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Issues of Stream-Aquifer Interactions in Grout Lined Channels in Urban Watersheds

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Abstract: Grout lined storm drains are used worldwide to convey storm runoff away from urban areas. They also convey dry weather flows such as car wash runoff, lawn runoff, and other "nuisance flows" in urban centers. Areas in Southern California and elsewhere have shallow water tables where dry weather flows in grout lined storm drains consist primarily of perennial groundwater baseflows. In these areas, groundwater leaks through cracks, joints, weepholes, and intentional dewatering structures into storm drains and eventually flows into natural channels, coastal wetlands, and estuaries. The "lined" sections of these channels are not always impervious; in fact, the lining of the channels often affords excellent opportunities to collect groundwater samples at discrete points that are usually not present along unlined channels where well control is sparse or where technical or legal issues prevent installation of piezometers. Frequently, as much as 95% of the nutrient and trace element loading to urban catchments during dry weather is from seepage of groundwater that is laden with pollutants. This project presents several examples of our experiences in conducting stream/aquifer studies in lined and semi-lined channels in Southern California. Sub-projects include evolution of groundwater quality along flowpaths, detection of unwanted recharge mounds in shallow groundwater systems due to leaky water main pipes, and comparisons of water quality in lined and unlined sections of a creek. Tools that are utilized and described in the paper include isotopic tracers; trace element and standard inorganic constituents; and innovative sampling methods.

Keywords: *stable water isotopes, urban groundwater, selenium, nitrate, hyporheic zone, liquefaction*

In urban areas many channels are lined with grout concrete. Some creeks are lined nearly 100% along their full extent, while others may be lined only beneath bridge overpasses. These channel linings are installed in order to route stormwater runoff away from urban areas as fast as possible and to protect urban infrastructure from erosion. One does not usually think of conducting research of stream/aquifer interactions along grout lined channels since the channels are often considered to be impervious to fluid flow, but typically they are not completely impervious. In this paper, we document our experiences in evaluating stream/aquifer interactions along grout lined storm drains and channels. The topics include descriptions of conduits as pathways for fluid flow between lined channels and groundwater. Three case studies of stream/aquifer interactions are also described including technical and policy issues related to local water resources management. Pertinent additional topics are addressed, including problems of composite sampling along lined channels, discussion of safety issues for any personnel engaged in this type of work, and discussion of opportunities for conducting research.

Channel Lining and Permeability Conduits along Lined Channels

Lining of channels is known to reduce streambed permeability and is done to reduce infiltration from rivers to underlying aquifers (Leggat and Davis 1966; Meyer 1976; Coachella Valley Water District 2006). Lined channels are not impervious to fluid flow and may in fact be moderately permeable depending on channel construction and

condition/weathering of the grout lining (Hibbs and Sharp 2012). Conditions vary but the flux between groundwater and surface water along lined channels generally depends on: 1) density of cracks and separation voids in the channel lining, 2) abundance and density of weepholes, 3) hydraulic conductivity of aquifer and hydraulic gradient near the channel, and 4) general construction and condition of the lined channel.

Typically, flood flows temporarily reverse hydraulic gradients in normally gaining urban channels, creating brief periods of aquifer recharge through the same weepholes that were installed to direct groundwater into the channel. Where many orifices exist, aquifers connected to lined stream channels can receive moderate amounts of recharge during flood flows due to higher head in the channel.

We have identified many types of permeability conduits along grout lined channels. The most common type is the weephole, installed along channel sides and bottoms to allow groundwater to seep out into the channel, thus lowering the water table (Figure 1). Weepholes reduce pore fluid pressure on the channel lining, thereby protecting the lining from cracking and degradation due to excessive pressure (Colorado Department of Transportation 2004). Weepholes are usually constructed with PVC pipe installed into the grout lining of the channel. The PVC pipe extends back behind the wall of the lining (Figure 1). Weepholes usually flow between 1 to 5 gallons/minute, although some may flow a little more than a fraction of a gallon per minute. Other weepholes occasionally exceed 15 gallons/minute. In watersheds in semi-arid areas such as Los Angeles, many creeks and streams are completely lined and groundwater baseflow along these permeability features reaches 100%. Frequently where channels have intermittent linings, groundwater seeps out in quantity along the lower end of the lining just where a section of unlined channel begins.

Weepholes are commonly found along open rectangular, open trapezoidal, and underground rectangular storm drains and channels (Figure 1). We have not found weepholes in circular grout lined storm drains. Presumably this is because the circular structure of the channel is strength-resistant to fluid pressure. Weepholes are not needed to reduce pressure in a circular drain because any orifice that is installed in a circular drain will weaken the overall integrity of the circular structure. However, we frequently found groundwater seeps along the joints between sections of circular pipe in circular storm drains (Figure 2). Some of these seeps were quite prominent and created a type of artesian groundwater flow emanating from the joint.

Secondary permeability conduits along cracks and cave-ins, created by settling or subsidence near a channel, are other important features in grout lined channels. The flux of water and solute occurs between channels with conduits and shallow aquifers. Permeability voids develop due to collapse features where subdrains merge with main drains in grout lined channels (Figure 3). Groundwater flow through these partings may exceed 0.2 cfs. These estimates were derived in some cases from chemical mass balance of distinctive input parameters in groundwater, and more often from channel gaging directly upstream and downstream of the channel parting input. Additional seepage features include ordinary cracks and voids caused by aging and breakdown of pipes and lined channels. In some cases, the original weepholes no longer function because secondary joints and cracks at channel grade allow groundwater to discharge into the channel (Figure 3).

Groundwater discharging into lined channels also occurs due to temporary and permanent groundwater dewatering infrastructure. Temporary dewatering equipment is used when construction is being done and when water table lowering is required; for example, during subsurface construction. Temporary dewatering systems may be active for weeks to months and may be replaced by passive French drains or other permanent dewatering apparatus when the construction project is completed (Figure 4).

