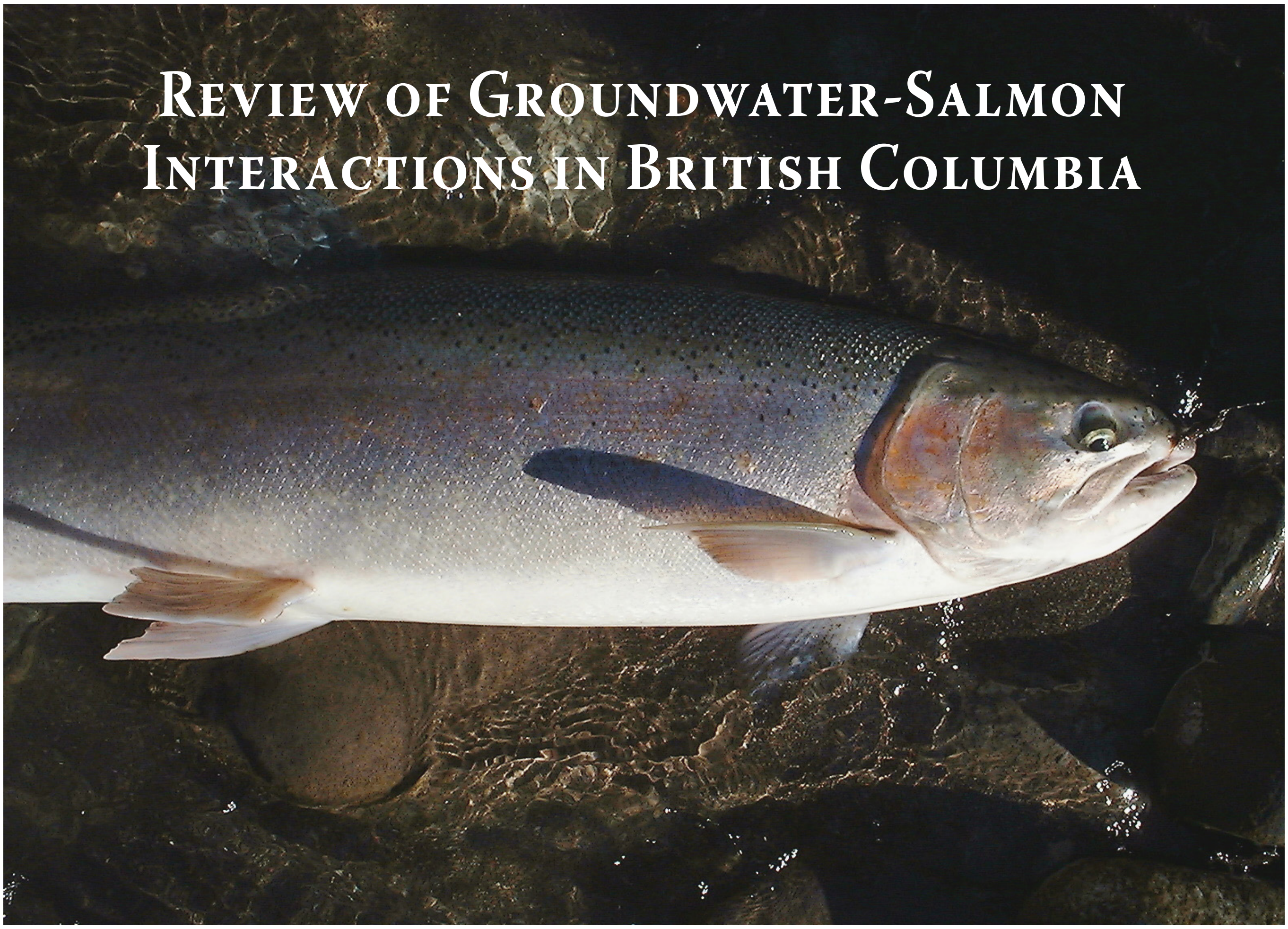
Review of Groundwater-Salmon Interactions in British Columbia



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Prepared by Tanis Douglas, RPBio., for:

Watershed Watch Salmon Society
www.watershed-watch.org

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Introduction

GROUNDWATER IS AN IMPORTANT AND often essential part of wild salmonid habitat. Yet, groundwater use is almost entirely unregulated in British Columbia, groundwater management rarely considers wild salmon, and British Columbia's water policy focuses mainly on surface water.

While certain protection measures are being phased in by government to address groundwater quality and use, better data on the importance of groundwater to salmonids – and on links between surface water and groundwater in general – are needed to properly protect and manage BC's water and fish resources. Groundwater-surface water interactions are currently of great interest to water managers, water users, First Nations and stewardship groups. However, information on such interactions is often scarce and/or scattered. Interest in groundwater-surface water issues and associated water conflicts and shortages will only increase, due to steadily increasing demands for already oversubscribed water resources, the effects of climate change on water use and demand, and the prevalent view that groundwater is an automatic alternative to surface water when surface water rights are unavailable. These factors inevitably result in heightened concerns about surface and groundwater depletion, including effects on wild salmon and other ecosystem values.

This review summarizes information on surface and groundwater links, the importance of groundwater to wild salmon, and groundwater use and policy. While there are many cases of groundwater extraction having negative effects on salmon and other fish (e.g. Glennon 2002), we found scant scientific literature directly addressing groundwater use relative to base flows and fish habitat needs in salmon-bearing streams. We believe this scarcity reflects a lack of proper groundwater management for ecosystem needs, as well as the difficulty and expense of groundwater management and monitoring. Managing for sustainable groundwater use and adequate fish flows is a major undertaking due to the expense and difficulty of mapping aquifers, identifying source water, monitoring water extraction, and understanding and accounting for complex interactions between surface water (e.g. streams) and groundwater. The lack of understanding of aquifer properties and water balance in general (especially the amount of water taken) also makes it challenging to accurately predict negative impacts of groundwater withdrawal on stream flow and quality (e.g. temperature)—despite recent advances in modeling tools (Gwyn Graham, BC Ministry of Environment hydrogeologist, personal communication).

Groundwater quality has been a provincial government focus since 2001, following the contaminated drinking water tragedy in Walkerton, Ontario. Groundwater quantity is now becoming more of a focus for managers in British Columbia. Groundwater-surface water interactions are being investigated in a few watersheds within the Okanagan Basin (with first results due April 2007; Vicki Carmichael, BC Ministry of Environment, personal communication), and in the Nicola Valley, with results expected to be relevant to other areas of the province that are or will be facing similar increased competition for scarce water resources.

