company. Boston, MA.

Naiman, Robert J. 1992. Watershed Management. Springer-Verlag. New York.

Naiman, Robert J.; Magnuson, John J.; McKnight, Diane M.; and Stanford, Jack A. 1995. The Freshwater Imperative: A Research Agenda. Island Press, Washington, D.C.

National Marine Fisheries Service (NMFS), Alaska Department of Fish and Game, and North Pacific Fishery Management Council. 1998. Essential Fish Habitat (EFH) Assessment Report. March 31, 1998.

Pacific Rivers Council. 1994. The Urgent Need for Watershed-Based Native Fish Protection in

Idaho, Montana, and Northwest Wyoming. Briefing book. Draft December 1994.

Pacific Rivers Council. 1995. Salmon and Stream Recovery Through the Farm Bill. Legislative Briefing Document. First Edition January 1995.

Pitz, Charles F. and Kirk Sinclair. 1998. Groundwater Baseflow Analysis Project/ Quality Assurance Project Plan. Dec. 10, 1998. Washington State Department of Ecology, Watershed Assessment Program, Watershed Ecology Section.

Squillace, Paul J.; E.M. Thurman; Edward T. Furlong. 1993. Groundwater as a Nonpoint Source of Atrazine and Deethylatrazine in a River During Base Flow Conditions. Water Resources Research, vol. 29, no. 6, June 1993. Pp. 1719-1729.

Stanford, J.A. & J.V. Ward. 1988. The Hyporheic Habitat of River Ecosystems. Nature, Vol. 335, No. 6185, pp. 64-66, 1 September 1988

Stanford, J.A.; J.V. Ward; and B.K. Ellis. 1994. Ecology of the Alluvial Aquifers of the Flathead River, Montana. From Groundwater Ecology. Academic Press. Pp. 367-390

Stanford, Jack A. July 1994. Instream Flows to Assist the Recovery of Endangered Fishes of the Upper Colorado River Basin. U.S. Department of the Interior National Biological Survey: Biological Report #24.

Stanford, J.A., J.V. Ward, William J. Liss, Christopher Frissell, Richard N. Williams, James A. Lichatowich, and Charles C. Coutant. 1996. A General Protocol for Restoration of Regulated Rivers. *Regulated Rivers: Research & Management.* Vol. 12, 391-413.

Toth, J. 1963. A Theorhetical Analysis of Ground Water Flow in Small Drainage Basins. Journal of Geophysical Research vol. 68. Pp. 4795-4812.

USEPA. 1993. Methods for Estimating Nonpoint Source Contaminated Groundwater Discharge to Surface Water. Training workshop reference manual, Boston Mass. Sept. 13-14 and Philadelphia, PA Sept. 27-28.. Groundwater Protection Division, Office of Water. U.S. Environmental Protection Agency, Washington, D.C. pp. 2-18 thru 2-25.

Weston, Roy F., Inc. 1998. Final Report: Groundwater/ Surface Water Interactions, Conceptual Models and Assessment Endpoints. USEPA Work Assignment No. 3-353. July 1998.

Williamson, Alex K. et al. 1998. Water Quality in the Central Columbia Plateau: Washington & Idaho, 1992-95. USGS Circular # 1144.

Winter, Thomas C. et al. 1998. Ground Water and Surface Water: A Single Resource. USGS Circular #1139