

**TESTIMONY OF ROBERT R. CURRY, Ph.D.,
REGARDING THE NEED FOR NEW STUDIES CONCERNING
SYAR INDUSTRIES' REQUEST FOR A FIVE-YEAR EXTENSION
OF ITS PHASE VI TERRACE GRAVEL MINING PROJECT
(PRMD FILE NO. PLP 05-0108)**

BEFORE THE PERMIT AND RESOURCE MANAGEMENT DEPARTMENT OF SONOMA COUNTY:

I. SUMMARY OF FINDINGS

1. The Environmental Impact Report ("EIR") that Sonoma County will prepare for Syar Industries' five-year extension of terrace gravel mining should address advances in science since preparation of the 1994 Aggregate Resources Management Plan that have revealed serious methodological defects in that Plan and its EIR. The new EIR should address (1) defects in the MODFLOW modeling utilized for the 1994 ARM Plan; (2) the effects of global warming on river flow and flooding; (3) the documented ability of the Russian River to "capture" terrace mining pits during periods of high flow, such as occurred earlier this month; and (4) the growing body of science documenting the importance – and vulnerability – of alluvial deposits such as those Syar proposes to mine in supporting the Russian River's food chain and providing long-term groundwater storage for domestic and agricultural uses. I summarize these areas of needed study below.

2. The MODFLOW modeling conducted by Luhdorff and Scalmanini (LSCE) for the 1994 ARM Plan EIR was profoundly flawed. The field research summarized in this report shows that the LSCE MODFLOW model was premised on an erroneous groundwater elevation model. Further, as stated in the independent assessment by GeoTrans, Inc., the firm that developed the MODFLOW model, LSCE's MODFLOW analysis is plagued by pervasive data entry errors, erratic and uneven methodology, and confused analyses. GeoTrans, Inc. concluded

that “(t)he three reports from LSCE containing results from the groundwater modeling simulations do not support their conclusions,” and that the LSCE models must be “corrected and rerun prior to being used for any future decision-making.”

3. LSCE’s MODFLOW model is premised on a demonstrably erroneous assumption. It assumes that groundwater flow west of the Russian River is roughly *parallel* to the Russian River, or flowing north to south. To the contrary, our field data detailed below show that, in fact, the groundwater flow both east and west of the Russian River is generally perpendicular the River. Thus, groundwater on the west side of the River generally flows from west to east, *not* from north to south as the MODFLOW model assumes.

4. Field data for the west side of the River was collected by three independent professionals under my direction: by me on March 12, 2005, Luciani Pump and Drilling on April 6, 2005, and Curtis and Associates Surveyors on April 11, 2005. These field data document a clear eastward groundwater gradient that directly contradicts published MODFLOW-calculated surface and groundwater elevations on which all LSCE’s studies and reports for the west side of the Russian River are based.

5. Once Syar’s Pits V and VI are sealed (a phenomena that LSCE’s February 8, 2005 testimony to the Sonoma County Board of Supervisors agrees will happen), compounded by the greatly narrowed and lowered separator between Pits V and VI (a reconfiguration which is contrary to the standards in the ARM Plan), and the perimeter berm is completed on Pit VI, the blocked groundwater flowing from the west must rise to the surface on the adjacent Adams and Palmer properties and can then only flow southward through the existing swale onto the Soracco vineyard parcels. There it will saturate and flood the Adams, Palmer, and Soracco properties. No floodway to transport these surface flows across Syar’s property to the Russian River has

been constructed. Flooding impacts and the impacts of saturated vineyard lands in both winter and spring on premium grape production have not been addressed or mitigated.

6. The observed field data show the LSCE MODFLOW model is useless to predict wastewater contamination and flood impacts, for two reasons: (1) it is not based on accurate and complete groundwater data, and (2) it is flawed by additional input and modeling errors pointed out by GeoTrans, Inc. in its 2003 study.

7. Field data collected by LSCE from monitoring wells and data collected by me and associated professionals from adjacent domestic and irrigation wells, confirm that the LSCE MODFLOW model is not based on accurate or complete field data, and thus is useless to predict future groundwater elevations. The actual groundwater flow looks quite different from that used by LSCE for the MODFLOW reports and technical memoranda. Actually, for much of the year, the flow will be from west to east – flowing directly into or against the pits, and thence south, flooding the Adams, Palmer, and Soracco properties.

8. Significant advances in science during the past decade have confirmed that global warming is accelerating, resulting in increases in the frequency and severity of perturbations in temperature, rainfall, and other climatic parameters. This means that flooding along the Russian River will likely increase in frequency and severity in the future. The EIR should address the impact of these changes on Syar's proposed 5-year extension of terrace gravel mining and, in turn, the likelihood that continued mining in the manner proposed by Syar will cause greater adverse environmental impacts than previously thought. For example, the likelihood of "pit capture" will increase as the frequency and severity of flooding along the river increases. The importance of the alluvial deposits underlying Syar's proposed gravel mining in providing a stable source of groundwater for domestic and agricultural uses will likely increase, as variations

in river flow – both flooding during winter rainfall and loss of flows during drought – will likely increase. All of these changes, both in the surrounding environment, and in the impacts of Syar’s proposed mining on the environment, must be examined utilizing the significant advances in science that have occurred during the past decade.