To help foster understanding of surface-groundwater interactions, and the proper management of water and fish, Watershed Watch has reviewed the following topics:

- Surface and groundwater interaction related to fish habitat. The main concepts found in the literature regarding interconnectivity of surface and groundwater (as relevant to fish) are summarized.
- Behavioural thermoregulation and redd site selection. Most literature reviewed in this category relates to groundwater upwelling areas in streams and lakes used by resident and spawning fish.

- Artificial groundwater recharge, and groundwater use in fish habitat restoration. Groundwater can be made more accessible to fish by replenishing aquifers (though fish are not usually the main driver for these actions), and by creating artificial groundwater-fed side channels to restore degraded river habitat.
- Management and use of surface and groundwater with respect to fish. Here we review the provincial approach to management and use, and issues and approaches used elsewhere.
- Groundwater-fish management needs. Management needs, approaches and issues are briefly summarized in this category.

This document is part of a Watershed Watch project on salmon and groundwater which includes three case studies, and a separate legal review of groundwater policy by the Sierra Legal Defense Fund (available at www.watershed-watch.org).

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1. Surface and groundwater interaction related to fish habitat

Groundwater exchange directly affects the ecology of surface water by:

- sustaining stream base flow and moderating water-level fluctuations of groundwater-fed lakes;
- providing stable-temperature habitats (i.e., thermal refugia for fish); and
- supplying nutrients and inorganic ions.

Groundwater also indirectly affects surface water by providing water for riparian vegetation, and by controlling the shear strength of bank materials, thereby affecting slope stability and erosion processes. In streams, the mixing of groundwater and surface water in shallow sediments creates a unique environment called the hyporheic zone, an important feature of the stream ecosystem (paragraph from Hayashi and Rosenberry 2002).

The diagram below helps portray flow interactions between streams and groundwater (from Winter et al. 1998, as quoted in Marti 2005). The three types of streams with respect to groundwater are: gaining streams (streams

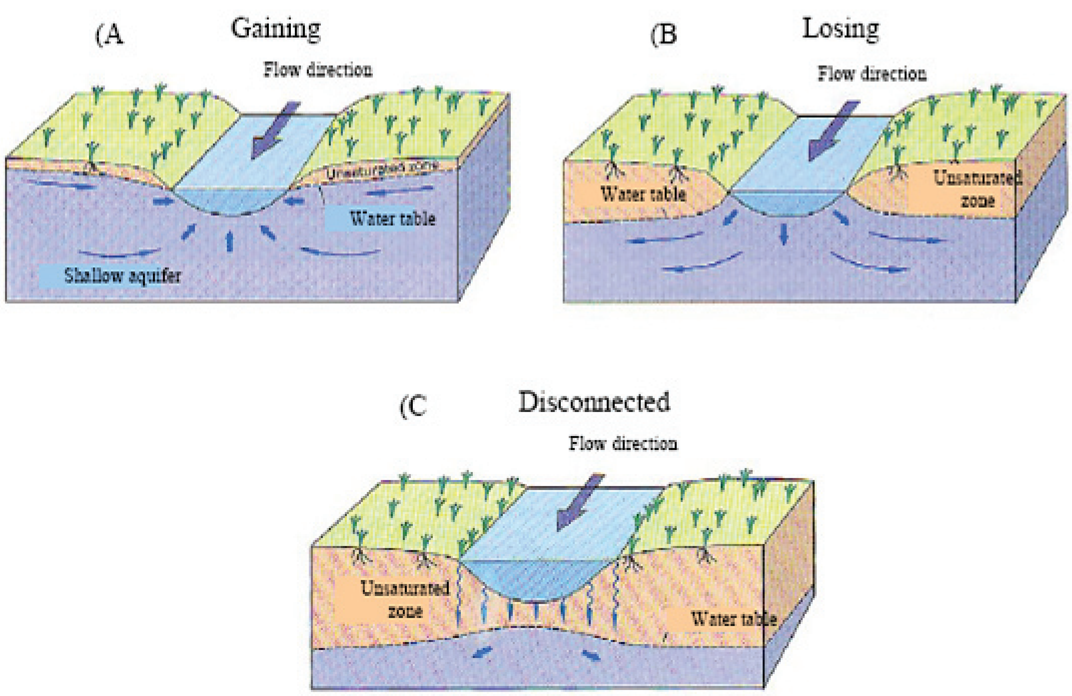

Figure 1.

Generalized depiction of stream and groundwater interchange within gaining, losing, and disconnected stream reaches (Winter et al. 1998) gain water from groundwater inflow through their streambed), losing streams (streams lose water through the streambed to groundwater), or disconnected streams, which are losing streams where there is an unsaturated zone of air between the stream and groundwater. Streams can be both gaining and losing, depending on changes in stream stage (hydraulic gradient) and location of reaches within the stream. The rate of exchange between a stream and groundwater depends on the conductivity of the streambed, the hydraulic gradient between the stream and groundwater, and the saturated area of the streambed where flow occurs. When streams are separated from groundwater by an unsaturated (disconnected) zone, the rate of loss depends on stream depth, geometry and streambed conductivity. According to Thierry Carriou (BC Groundwater Consulting Services Ltd., personal communication), losing stream reaches are susceptible to depletion from nearby wells connected to the same aquifer, as the depletion is direct – water is taken preferentially from the surface. Gaining streams are at a lower risk of depletion, but indirect depletion occurs when water is captured that would otherwise flow into the stream. Disconnected streams are at minimal risk of depletion by nearby wells, as their rates of leakage would not be controlled by well pumping rates.

Two types of groundwater influence streams: hyporheic groundwater, and phreatic groundwater (Poole and Berman 2001). Hyporheic groundwater is from the hyporheic zone, which is the alluvial material underlying the stream bed that contains a portion of the 'alluvial aquifer' – an aquifer that contains stream water that travels along localized subsurface flow pathways for relatively short periods of time (minutes to months), before re-emerging further downstream. Phreatic groundwater comes from the catchment aquifer, and feeds a river by entering the bottom of the alluvial aquifer and mixing with hyporheic groundwater. Depending on localized subsurface flow, groundwater entering the stream channel may be predominantly phreatic, predominantly hyporheic, or a mixture of both. Groundwater from the phreatic aquifer influences channel water temperature when it enters the stream channel. Additionally, the two-way water exchange between the alluvial aquifer and the stream channel (hyporheic flow) is perhaps the most important stream temperature buffer. Various factors such as the stream channel pattern and streambed will determine the magnitude of the hyporheic flow. Poole and Berman also discuss human influences on stream temperature and groundwater. Human activities affect water temperatures in various ways. With respect to phreatic groundwater, reduced groundwater discharge via removal of upland vegetation or well pumping reduces the stream's ability to assimilate heat. Similarly, simplification or entrainment of stream channels reduces hyporheic flow and the stream's capacity to assimilate heat.