Shallow groundwater dewatering facilities lower the water table near construction sites, bridge underpasses, and high rises. Permanent dewatering structures may be used where basements or road underpasses are installed near urban structures (Figures 5 and 6). Frequently, groundwater dewatering flows contain excessive nutrients, trace elements, and organic contaminants that are discharged to storm drains (Hibbs and Sharp 2012).



Figure 1. Weepholes installed along the sides and bottom of trapezoidal grout-lined channels.



Figure 2. Circular storm drains with groundwater flowing through the joint between sections of pipe.



Figure 3. Groundwater flowing through partings and degraded linings of underground and aboveground storm drains.

Many older dewatering operations that discharge to storm drains are not archived in as-built plans and are detected only when underground inspections are done. Older, permanent dewatering operations are sometimes grandfathered by regulators. In such cases, solute-laden groundwater continues to flow unabated into storm drains (Hibbs and Sharp 2012).

In Figures 5 and 6 we show permanent, high discharge and low discharge dewatering units. These designs incorporate an underground dewatering sump that passively collects groundwater until the sump is filled. The water in the sump is then pumped out into the channel when a check valve indicates the sump is ready to be evacuated. In these types of dewatering systems we have observed pumping cycles occurring every ten minutes to two hours with a five to twenty-minute pumping period. Other systems have been reported to cycle for only a few minutes once or twice daily. The frequency and duration of pumping is a function of the hydraulic gradient toward the sump and aquifer permeability.

Some channel linings provide armoring and are permeable to fluid flow. In one such case a permeable armoring was placed along part of upper San Diego Creek in Orange County, California (Figures 7 and 8). The permeable lining was expected to provide channel stability while offering semi-riparian channel habitat. Unfortunately, the extreme liquefaction potential along this channel led to the destruction of the pervious armoring during a flood when the liquefaction made the stream sediments highly unstable (Figure 7).

Motivation for Studies of Stream/Aquifer Interactions along Lined Channels

Many groundwater sampling orifices in grout lined channels can be integrated in studies of stream/aquifer interactions. Owing to the frequent lack of shallow well control along urban channels, these orifices can provide a means to collect groundwater issuing into surface channels. Orifices emitting groundwater along grout lined channels provide supplemental data as needed when there is limited shallow well control (Hibbs and Lee 2000; Meixner et al. 2004). Sometimes the orifices along lined channels provide the only groundwater data in a study (Hibbs et al. 2012; Bardsley et al. 2015). In addition, well purging and disposal of excess purge water is not required in contaminated settings because weepholes and other orifices discharge groundwater directly into the channel.

Demonstration Case Studies

We describe three of our case studies to illustrate methodology and to demonstrate effectiveness of research projects in grout lined channels (Hibbs and Lee, 2000; Hibbs et al. 2008; Harrison and Hibbs in press). The first case study documents groundwater evolution along a flowpath leading to an important hypothesis of trace element release in a sensitive terrestrial watershed. The second case study documents use of stable water isotopes to detect unwanted leakage from an underground water main. The third case study compares redox processes and pollutant loading in stream/aquifer systems that are both lined and unlined.

Case Study 1: Hydrochemical Evolution along a Groundwater Flowpath

A study in El Modena Channel in San Diego Creek Watershed of Orange County, California demonstrates important stream/aquifer interactions associated with changing land use activity along this lined channel. El Modena Channel flows into the main stem in the watershed, Peters Canyon Wash (Figures 8 and 9). Near-channel groundwater sample points included four weepholes (EMW-1weep, EMW-2weep, EMW-4weep, EMW-Wweep) and a shallow water well in the dividing area between Peters Canyon Wash and El Modena Channel (CW1-2D) (Figure 9). These weepholes and water wells are oriented along a groundwater flowpath oriented subparallel to the direction of surface water flow in Peters Canyon Wash and El Modena Channel (Figure 9). This channel begins above, and later enters a land region that was once occupied by a large regional marsh known as the "Swamp of the Frogs Marsh" (Hibbs 2001). The channel is lined along the whole reach investigated.

Chloride, sulfate, and selenium data collected from weepholes and from the shallow water well are plotted as bar graphs and line graphs (Figures 9 and 10). The graphs indicate that selenium and sulfate increase significantly between Bryan Avenue and Walnut Avenue. In this region, selenium increases from a low value of 20 μg/L (weephole EMW-2)



Figure 4. Circular storm drain with groundwater constantly discharging from a French drain dewatering apparatus that extends laterally beneath a residential area.



Figure 5. Small discharge dewatering operation that cycles every 40 to 50 minutes when an underground sump fills up with groundwater. The sump is then pumped out for 10 to 15 minutes.



Figure 6. Large discharge dewatering operation that cycles every 50 to 60 minutes when an underground sump fills up with groundwater. The sump is then pumped out for 10 to 15 minutes.



Figure 7. A permeable stream bed lining installed, San Diego Creek. The high liquefaction activity in this stream (see quicksand photo) led to the destruction of the permeable lining after a series of storms. Photo credit, Henry Jones.

to a high value of 178 µg/L (weephole EMW-W) along the groundwater flowpath. Sulfate increases simultaneously from a low value of 458 mg/L (weephole EMW-2) to a high value of 1430 mg/L (weephole EMW-W) as groundwater flows down the hydraulic gradient. Chloride concentrations do not increase proportionately to sulfate and selenium concentrations along the hydraulic gradient. Chloride varies from a low of 189 mg/L (weephole EMW-2) to a high of 251 mg/L (weephole EMW-weep) in the other wells and weepholes (Figures 9 and 10).