The hyporheic zone (the region of interstitial mixing between subsurface water and surface water) is a region of intense biogeochemical activity. Biogeochemical processes within the upper few centimeters of sediments beneath nearly all bodies of surface water have a profound effect on the chemistry of groundwater entering surface water, as well as on the chemistry of surface water entering groundwater (Sophocleous 2002). Malcolm et al. (2003) state that the highly interactive nature of physical, chemical and biological processes in the hyporheic zone dictate that this ecotone has a central role in the functioning of steam ecosystems.

According to Smith (N.D.), the contribution of groundwater to surface water sources varies according to surficial geology and other factors. In some areas of Ontario where silt and clay soils predominate, groundwater flow contributes less than 20% to stream flow, while it can contribute up to 60% where sandy soils dominate, including many interior regions of British Columbia (Kidd 2002).

2. Behavioural thermoregulation and redd site selection

Behavioural thermoregulation and redd (nest) site selection are site-specific aspects of fish-groundwater interactions and a particular focus of fisheries biologists.

The temperature of shallow groundwater is very stable relative to surface water and is approximately equal to the average temperature of the ground subsurface, which in turn is similar to, or a few degrees higher than, the annual mean air temperature. Localized areas of groundwater discharge have a stable temperature regime and provide thermal refugia for fish in both winter and summer (Hayashi and Rosenberry 2002). Power et al. (1999) detail how, for part or most of their lives, many stream-dwelling fish are dependent on groundwater and interstitial water within the substrate (Table 1).

Temperature refugia are an important part of this relationship. In summer, groundwater discharge areas provide refuge for species otherwise exposed to temperatures approaching their upper thermal limits. Because groundwater provides wintering habitat free of subsurface ice, the relative importance of groundwater in winter increases northwards. Power et al. also say that fish can migrate considerable distances to take advantage of groundwater refugia in both winter and summer. Table 1, from a comprehensive review by Power et al. (1999), summarizes the seasonal role of groundwater in terms of providing habitat for stream-dwelling fish.

One characteristic of groundwater of particular importance to the oxygenation of salmon redds is that it is often lower in dissolved oxygen than surface water, and more variable in oxygen concentration (Peterson and Quinn 1996, in Quinn 2005).

Groundwater influences the spawning behaviour and distribution of some fish. Sockeye salmon (*Oncorhynchus nerka*) spawning habitats and redd characteristics were monitored by Lorenz and Filer (1998) in the Taku River, where upwelling ground-

TABLE 1. The importance of groundwater to fluvial fishes

GROUNDWATER ROLE	FALL/WINTER SEASON	SUMMER/AUTUMN SEASON
Provision of baseflows	Maintains free flowing water, habitat and migratory channels through winter minimal flows.	Maintains minimal flows and wetted perimeter and living space through dry periods when evapotranspiration exceeds precipitation
Modulation of temperatures	Prevents or delays ice formation. Provides areas with temperatures above 0°C. Influences ice thickness and break up.	Dampens diel fluctuations in temperature, slows and limits seasonal warming, delays cooling in autumn.
Influences water quality	Supplies dissolved inorganic and organic nutrients and oxygen to stream. Water quality tempered by hyporheic exchanges.	Helps maintain stream productivity by steady input of nutrients. Stimulates macrophyte growth. Water quality tempered by hyporheic exchanges.
Provision of refugia	Sets size and quality of winter refugia. Influences mortality and may set overwintering carrying capacities.	Provides protection from upper lethal temperatures. May set carrying capacities in hot dry summer weather.

water influenced habitat use in the river mainstem – upwelling water was detected in nearly 60% of the sites sampled. Leman (1993) states that in northern rivers, low temperatures and freezing are threats, and salmon seek areas of upwelling groundwater for spawning. There are extensive studies of the reliance of brook trout (*Salvelinus fontinalis*) on groundwater for redd site selection (Witzel and Maccrimmon 1983; Curry and Noakes 1995; Curry et al. 1995; and studies in Power et al. 1999). Biro (1998) demonstrated thermal habitat selection and behaviour by young-of-the-year (age-0) brook trout, including preferences for cooler water in summer when the flow rate of cold groundwater accounted for 87% of the variance in trout density. Biro suggests cold groundwater may be a limiting resource in summer, and that resource managers should thus protect such areas from lakeshore development and logging. Similar conclusions were reached in another study where lake trout (*Salvelinus namaycush*) were monitored with temperature-sensing ultrasonic transmitters (Snucins and Gunn 1995).

Temperature-sensitive transmitters were also used to study behavioural thermoregulation of 19 adult spring Yakima River Chinook salmon (*Oncorhynchus tshawytscha*) for four months in freshwater prior to spawning (Berman and Quinn 1991). Chinook maintained an average internal temperature 2.5°C below ambient river temperature. The resulting 12%–20% decrease in basal metabolic rate translated into extra energy available for spawning. Berman and Quinn point out that cool water areas need to be abundant and available to fish, and that the availability of appropriate holding habitat within mainstem rivers may affect long-term population survival. Baird and Krueger (2003) conducted a similar study with brook and rainbow trout (*Oncorhynchus mykiss*), with similar results, and state that groundwater discharge areas within pools and certain tributary confluences were critical habitat for behavioural thermoregulation.

Topography (topographic index approach) has also been used to predict groundwater upwelling lakeshore sites used by brook trout (Borwick et al. 2005). Fish distribution in watersheds is driven by multi-scale factors (Thompson and Lee 2000; Rich et al. 2003). One fundamental multi-scale habitat feature for some fish species is the relationship between site-specific groundwater upwelling and watershed geomorphology and topography. The GIS modeling technique used for this project is promising, as it links small-scale site choices made by fish in lakes to watershed processes at larger scales, which is useful for effective management and conservation of fish habitat (Borwick et al. 2005).

The spawning locations of bull trout (*Salvelinus confluentus*) were investigated at the watershed and reach scales in a Montana stream (Baxter and Hauer 2000). Baxter and Hauer found spawning increased in confined stream segments characterized by complex patterns of hyporheic exchange and extensive upwelling. At a reach scale, though, redds were located in downwelling zones, emphasizing the importance of accounting for multiple spatial scales when planning bull trout conservation and restoration.

Ebersole et al. (2003) point out that associations between stream channel thermal diversity at the reach scale, and physical characteristics of floodplains and channels, have seldom been explored. They believed it would be useful to link management of streams with high ambient temperatures with channel characteristics known to create thermal refugia for fish, and thus incorporated cold-water refugia into habitat models to predict salmonid abundance based on refuge and other habitat conditions in northeastern Oregon streams. In their modeling, they found a small but significant effect of cold-water patches on Chinook salmon and rainbow trout.

Thermal refugia for Chinook salmon were investigated at multiple scales in degraded and wilderness streams in Oregon (Torgersen et al. 1999). Thermal remote sensing, used for between-reach comparisons of temperature, in addition to investigations of within-reach temperature variation, showed that thermal refugia are most numerous in intact riverine ecosystems with extensive coupling of main channel and streamside forest habitat, floodplain forests, and groundwater (Bilby 1984, Sedell et al. 1990). These studies also indicate that thermal patchiness in streams should be recognized for its biological potential to provide habitat for species existing at the margin of their environmental tolerances, and that thermal refugia are responsible for the persistence of these stocks in rivers where water temperatures routinely exceed 25°C.

Studies (including Chinook enumeration: Farwell et al. 1999, 2000, 2001) conducted since 1995 in the Nicola River (southern interior British Columbia) have explored using the Nicola River spring Chinook as an indicator stock (Richard Bailey, Fisheries and Oceans Canada, personal communication).

- spring Chinook likely survive as adults only because of the thermal refugia created by influent groundwater;
- adults enter the river in the 2nd or 3rd week of April, their arrival peaks in the 3rd week of July, and is complete by the 3rd week of August;
- locations of these adults are predictable based on depth and temperature;
- when water temperature exceeds 24°C adult Chinook move from pools into better-oxygenated riffle habitats, where they stay until the temperature drops to 23°C, at which point they move back into pools because of associated lower rates of predation;
- juvenile Chinook burrow into the streambed gravel in groundwater upwelling areas during the hottest part of the day, where temperatures are 16°–17°C compared to ambient river temperatures of 23°—25°C; and
- groundwater significantly influences redd site selection.

Kokanee salmon (*Oncorhynchus nerka*) may also enhance incubation success by depositing eggs in groundwater upwelling sites, even though these areas may have lower water velocities and a higher proportion of fine sediments than redds without groundwater influence (Garrett et al. 1998). This success is attributed to higher temperatures (+2.5°C) that accelerate rates of development and protect embryos from freezing. These higher incubation temperatures may increase survival of fry recruiting to rearing lakes.

Climate change may also broadly affect fish habitat by simultaneously increasing water temperature, and reducing (or altering) water flow and volume. Climate change will also likely have a negative though imperfectly understood effect on groundwater. Meisner et al. (1988) suggest that optimal thermal habitats will likely shrink in summer, with the converse occurring in streams at high altitudes and latitudes, due to changes in groundwater temperature. Brandes et al. (2005) predict that groundwater supplies will be affected across Canada due to climate change.

A recent report on the state of coastal areas in BC (BC Ministry of Environment et al. 2006) associates current climate change with wetter winters and drier summers. Declining snow packs will reduce water available for drinking and irrigating (and likely for fish, as well). The diminished availability of snow will be a major issue for interior streams where peak flows are driven by snow melt. The Okanagan Basin and other regions already under stress are most vulnerable to the effects of climate change.

3. Artificial groundwater recharge, and groundwater use in fish habitat restoration

Groundwater may be artificially 'recharged' by directing water to areas where it can percolate back into the ground to raise water levels in the aquifer below. Weeks (2002) documents many examples of successful recharging efforts for various reasons over the past century. According to Arizona water managers (Central Arizona Project 2006), artificial recharge is a water management tool commonly used to:

- store excess surface water for future uses;
- replenish groundwater supplies;
- prevent or mitigate saltwater intrusion;
- improve water quality by natural filtration; and
- prevent land subsidence.

Artificial recharge is now underway on a trial basis in the Walla Walla Basin in Washington and Oregon. This watershed suffers from declining aquifer levels, and water supply is a concern for fish and people. Until 2001 when surface fish flows were negotiated, the Walla Walla River had run dry every summer irrigation season for the past 100 years. This project is designed to test active recharge as a tool to supplement the natural recharge of the Walla Walla Basin shallow aquifer, to rejuvenate wetlands in nearby spring (groundwater-fed) branches, to restore shallow wells in the immediate vicinity, and to attempt to increase the groundwater base flow return to the mainstem Walla Walla River. Water is diverted to the site into spreading basins where it passively recharges the shallow aquifer. The project is operating under a temporary water licence and water may be diverted only when there is sufficient flow in the Walla Walla River to honour all existing water rights (Walla Walla Basin Watershed Council 2006). In the first two years (2003 and 2004), 2,740 acre feet of water was diverted into the aquifer, or the equivalent of water a foot deep over 4.5 square miles. This diversion has been done during discrete episodes between November 1st and May 15th when unsubscribed water was available. The alluvial aquifer has responded significantly, and this recharge is tracked in local down-gradient wells and in surface flow in two sub-basins. Further testing and studies will be done over the remaining years of the five-year permit, to better understand the impact of artificial recharge on shallow groundwater, and the utility of artificial recharge for managing water resources in the basin (Bower 2005).

Other methods of artificial recharge include direct injection of water through wells, which usually requires filtration prior to injection (Gwyn Graham, BC Ministry of Environment, personal communication).

Artificial recharge is a major proposition that will often benefit fish while also meeting other water objectives. The creation of groundwater channels for fish is a more common way of artificially increasing access to groundwater, and is done in areas where shallow groundwater is abundant. Artificial 'side channels' are a restoration response to river simplification and the resulting loss of fish habitat. When channels are simplified due to direct and indirect human influences, hyporheic flow is reduced, and thus cool groundwater refugia and general exchange of cooling groundwater to streams is reduced (Poole and Berman 1991). Greater access to subsurface flow is the goal of groundwater channels or side channels created by fisheries biologists to improve salmon habitat. Channels are often created in areas where the river floodplain has been altered significantly by development-related dykes or channel straightening, and channels are also a means of creating high quality spawning habitat, or off-channel wintering habitat (Slaney and Zaldokas 1997). These areas are valued for their stable flows, and temperature differences in summer and winter can also be an advantage. Groundwater is often cooler than surface water in summer and warmer than surface water in winter, and thus can enhance egg incubation and provide summer cold-water refugia.