Hibbs and Lee (2000) and Hibbs (2001) speculated that groundwater evaporation alone could not explain selenium enrichment in groundwater; otherwise, the conservative chloride ion would become similarly enriched. Chloride concentrations are fairly constant in groundwater in the data set. Therefore, evaporation cannot be the primary agent enriching sulfate and selenium along the groundwater flowpath. This led to the hypothesis of selenium remobilization from reduced forms in the Swamp of the Frogs Marsh. Hibbs and Lee (2000, p. 40-41) discuss the geologic source of selenium and sulfur in shallow groundwater in marsh sediments:

> *"During the historic period of the Swamp of the Frogs Marsh, any forms of selenium and sulfur that flowed into the marsh were probably derived from surface runoff from the highlands in the oxidized forms (SeO_4^{2-} and SO_4^{2-}). Once the oxidized forms of selenium and sulfur reached the anoxic waters of the marsh, these oxidized species were probably reduced to SeO_3^{2-}, elemental Se(0), Se^{2-}, H_2S, and HS^-. These forms would be expected to be removed from the waters in the marsh and sorbed onto solid particles, precipitated as crystalline and amorphous polymorphs, or transformed into volatile gases.*
>
> *Once immobilized in solid forms, the selenium and sulfur solids would tend to remain stable in the soil substrate as new sediments and organic matter in the marsh continued to accumulate. When the Swamp of the Frogs Marsh was drained in the late 1800's and early 1900's, the shallow subsurface was transformed into an oxic environment. In fact, the shallow groundwater flow system today is being recharged by oxygen-enriched water that retains some dissolved oxygen as it flows through the old marsh deposits. The groundwater data collected during this study indicate that groundwater contains relatively high concentrations of dissolved oxygen (usually 0.3 to 5 mg/L), very high ratios of dissolved nitrate to nitrite, and the general absence of iron and manganese. These hydrochemical signatures indicate an oxic groundwater flow system.*
>
> *Oxidizing groundwaters flowing through the old marsh sediments today remobilizes the bound forms of selenium and sulfur into their oxidized and mobile forms (SeO_4^{2-} and SO_4^{2-}). Thus, we can account for high sulfate and selenium in groundwaters in large part from remobilization of reduced forms of selenium and sulfur as oxic waters flow through the historic marsh sediments."*

This primary set of observations along El Modena Channel and additional data collected along unlined and lined channels in the catchment resulted in expanded studies in San Diego Creek Watershed. In the subsequent work we investigated the release of toxic trace elements from the Swamp of the Frogs Marsh, including selenium and arsenic. Today the hypothesis of selenium mobilization from the Swamp of the Frogs Marsh is widely accepted and recognized by the technical hydrological community (Larry Walker and Associates and CH2M Hill 2007; Presser and Luoma 2009; Daniel B. Stephens & Associates, Inc. 2013).

Case Study 2: Use of Stable Water Isotopes to Detect Leakage from an Underground Water Main

Another example of a baseflow-fed drain includes Valencia Drain in San Diego Creek Watershed. Valencia Drain flows into Peters Canyon Wash (Figures 8 and 11). Baseflow was confirmed by analysis of hydrochemical constituents (e.g., selenium, nitrate) emitted by the drain, and by underground inspection of the drain where we found many flowing weepholes and flowing seams inside the drain. The discharge from this storm drain is typically 0.75 to 1.25 cfs during dry weather flows (Meixner et al. 2004).

Samples were collected inside Valencia Drain for measurement of selenium and arsenic species, other inorganic species, and stable isotopes. Our discussion in this paper covers stable water isotopes analysis (O, D) only. A large number of flows from seams and weepholes were sampled for water isotopes during dry weather conditions (Figure 11). Sample stations in Figure 11 are labeled by distance from Peters Canyon Wash to the point in the drain where the sample was collected, in feet. Valencia Drain is oriented almost perfectly in-line with a groundwater flowpath in the shallow aquifer. IRWD well 86N is very close to Valencia Drain and was included in the analysis. This well is the upgradient point in flowpath analysis.

Previous samples collected for isotope analysis from springs, weepholes, and water wells near Peters Canyon Wash plot along an evaporation water line of locally derived water (Figure 12). This identified a local groundwater evaporation line. Most groundwater depths in the Peters Canyon Wash and San Diego Creek area are shallow, sometimes only 6 to 8 feet beneath the land surface. In these areas, groundwater evaporates partially

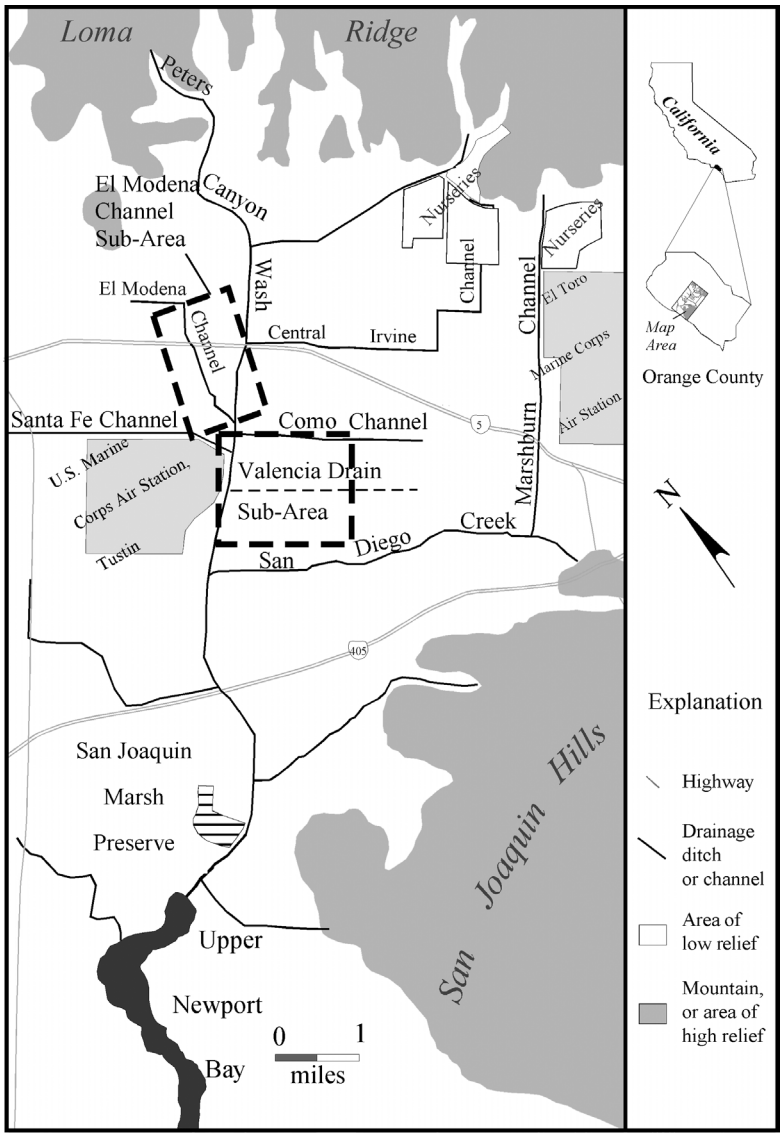

Figure 8. San Diego Creek Watershed showing index subareas for El Modena Channel (Case Study 1) and Valencia Underground Drain (Case Study 2).

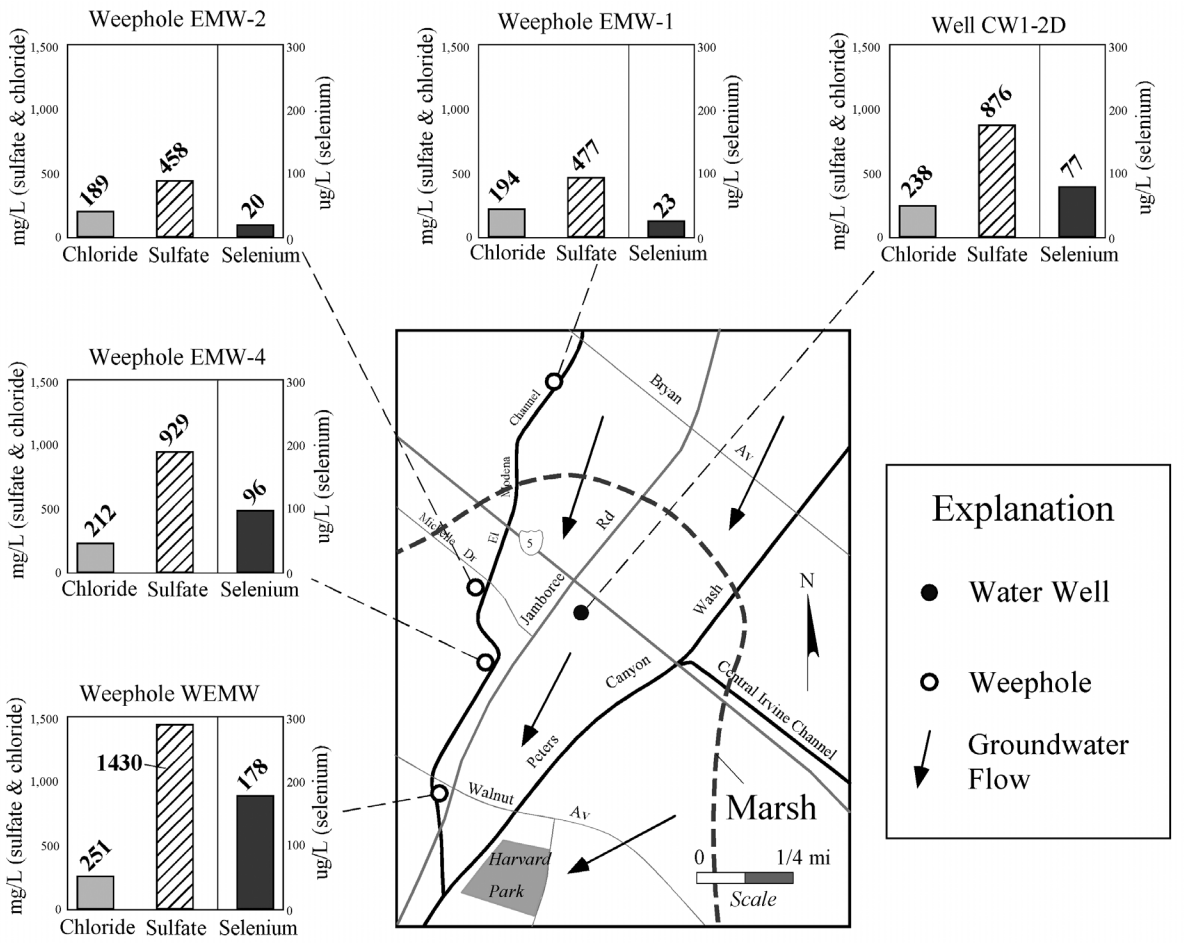

Figure 9. Weepholes and a shallow monitoring well were sampled along a groundwater flowpath along El Modena Channel, showing rapidly increasing sulfate and selenium concentrations down the hydraulic gradient, with little increase in chloride, suggesting a geological source of selenium and sulfate.