The Watershed Restoration Program managed by the BC Ministry of Environment funded many groundwater side channel projects between 1994 and 2002. British Columbia was once considered a leader in this area, and many of these projects were done (and are still done) with the involvement of Fisheries and Oceans Canada. These projects are generally considered to be effective in producing high quality habitat. Morley et al. (2005) recently compared constructed channels to natural channels in western Washington, finding that constructed channels supported densities of juvenile salmonids equal to or greater than in natural side channels. They also found fish densities in both the constructed and natural side channels were consistently much higher than in other stream habitats.

4. Management and use of groundwater with respect to fish

A pumping well affects a stream by reducing groundwater levels, creating a gradient that captures some of the surrounding groundwater flow that would have otherwise discharged as base flow to the surface water. When pumping rates are sufficiently high, declining groundwater induces flow out of the surface water and into the aquifer. This leads to stream flow depletion as water demand increases (Sophocleous 2002), a phenomenon particularly acute in dry areas. In Arizona, groundwater pumping has dried up or degraded 90% of the state's once perennial desert streams, rivers, and riparian habitats. Problems can occur even in wet areas: in the northern Tampa Bay region in Florida, groundwater pumping has seriously harmed or dried up half the lakes, and only 7% of the regions' lakes are considered healthy (Glennon 2002).

The BC Ministry of Environment, the agency responsible for water management in British Columbia, noted in a 1994 report that there was then no federal or provincial legislation directly related to protecting groundwater or regulating its use, but that some measure of protection was afforded by the many acts, regulations, guidelines, bylaws, standards and objectives enacted over the years by federal, provincial and municipal levels of government. This includes the provincial environmental assessment law, which requires approval for large projects where groundwater extraction will exceed 75 litres/second (an uncommon level of extraction). The lack of direct legislation is no longer the case, as BC passed its Ground Water Protection Regulation in 2004. This Regulation and related changes to the BC Water Act are focused on standards for well construction and maintenance, as well as groundwater quality protection. However, groundwater allocation and quantity control is minimal and discretionary. BC remains the sole jurisdiction in Canada that has no general permitting requirements for groundwater extraction (Nowlan, 2005). The Ministry of Environment webpage (MOE 2006b) states that the Ground Water Protection Regulation (GWPR) does not restrict a well owner's ability to drill new wells. Wells regulated under the GWPR are not licensed and the province does not charge any fee or rental for extraction of groundwater. However, with the approval of the Minister of Environment, the new legislation may allow for groundwater licensing provisions within discrete areas of the Province covered by Water Management Plans.

Phase 1 of the Ground Water Protection Regulation came into force on November 1, 2005, with a 'grace period' extending to November 2007. Phase 1 applies to the proper construction, deactivation and protection of wells. Further information on the in-progress Phase 2 and 3 of the Regulation was provided by Gwyn Graham, regional BC Ministry of Environment hydrogeologist (personal communication 2006), as well as by the BC Ministry of Environment (2006b). Phase 2 will include additional standards for wells including pumping tests for new wells and a requirement to submit well records. Until this law comes into effect, the Province is not informed when a property owner drills a well, unless the owner voluntarily submits their records. Phase 3 is an amendment to the BC Water Act to allow Water Management Plans in designated areas, as mentioned above. These plans will include groundwater and are regionally specific, with associated regulations specific to each plan area. Each plan must be approved by the Minister of Environment and with approval comes an implementation regulation. As of July 14th, 2006, the township of Langley has operated under a Ministerial Order making it the first municipality to proceed with a Water Management Plan. Depending on the issues in a water management plan area (i.e. if there are competing use issues), it is possible that there could be a permit authorization process for groundwater extraction (Antigone Warren-Dixon, Township of Langley hydrogeologist, personal communication). While the region-specific approach will enhance flexibility to meet local conditions, it also creates a capacity issue, as there are a limited number of plans that can be dealt with at any one time. A comprehensive provincial approach to groundwater extraction is unlikely until further changes are introduced. The Ministry of Environment webpage (MOE 2006b) also notes that Phase 3 of the Regulation will include drilling authorizations (if necessary) as well as other measures for aquifer quality and quantity protection and use.

According to Brandes et al. (2005) "the current surface water licensing approach in Canada is oriented to regulating consumptive use of water rather than ensuring instream needs are met. Maintaining natural flows for the protection of ecosystems, wildlife habitat, fisheries, or traditional uses is, at best, a secondary consideration. The limited environmental protection that does exist is not required, and instead, relies on the discretionary power of decision-makers. This approach is generally considered to provide inadequate protection for maintaining instream flows and groundwater supply." Brandes et al. go on to state that groundwater licensing schemes across Canada are also deficient, and little effort has gone into identifying the interconnections between surface and groundwater.

We believe the lack of consideration for ecosystem impacts may apply even more strongly to groundwater extraction than to surface water licensing. As mentioned, there is no licensing approach for groundwater use in British Columbia, making it difficult to know anything about the relationship between ecosystems and human use of groundwater.

The Province of BC's State of the Environment Reporting (BC MWLAP 2002) describes industry as the largest user of groundwater (55%), followed by agriculture (20%) and municipalities (20%). (The BC MOE (2006a) describes rural domestic users at 7%.) The State of the Environment report states that groundwater levels are not declining province-wide, but are declining in local areas where groundwater withdrawal and urban development has been intensive. Observation wells have shown water level declines in the Lower Mainland (five wells), Okanagan (three wells), and along the southeastern coast of Vancouver Island and on the Gulf Islands (seven wells). This accounts for 14% of all wells monitored from 1995 to 2000. In previous years this percentage was higher, and the change may reflect changes in the distribution of wells and in groundwater demand.