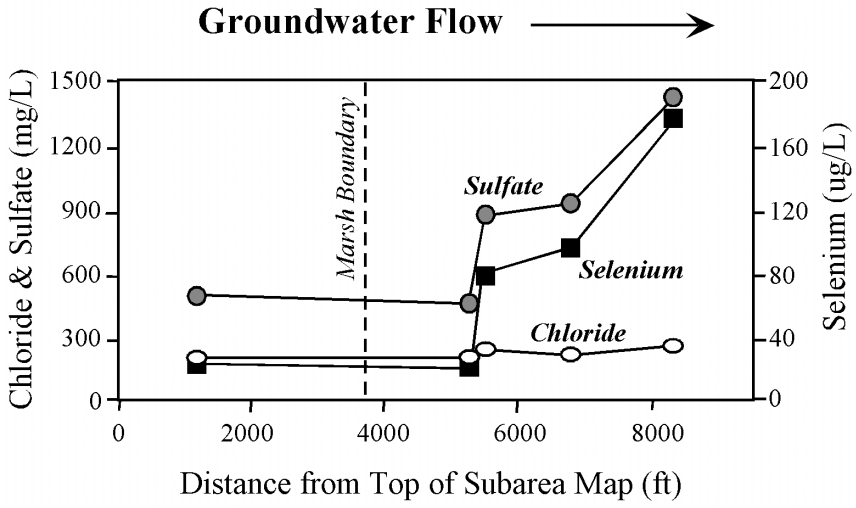

Figure 10. Data from Figure 9 denoting the step increase in sulfate and selenium concentration when groundwater flows across the Swamp of the Frogs Marsh boundary (stipled line). Chloride does not increase significantly along the groundwater flowpath.

by a wicking effect as atmospheric winds create venting of soil vapor, allowing physical evaporation of groundwater. Fine textured soils allow capillary rise up to a few feet above the water table, which can accelerate evaporative effects. Evaporation of soil moisture or irrigation water is also possible prior to recharge, and may explain evaporative effects shown in Peters Canyon Wash and San Diego Creek isotope samples (Figure 12) (Clark and Fritz 1997; Song et al. 2009; Wang et al. 2012).

Most of the data collected from Valencia Drain plot very close to the evaporation line developed for shallow groundwaters in the Peters Canyon Wash area, clustering within the region identified as "Local Water" (Figure 12). Other points plot along a mixing line between the region identified as "Local Water" and "State Project Water." State Project Water is imported from the California State Water Project system in Northern California and is isotopically distinct from local water in the Los Angeles Basin. In recent studies by the U.S. Geological Survey (Reichard et al. 2003), the isotopic signature of imported State Project Water was identified in the Los Angeles Basin. Imported State Project water ranges narrowly about a mean of around -9.5 per mil del ^{18}O and -75 per mil del D (Reichard et al. 2003). Sample point 3534 ft in Valencia Drain is also in this range, identifying this sample as almost entirely sourced from imported State Project Water (Figure 12).

The reason for recharge of State Project Water near a section of Valencia Drain was due to a prominent subsurface water main pipe leak. This fact was established after our findings were reported to Irvine Ranch Water District when the suspected leak was confirmed. The leaky pipe was

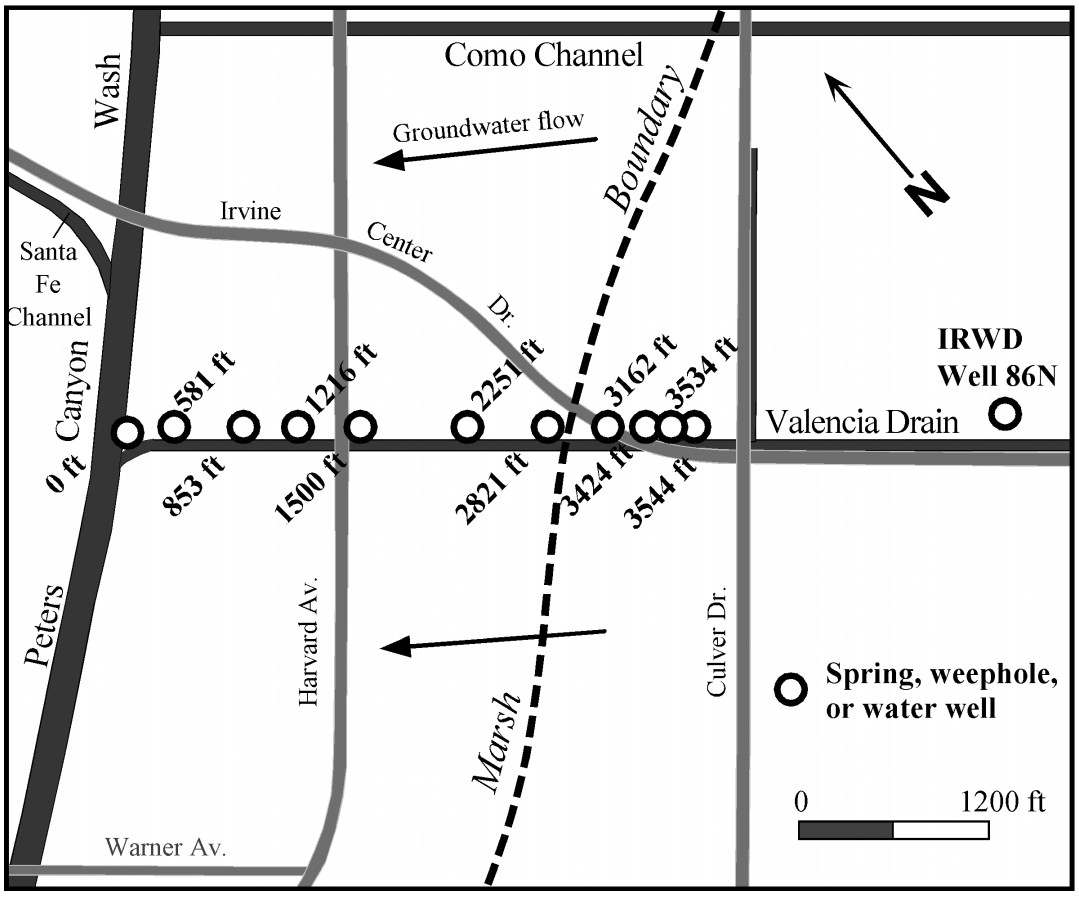

Figure 11. Groundwater sampling points in Valencia Underground Storm Drain include weepholes, channel partings, and a shallow observation well (IRWD Well 86N) installed adjacent to the storm drain.

subsequently repaired (Norris Brandt, personal communication 2006). Other samples have mixed proportions of State Project Water and Local Water (Figure 12). The underground studies identified an area of unwanted leakage from a large underground water main and allowed a water loss to be stopped.

Two years after this leak was identified by isotopic analysis, we returned to sample the weepholes inside the drain. We found that subsequent flows showed little to no imported State Project Water. Apparently after repair of the unwanted leak, most of the imported State Project Water that had recharged the aquifer near Valencia Drain had discharged into the drain and/or mixed with native groundwater. Dilution and outflow accounted for the absence of State Project Water two years after the leak in the water main was first identified and later repaired.

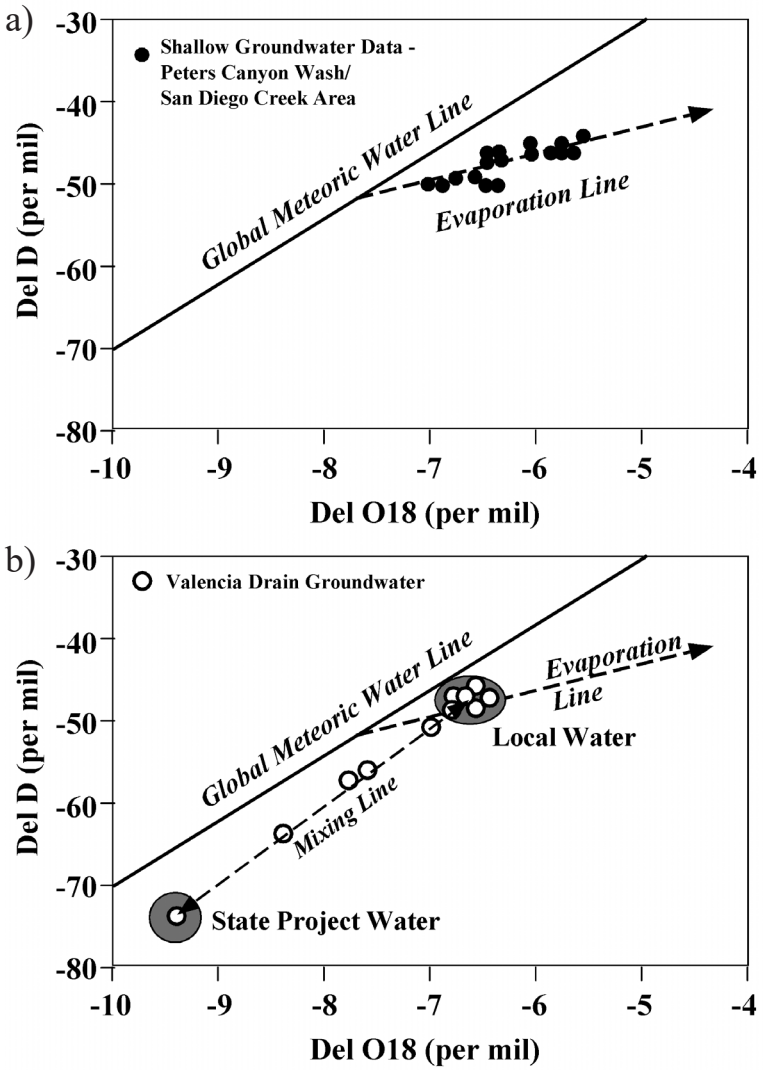

Figure 12. Oxygen and hydrogen isotopes in shallow groundwater in the study area. Figure 12a shows samples collected from springs, weepholes, and shallow water wells in the sub-regional vicinity of Peters Canyon Wash and San Diego Creek, following an evaporation line. Figure 12b shows groundwater data collected from within Valencia Drain, including waters that are derived from local precipitation and waters containing mixtures of imported State Project Water. Most samples cluster along the local evaporation line and are locally derived, but a few samples trend toward the isotopic region defined as State Project Water. Those samples lying along a mixing line with State Project Water obtain their isotopic signature from leakage of a water main pipe into the shallow aquifer adjacent to Valencia Drain.

Case Study 3: Comparative Issues in Lined and Unlined Channels

Frequently channels in urban settings include lined and unlined reaches at various locations. For example, sometimes the rate of groundwater seepage is so great that it is impossible to install a lined channel along a certain reach due to high fluid pressures. This type of a situation is found in part of San Diego Creek in Orange County, California (Sprotte et al. 1980) and along the "narrows" of the Los Angeles River, near Griffith Park (Brown 1975; James M. Montgomery, Inc. 1992). In other cases, unlined channels are retained for aesthetics and for the benefit of wildlife habitat and recreation.

Dynamic redox processes occur during stream/aquifer interactions in unlined channels due to the presence of hyporheic zones. Hyporheic zones are vegetation/carbon rich saturated areas occupying streambeds and streambanks adjacent to unlined open channels. Biogeochemical processes are operative in hyporheic zones due to plant and animal respiration, organic matter decay, and fluid flux caused by fluctuating stream hydraulic head. Such dynamic processes are restricted along concrete-lined channels.

Hyporheic zones are often suboxic to anoxic due to large amounts of decaying organic matter contained in them. While such conditions may be spatially and temporally transitory depending on scour and fill processes, the bulk of the time suboxic to anoxic conditions exist in hyporheic zones remaining favorable for processes such as denitrification, trace element speciation/removal, and organic contaminant degradation. Aquifer flow through hyporheic zone to stream often transitions respectively from oxidizing, to reducing, to oxidizing conditions, providing a robust set of transitioning processes influencing contaminant attenuation and removal.