Regarding the major users of groundwater in the province, the BC Ministry of Environment (1994) quotes Liebscher (1987): "Agriculture and industry are the major users of groundwater in the province and include irrigation, pulp and paper, fish hatcheries, food processing, mining, chemical, petrochemical, parks, airports etc." The Ministry of Environment document goes on to mention that conflicts between surface and groundwater users and depletion of groundwater supplies will become increasingly frequent with further development. Below normal groundwater recharge to creeks and streams during low flow periods could result in reduced supplies for licensed surface water sources, and may also prevent salmon from reaching spawning areas. Though this report was written some time ago, it is still relevant to the drier areas of the province (e.g. Nicola Valley) where groundwater supply for fish is critical. According to Richard Bailey (Fisheries and Oceans Canada, personal communication 2006), the Chinook stock in the Nicola River is in significant jeopardy due to expanded groundwater extraction, and continued groundwater development will increase this risk. In this temperature sensitive stream, the fish rely on cooler (by a difference of at least 7°C) groundwater to survive.

A Fisheries and Oceans guidance document (Ingimundson and Engelbrecht 2005) includes the following in a list of potential impacts to fish habitat that may be caused by groundwater extraction:

- Reductions in flow, water level and surface water availability in year round and seasonal rearing and spawning habitats;
- Impacts to groundwater flow (springs, seepage) critical for maintenance of forest and grasslands habitat, or wetlands that are related to fish habitat;
- Changes in surface water temperature caused by groundwater removal;
- Increases in sediment loads in surface waters due to an increase in stream flow and/or surface runoff caused by construction and/or creation of uncontrolled artesian wells near fish habitat, and;
- Changes in chemical and biological surface water quality.

The Water Stewardship Division webpage (BC MOE 2006a) describes examples of groundwater resource conflicts, including groundwater-surface water conflicts, particularly where surface water is fully licensed and groundwater extraction depletes surface water availability and flow (e.g. Cherry Creek/ Kamloops, Chimney Creek/Williams Lake, Kalamalka Lake). This webpage also: acknowledges that, in some areas, further well drilling and further groundwater extraction and surface water allocation would threaten the entire hydrologic regime; mentions the importance of groundwater in maintaining base flows in rivers and streams during periods of drought; and highlights the critical nature of groundwater in maintaining fish habitat.

The Province of BC (1984, recently updated) provides information to the public on well digging, though interaction with surface water is not listed as a consideration, nor are fish mentioned.

The topic of groundwater-surface water interactions is timely and of concern to various government agencies, First Nations, and stakeholder groups in British Columbia. Studies have been initiated regarding groundwater-surface water interactions in a few watersheds in the Okanagan Basin (a basin already the focus of stakeholder and management efforts to develop a sophisticated, accessible Fish-Water Management Tool). Initial results on groundwater-surface water interactions in the Okanagan are expected in April 2007 (Vicki Carmichael, BC Ministry of Environment, personal communication). The diverse group developing the Nicola Water Use Management Plan is keenly interested in groundwater-surface water supply and interactions, currently the area of greatest uncertainty (John Anderson, Chair, Nicola WUMP, personal communication). In July 2006, this group received provincial funding for a project to explore groundwater-surface water interactions, current water supply, and forecasting of water supply.

Groundwater depletion is an issue in the township of Langley in BC's Fraser Valley, where a groundwater model has been developed to better understand the issues. This model, necessarily approximate in nature because groundwater use is not measured in BC, revealed disturbing trends. Since a pre-development estimate of baseflows in streams, baseflows in streams fed by the four most heavily used aquifers are estimated to have declined between 12% and 70%. Further expected growth will further decrease baseflows, and one creek is predicted to have baseflows of less than zero, meaning that water from the creek will flow into the aquifer, rather than the reverse. Current information suggests that any further water withdrawals from two of the aquifers cannot be sustained without compromising baseflow in local watercourses (Golder 2005).

Other jurisdictions have similar issues and many (e.g. the United States) have more advanced problems related to prolonged overuse of groundwater. The Santa Cruz River in Arizona is dry most of the year due to groundwater pumping, but previously hosted fish as well as riparian plants and wildlife (Glennon 2002). In the Cosumnes River in California, groundwater overdraft has converted the river to a predominantly losing stream, practically eliminating base flows (Fleckenstein et al. 2004). Declining fall flows (to the point of a dry riverbed for much of the migration period between October to December) limit the ability of the river to support large fall runs of Chinook salmon that were historically present. Cosumnes Chinook are listed as an endangered species (Glennon 2002). Fleckenstein et al. examined management scenarios for the Cosumnes River, and determined that increases in net recharge on the order of 200 to 300 million m^3/year would be required to reconnect the regional aquifer with the channel and in turn re-establish perennial base flows. Options that combine surface water augmentation with groundwater management are most likely to ensure sufficient river flows in the short-term and to support long-term restoration of regional groundwater levels.

Fleckenstein et al. (2004) also mention work done by Kondolf et al. (1987) looking at the impacts of groundwater pumping on stream flows in a case study of the Carmel River in California. Groundwater withdrawal decreased or even eliminated base flows and inhibited steelhead migration. Quantity and timing of base flows were identified as crucial for fish migration. Another example of an American river affected by groundwater pumping is the San Pedro River in Arizona, which relies on declining and threatened groundwater flows to support a federal Natural Conservation Area and globally important bird habitat (Glennon 2002).

In Washington and Oregon, a watershed council (a stakeholder group supported by state legislation) and agencies have been working to restore fish flows to the Walla Walla Basin, following endangered species listings for bull trout and summer steelhead. According to Bruce McFarlane (BC Ministry of Environment, personal communication), this dry basin is instructive to BC managers. Water issues appear well advanced and severe, and thus can be illustrative of possible future issues and solutions in British Columbia. There has been a large focus on surface flows in the Walla Walla Basin (particularly since the river has a long history of drying up), but water budgets that include groundwater have been developed and are being refined. A report on surface-groundwater interactions was prepared in 2001, and an assessment of irrigation ditch losses to groundwater was done in 2003. Currently, a regional hydrologic simulation model is being developed for part of the basin, which will test scenarios of groundwater pumping, infiltration basin operations (artificial recharge that is underway – see previous section), surface water extraction, and climate change inputs (Walla Walla Basin Watershed Council 2006). Since water is taken from two aquifers as well as from surface water, the model should be able to simulate the interaction between aquifers, the artificial recharge project area, and the effect on rivers and springs (Petrides 2006).