Differences in redox conditions beneath lined and unlined channels bring up two important topics. First, from a regulatory perspective, grout lined channels do not have the natural bioremediation potential offered by the hyporheic zone as seen in unlined channels. Consequently, lined channels are likely to have greater contaminant loading via groundwater seepage through weepholes and other seepage surfaces along lined sections. This may become an especially significant problem where grout lined channels discharge into sensitive environments such as lakes, marine environments, and marshes. With respect to the main thrust of this paper, the presence of a stream with and without grout linings along alternating reaches offers excellent research opportunities for comparing variable redox processes in proximal lined and unlined sections.

An example is summarized in our current study in El Camino Real Creek in the Malibu Creek Watershed of Southern California. Here we have identified springs and seeps emanating from unlined and lined parts of the creek. Groundwater seeps along lined segments of the channel emit higher nitrate and selenium with low concentrations of manganese and iron (Table 1). This suite of parameters is indicative of oxidizing conditions in the aquifer because dissolved oxyanions of selenium and nitrate are stable in oxic waters, while iron and manganese remain stable as oxide cements that are mostly insoluble

Table 1. Comparison of redox sensitive parameters in unlined and lined groundwater discharge orifices in El Camino Real Creek, Malibu Creek Watershed.

Station	Conductivity (uS/cm)	NO_3-N (mg/L)	Se (ug/L)	Mn (ug/L)	Fe (ug/L)
Weephole 1 lined	4444	4.9	27.0	0.5	10.0
Weephole 2 lined	4436	6.8	36.0	36.0	30.0
Spring 1 unlined	4481	0.3	1.0	19,000	5100
Spring 2 unlined	4680	0.3	1.1	1100	180

in oxidizing waters. The slightly to moderately saline water derives from dissolution of gypsum contained in Miocene marine shale units from which groundwater issues.

Groundwater issuing from springs along the unlined section of the channel flows through a hyporheic zone and contains relatively low concentrations of nitrate and selenium and higher concentrations of manganese and iron (Table 1). This suite of parameters is demonstrably associated with reducing conditions. The reducing environment removes nitrate due to denitrification and dissimilatory nitrate reduction while reducing selenium to low solubility forms (as discussed in case study 1). Furthermore, the iron and manganese oxides in the sediments in the hyporheic zone are reduced into their soluble forms, Fe^{2+} and Mn^{2+}. This suite of data explains why iron and manganese are elevated in springs issuing from unlined sections of the creek (Table 1). Nitrate and selenium concentrations are of greatest concern with respect to pollutant loading to the receiving waters, and these are elevated in springs issuing from weepholes along lined channels (Table 1). Other details on chemistry of streamflow and loading of baseflow in local streams are found in Harrison (2016).

In summary, the hyporheic zone has been found in our research to remove nitrate and selenium through denitrification and trace element reduction to low solubility forms and inert gases. The carbon and vegetation-rich environment beneath unlined channels is demonstrably associated with the removal of nitrate and selenium in groundwater as it flows into open channels. This occurs due to suboxic to reducing conditions created by the organic matter decay and carbon production in the hyporheic zone. Such processes are usually absent along grout lined channels, where conditions often remain oxidizing. In these areas, groundwater seeps through the lining of the channel, unabated by complex biogeochemical removal processes observed where hyporheic zones are present.

Composite Sampling and Sample Reliability Issues

Regarding sample reliability, another concern focuses on the coarse textured material that is frequently constructed as an inert base below concrete drainage infrastructure. This material is installed to prepare a firm, non-corrosive base below the concrete lining of a channel or drain. Coarse textured material is more permeable than most shallow aquifer material and it may act as a sink to groundwater flow, creating lateral flow pathways underneath and alongside a drain or channel (Figure 13). Composite mixing of groundwater (compositing) can occur in such instances, making it difficult to decipher hydrochemical processes developing along groundwater flowpaths. This problem is not uniquely restricted to grout lined channels. Similar compositing issues arise in conventional hydrogeological studies where screens of high capacity water wells penetrate multiple intervals in an aquifer. In such cases wells also provide an integrated composite water quality sample.

In the case of grout lined storm channels, it is necessary to determine if a composite sample might be obtained at a sample point. The chance of this happening is minimized when the water table adjacent to the concrete lined channel is more than a foot above channel grade. In our studies we have been fortunate not to have experienced many cases of severe composite sampling. Weepholes, cracks, and other groundwater sampling orifices provided water quality values that appear to be directly related to the aquifer strata in the immediate vicinity of the orifice sampled (Hibbs and Lee 2000; Meixner et al. 2004; Hibbs et al. 2012).

Losing or gaining stream reaches are easily determined where shallow well control is available near the channel. Hydraulic head differences between stream and interconnected aquifer make this determination possible. Analysts must take care to assure that well control is not collected from a small, localized perched aquifer system however. Where well control is not available, the input from groundwater may be assessed by gaging upstream and downstream of segments of channel and by assuring that any influent waters along the gaged reach are not from urban runoff. Visual inspection for urban runoff conduits and flows are usually done. Where hydrochemical differences exist between urban runoff and shallow groundwater, conservative environmental tracers can make it a routine analysis to determine if the stream

reach in question is a gaining or losing reach. If it is a losing reach, there will be little change in chemistry between upstream and downstream segments of the monitored segment of stream. If it is a gaining reach, the influent groundwater will result in chemistry changes where tracer concentration in groundwater and urban runoff are significantly different, and where the amount of additive baseflow along the characterized reach is more than 5 to 10% of total streamflow.