Because ground and surface waters typically connect, extracting from one affects the other. Policies to manage ground and surface water should therefore be integrated, and this is the case in Connecticut (Brandes et al. 2005). Connecticut's Water Diversion Policy Act applies the same criteria to surface water and groundwater applicants, and unless the applicant can prove otherwise, the state will presume that groundwater withdrawal will create an equivalent

(1:1) reduction in surface flow. Europe is also moving toward integrated management of ground and surface waters; under the European Water Framework Directive, groundwater withdrawals must not exceed the average rate of recharge less the rate of flow required to achieve ecological quality objectives for associated surface waters and terrestrial ecosystems such as wetlands (Brandes et al. 2005).

In the United States, Florida and Arizona are leaders in water management (Brandes et al. 2005), probably because they have such advanced water issues. Florida's law requires Water Management Districts to establish minimum instream flows and levels for surface and groundwater within their jurisdiction, and set aside water for the protection of fish and wildlife. Withdrawal permits typically contain monitoring requirements and requirements to maintain minimum aquifer levels and provide water use reports. Arizona has had serious problems with groundwater overdraft and now is working towards "safe yield" by 2025 by developing innovative programs to achieve groundwater balance within the five areas where overdraft is most severe (Brandes et al. 2005).

In Ontario, Conservation Authorities (municipal-like water planning agencies) have had a focus on groundwater management and protection since the 2000 Walkerton tragedy, where contaminated drinking water sickened thousands of people and killed or contributed to the deaths of 21 others. In response, groundwater studies were initiated across Ontario in 2003. These studies characterized regional aquifers to assess their intrinsic susceptibility to contamination, to inventory contaminant sources, and to define wellhead protection areas. The Niagara Peninsula Conservation Authority (NPCA), one of 13 Conservation Authorities, has recently completed a groundwater study (Waterloo Hydrogeologic Inc. 2005) on minimizing groundwater contamination, managing water for sustainable use, and promoting water conservation and good well management and decommissioning practices. The study notes that groundwater feeds the only identified cold water stream in the NPCA watershed, which supports Niagara's last self-sustaining population of brook trout. A more detailed management and protection strategy is recommended for this local area. In general, the groundwater studies done or underway for areas managed by Conservation Authorities have a strong focus on water quality and source protection and do not have a strong focus on fish habitat.

In jurisdictions where groundwater extraction is regulated, extraction is often governed by the principle of 'safe yield,' meaning groundwater extraction must be balanced by natural groundwater recharge. However, Sophocleous (2002) is adamant that this does not represent sustainable use, stating: "Aquifer drawdown and surface-water depletion are two results of groundwater development that affect policy. Both are fundamentally related to pumping rate, aquifer diffusivity, location, and time of pumpage. The natural recharge rate is unrelated to any of these parameters. Nonetheless, policy makers often use natural recharge to balance groundwater use, a policy known as safe yield. However, this policy completely ignores natural groundwater discharge, and eventually leads to the drying of springs, marshes, and riverine–riparian systems that constitute the natural discharge areas of groundwater systems, as has already happened in many parts of the world (Sophocleous 1997, 1998, 2000a, 2000b). As Balleau (1988) points out, "public purposes are not served by adopting the attractive fallacy that the natural recharge rate represents a safe rate of yield."

One of Watershed Watch's initial questions regarding groundwater usage was whether the demand for groundwater by aquaculture rearing facilities might negatively affect wild fish. Literature on this subject is scarce and confounded. For instance, Marine Harvest, one of the largest aquaculture companies in the world, reports annual groundwater use – combined over all its European and Chilean operations, and combined for hatcheries and tanks – at 567 million cubic meters per year (Marine Harvest 2005). These operations use an additional 930,696 m^3 of freshwater each year, mainly for processing of fish, but no data on water use are available for Marine Harvest Canada operations "as processing is carried out by contracted third parties and the scale of farming activities is much smaller than that of Norway (Marine Harvest 2005)."

Nor did we find much quantitative information on the use of groundwater for production and enhancement (non-aquaculture) facilities, though Fisheries and Oceans Canada has published a guidance document for assessing impact on fish habitat from groundwater extraction (Ingimundson and Engelbrecht 2005), and this document includes groundwater extraction for fish hatcheries as posing a potential moderate to high risk to interactions between groundwater and surface water (and thus fish-bearing habitat). The BC Ministry of Environment (1994) acknowledge that groundwater is often essential for hatcheries, and enumerate the various public salmon and trout hatcheries in the province (approximately 30 as of 1985) that use groundwater. (This is additional to private hatcheries, including those associated with aquaculture.) The Fraser Valley Trout Hatchery, a case study described by the BC Ministry of Environment (1994), relies exclusively on groundwater, and has needed to devise a system to recycle groundwater due to the limited availability of water from the Abbotsford aquifer. Nearby test wells have been showing a decline in water levels and concern has been expressed that this may be due to groundwater 'mining.' The document does not specify if this is solely due to the hatchery or if other causes may also contribute.

We thus interviewed Don MacKinlay, a Fisheries and Oceans Canada biologist working for the Enhancement Support and Assessment Unit of the Salmonid Enhancement Program. MacKinlay, knowledgeable on hatchery operations, expressed the view that hatchery use is a non-consumptive use of water, as water is returned to the nearby watercourse. Additionally, he indicated that hatcheries are always located next to significant streams, and use only a small fraction of the abundant water supply (though this does not coincide exactly with the experience at the Fraser Valley Trout Hatchery, above).

MacKinlay also believes that hatchery extraction of groundwater sometimes benefits wild fish, as hatchery outflows may create more permanent and stable habitat where previously only ephemeral habitat existed. An example is Inch Creek in the Fraser Valley, where groundwater pumping for a hatchery means that a floodplain channel now flows with groundwater year round instead of seasonally. MacKinlay emphasized the importance of groundwater to hatcheries: the water is clean and disease free, and its temperature difference can be an advantage. (Groundwater is usually clean but sometimes does not meet drinking water or aquatic life standards, particularly when it is contaminated by land use activities.) MacKinlay acknowledges that the water may not be disease free once it leaves the hatchery. We did find one study (Kolodziej 2004) noting the presence of hormones in hatchery effluent, but this paper also notes the same concentrations were found in a natural stream at spawning time.

5. Groundwater-fish management needs and approaches

According to the BC Ministry of Environment (1994), long-term effective groundwater management in BC will require legislation that is coordinated with users and with those who have jurisdiction over all activities that impact on the resource. Considerations for long-term groundwater management in British Columbia described in this 1994 document include inventory, mapping, protection, legislation, land use, monitoring, coordination, and increased funding.