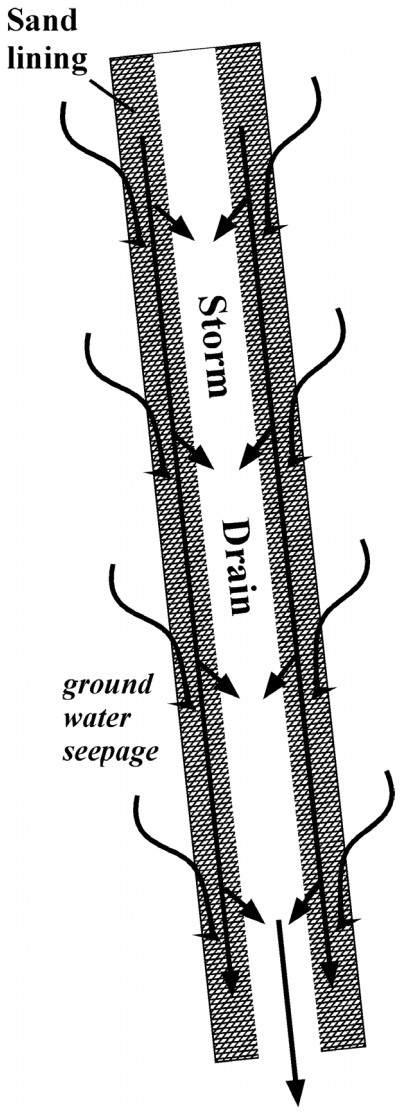

Figure 13. Groundwater compositing along a grout lined channel or storm drain can result in undesirable mixing. Groundwater compositing is limited when the hydraulic gradient of the aquifer is directed sub-perpendicular to the drain.

A question has come up during our discussions of this methodology. Does the grout lining affect the hydrochemistry in the groundwater emitted at the orifice? In our sampling comparisons between shallow wells and adjacent weepholes we have noted no significant irregularities or differences in groundwater quality with respect to general minerals, trace elements, and environmental isotopes. We have observed mineralized surfaces that build up on the walls of the concrete, thus isolating concrete surfaces from direct contact with groundwater (Figure 14). Given the usually high rate of flow that often occurs through the concrete orifices, it is improbable that hydrochemical interactions occur to any noticeable degree between concrete lining and groundwater flowing through the orifice. Accordingly, we feel that weepholes, cracks, and other orifices in lined channels generally provide reliable groundwater chemistry data.

Safety Issues

This work presents several potential hazards. The main hazard is operating in confined spaces due to the possible presence of toxic gases caused by runoff of accidental or purposeful spills of chemicals from industrial and residential areas. Extreme hazard can develop in such cases due to the possibility of respiratory poisoning. While operating in confined spaces it is essential to have gas sensors, air tight goggles, and emergency oxygen breathing equipment available. Only the most experienced personnel should engage in studies in confined spaces.

Another concern includes wildlife that occupies lined channels and tributary subdrains. We have encountered poisonous snakes (Figure 15), poisonous spiders, rats, bats, coyotes, and raccoons in or alongside channels during our studies. Dangers from these wildlife are not specific to urban infrastructure, but in natural habitat there are easier opportunities for wildlife and humans to retreat from a possible confrontation. In urban storm drains avenues of escape are often restricted. Wildlife may react aggressively to a "trapped" situation. Animals nursing young can be especially dangerous. Rabid animals, especially bats, present a constant threat. Fortunately, our encounters with wildlife have proven relatively harmless so far.

Flooding is usually not a serious threat during dry weather studies except in unusual circumstances. Fire hydrants and water pipes may rupture, releasing a torrent of flows into urban channels. Purposeful discharges into storm channels may also occur during construction dewatering. Vertically walled channels are particularly hazardous in such circumstances due to the difficulty of escape. Ladders are often installed at locations in urban channels but are often sporadically placed.



Figure 14. Mineralized surface built up along the seam between two sections of underground circular pipe in a stormdrain. Groundwater flowing along the seam for many years created the mineralized surface due to outgassing of carbon dioxide and precipitation of a calcite cement.



Figure 15. Studies in grout lined channels present risks to investigators. Risks include wildlife, flooding, and toxic gases in closed spaces.

An especially hazardous flooding situation was encountered by the main author of this paper. While performing surveys with a graduate student along the underpass section of Central Irvine Channel at the Interstate 5 Freeway, an estimated 16 to 20 inch wall of water cascaded at a high rate of flow down Central Irvine Channel toward the author and student (Figure 8). We were forced to run downstream for our safety to the outlet of the underpass. When we emerged from the underpass part of the flow had already started to wet our shoes. After escape from this dangerous situation, we stood in a safe zone and witnessed an enormous torrent of water entering the larger section of Peters Canyon Wash. Some hours later we learned that a very rare and very dangerous scenario had occurred upstream, when a 69-inch principal water main supplying large areas in Orange County ruptured, spilling 5 million gallons of water across the upper part of San Diego Creek Watershed (Harris and Roug, Los Angeles Times 1999). The disintegrating pipe under high pressure threw large chunks of concrete into the air from the force of the rupture. Amazingly, the pipe was buried 25 feet underground. This type of incident occurs rarely; it won't be forgotten.

Conclusions

Many of our research studies in urban watersheds and along lined channels have been fruitful, with results identifying leakage of water main ruptures flowing into storm drains via groundwater seepage; infiltration of contaminated stormwater runoff into groundwater; evolution of hydrochemical patterns along groundwater flowpaths; and detection of groundwater mounding areas appearing as rising groundwater at storm drains. This type of research is possible when shallow well control is either not available or where financial or regulatory hurdles undermine the conventional means of evaluating stream/aquifer interactions in urban corridors via installation of shallow groundwater monitoring wells. Safety considerations are paramount in this kind of work. Suggestions are provided to help avoid notable hazards.

The findings from this work reveal many opportunities for collecting groundwater data along grout lined channels. This work is paramount

where loading of solutes is due to groundwater baseflow and where shallow well control is absent. Endmember groundwater concentrations can be collected directly at the point of groundwater issue into streams. Our work has also commented on the hydrochemical differences of groundwater baseflow issuing from grout-linings and organic rich streambed sediments. These differences relate to practical applications of undesirable pollutants where channels are unlined, while emphasizing the value of rehabilitating and restoring urban channels where technical and regulatory issues make stream restoration possible.

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