According to Brandes et al. (2005), instream flows must be determined and protected on a watershed-by-watershed basis, and potentially for each river on a reach-by-reach basis, to ensure that no part of a river's flow is significantly affected. Similarly, groundwater balance must be considered on a catchment-by-catchment basis. Such a system is in place in other jurisdictions such as Florida and Arizona (Section 4).

Gartner Lee et al. (2002) developed a document for the Ontario Ministry of Environment that describes the determination of instream flows for fish relative to water extraction in the following manner: numerous methodologies are proposed and applied, but "currently no scientifically defensible method exists for defining the instream flows needed to protect particular species of fish or aquatic ecosystems" (Castleberry et al. 1996). Gartner Lee et al. quote Orth (1987) in saying that the expense of increasing our knowledge base may not be feasible for agencies to consider. In response, they believe that more comprehensive responses to altered flow regimes will be needed before simpler and less costly methods evolve. Evaluation tools are required to predict the effects of change on fish habitat, particularly as project approvals must comply with the Federal Fisheries Act, which directs that there be no harmful alteration, disruption or destruction of fish habitat.

This same document also describes site-specific investigations (potentially within a watershed framework) to determine the effect of groundwater extraction. At a minimum, the present practice to be followed is: geologic investigation, test well construction and pump testing for aquifer yield, and site specific water budgets and hydrogeological studies for larger takings. Where the possibility of interference with ecological features (e.g. streams and wetlands) is identified, longer pump tests (e.g. one week to three months) and more specialized instrumentation (e.g. piezometers to measure vertical hydraulic gradients, or in some cases seepage meters) are required. Seasonal differences and habitat requirements need to be taken into account with timing of pumping tests, and monitoring and documentation of actual effects is key. Ideally this is done within a watershed framework, which typically requires agency involvement with water modeling and use of regional data.

According to Rick Palmer (Gartner Lee expert, personal communication 2006), current pilot projects to determine appropriate levels of groundwater pumping near small brook trout streams have been ongoing in Ontario. Gartner Lee have found that the most effective approach is a multi-disciplinary effort that involves pumping tests (at varying levels of extraction) in concert with monitoring surface flows and groundwater gradient, and field observations of changes to fish habitat and fish behaviour. This is more effective than typical modeling approaches based on limited data, but is also expensive and labour intensive. This adaptive management approach is best done over several years to determine water-taking effects, and hence is not practical for determining water-taking thresholds in most cases. The approach is still being refined.

Scale is an important issue in groundwater management for fish. Sophocleous (2002) reiterates the challenge of linking processes at multiple scales, stating that upscaling from reaches to watersheds remains a major research and management challenge. (Sophocleous also notes that the present inability to characterize subsurface heterogeneity exacerbates the upscaling problem and leads to great uncertainties in data interpretation.) Ebersole et al. (2003) and Borwick et al. (2006) have attempted to translate site-specific groundwater habitat use by fish into a larger-scale context that will allow for management and conservation of fish habitat. While both these studies are not necessarily transferable to other areas, they do highlight the necessity and difficulty of taking a watershed-scale approach. In the Cosumnes River in California, detailed modeling has provided a basis for a watershed approach to restoring groundwater base flows as well as surface flows; this is done at a coarse scale. To develop a detailed management strategy to restore fall flows, a model with more spatial and temporal detail will be required (Fleckenstein et al. 2004).

The Nature Conservancy (Brown et al. 2005) discuss ways to link groundwater to biodiversity (including fish) at a watershed scale. They have developed a set of tools and an approach for the Deschutes River Basin, Oregon, that they hope will translate to other areas in the Pacific Northwest. They believe that these tools are technically sound yet accessible to non-hydrologists.

Temperature is a major theme with respect to groundwater-fish interaction. Poole and Berman (2001) provide detailed discussions on heat energy exchange and transport within stream systems, because these processes provide great promise for successful stream temperature management. The relative importance of groundwater in this equation will vary spatially along with climate, stream morphology, and riparian canopy condition (Sullivan and Adams 1991).

One obstacle to managing for fish flows and other resources is the long-term data required to understand groundwater/surface water interaction and development-related changes to flows. Pucci and Pope (1995) have developed a simulation of the effects of groundwater development on surface water discharge for an area in the eastern U.S.A. This simulation estimates pre-development flows, and can compensate for lack of data in determining management decisions.

Power et al. (1999) make a number of good points regarding groundwater management: "Since groundwater exerts such an important influence on river habitats, its quality, quantity and sustainability should be considered before development proposals are approved which could alter it. Examples of the role of groundwater in the ecology of some species show how localised and critical habitats influenced by groundwater can be, and, as a consequence, how necessary it is to protect them. Protection is complicated because groundwater distribution pathways are often unknown and recharge areas may be remote from discharges. Scale becomes important in identifying potential risks to critical stream habitats from all types of landscape modification and water abstraction. Groundwater temperatures reflect mean annual air temperatures and are likely to change as global climates respond to increases in greenhouse gases in the atmosphere. This could profoundly change critical fish habitats, particularly those at the margins of species distributions or those that are already overcrowded. Such considerations emphasise the importance of developing proper strategies for the conservation of groundwater."

Power et al. also stress the need for connectivity between groundwater refuge areas. Connectedness of randomly spaced winter and summer refugia, staging, nursery, and feeding habitat is essential. Isolation of species in small habitats prevents genetic exchanges between units of stock, with risks of extinction. Restricting species access to critical habitats similarly leads to extinction (Powers et al. 1999).

Conclusions

The importance of groundwater to fish is clear but not always adequately considered. Many studies document the reliance of different species of salmonids on groundwater for key habitat needs, and in many cases, for their very survival in streams with high ambient temperatures. Powers et al. (1999) provide a useful summary of fish reliance on groundwater and management considerations, while Fleckenstein et al. (2004) describe a river with severe problems related to groundwater extraction and fish habitat, and drastic management measures to restore flows. Management approaches in the Walla Walla Basin in Oregon and Washington are also instructive to BC water managers and users. The severe water shortages and related issues seen elsewhere are potential future scenarios for many areas in BC if groundwater extraction is not better regulated and its link to surface water accounted for in water management decisions. Our ability to measure and manage water would also be improved by better data on use of water in hatchery and aquaculture operations. Much of the literature calls for better protection of groundwater for fish habitat needs, yet does not provide specific guidance for how this might be done. This may not be surprising, given that management solutions are usually linked to local issues and governance, and because of the difficulty and expense of monitoring and managing groundwater at a basin-wide scale.

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