II. STATEMENT OF QUALIFICATIONS

9. I am a Professor Emeritus of Geology at the University of California, Santa Cruz, and Research Director of the Watershed Institute at California State University, Monterey. I received my Ph.D. in Geomorphology and Paleoclimatology in 1967 from the University of California at Berkeley. I have over 40 years of training and experience in the fields of fluvial geomorphology and hydrology, and have authored over 100 scholarly papers in these fields. I have conducted extensive geomorphological field investigations throughout all three reaches of the Russian River, and have conducted extensive studies of the effects of gravel mining on the river’s geomorphology since 1962. I am a Registered Geologist in the State of California, and submit this Testimony based on facts within my personal and professional knowledge.

10. I wish to submit this statement to address the need for new studies regarding the likely adverse hydrologic impacts of Syar’s proposed 5-year extension of its Phase VI Terrace Gravel Mining Project. I have reviewed the current proposal by Syar for a 5-year extension of time to excavate this project, the Sonoma County Permit and Resource Management Department’s draft Mitigated Negative Declaration dated October 13, 2004, related materials developed by the County, the project proponent (including Syar’s Mining and Reclamation Plan dated June 2004), the County’s 1994 Aggregate Resource Management (“ARM”) Plan and EIR, the reports prepared by Luhdorff and Scalmanini Consulting Engineers (LSCE”) in 1997 and subsequently, including LSCE’s January 19, 2005 submittal, regarding the hydrologic effects of

terrace gravel mining at this site, the Wastewater Outfall Relocation Project Groundwater Modeling Review draft report prepared in January 2003 by GeoTrans for the North Coast Regional Water Quality Control Board regarding the LSCE modeling reports, and other associated governmental and private studies and reviews regarding gravel mining at this location.

11. I am familiar with this reach of the Russian River, having conducted numerous field investigations along the Middle Reach of the Russian River including this site located just downstream from the confluence with Dry Creek. I participated in the drafting of the 1994 ARM Plan and am intimately familiar with its purposes to protect the ground and surface water flows and quality of the Middle Reach Russian River as well as the stability of the Russian River's hydrologic regime. Over the past 40 years I have conducted numerous studies regarding the Russian River's hydrologic conditions, sediment budget and riverbed and riverbank stability, including participation in the preparation of Professor Einstein's benchmark sediment report for the Russian River in 1964. I have been asked by the Westside Association to Save Agriculture to review Syar Industries' proposed 5-year extension of time to excavate its Phase VI gravel mining project and provide this Department with my professional opinion regarding the need for additional studies of its potential adverse environmental impacts.

III. FINDINGS

12. In my professional judgment, the conclusions reached in the County's Subsequent Mitigated Negative Declaration dated March 18, 2005 ("SMND") that Syar's proposed Phase VI project will not have a significant effect on the environment are without scientific foundation and contrary to the hydrologic data available to the County. The 1994 ARM Plan specifies conditions for future terrace mining that would have to be met in order to mitigate both their site-specific and cumulative environmental impacts. These conditions have not been met for Syar's

proposed Phase VI project, nor has either Syar or the County intimated any intent to meet these conditions. Rather, Syar and the County assume, erroneously, that this project's non-compliance with those conditions can be excused because the resulting impacts on adjacent groundwater tables will be less than one foot in elevation. This assumption, which is based solely on the 1997 LSCE report, as supplemented by technical memoranda in February 1999, February and May 2001, November 2002, May 2004, and January 2005, is unsupportable. The modeling conducted by LSCE is profoundly flawed. It is premised on an erroneous groundwater elevation model, and as stated in the independent assessment by the firm that developed the MODFLOW model, GeoTrans, Inc., LSCE's MODFLOW analysis is plagued by pervasive data entry errors, erratic and uneven methodology, and confused analyses.

13. All of the LSCE reports assume incorrectly that groundwater elevations on the west side of the Russian River downstream from its confluence with Dry Creek are arranged in east-west contours roughly *perpendicular* to the Russian River, descending as one moves south from Mill Creek, the lowest tributary of Dry Creek. An east-west contour indicates flow from north to south. (See, for example, Figure 3-10 to LSCE's 1997 Model Report, which is annexed to LSCE's January 17, 2005 report and appears as page 198 of the PRMD Report to the Sonoma County Board of Supervisors for its February 8, 2005 hearing.) In fact, along this reach, as shown by the well data I discuss below, groundwater contours west of the Russian River generally *parallel* the Russian River, just as they are reported to do on its east side. In addition, as confirmed by the independent assessment conducted by GeoTrans, Inc. in January 2003 for the North Coast Regional Water Quality Control Board, "[t]he three reports from LSCE containing results from groundwater modeling simulations do not support their conclusions." *Id.*

at p. 1, Executive Summary. Therefore the LSCE models must be “corrected and rerun prior to being used for any future decision-making.” *Id.* This has not been done.

14. As I explained in my January 19, 2005 testimony to the Planning Commission which I submitted to the Board of Supervisors on February 8, 2005, and to which I respectfully refer this Department, in my professional opinion there is a substantial probability that this project would cause a greater than one-foot change in groundwater tables on adjacent properties, triggering application of the 1994 ARM Plan criteria which this project openly violates. Field data obtained last March and April directly contradict the groundwater elevation model on which all of LSCE’s studies and reports are based.

15. Further, Syar’s proposed 5-year extension of mining of Pit VI, and consequent delay in remediation of this land, would cause additional flooding of adjacent lands to the west and south, as ground- and surface flows are deflected from Syar’s self sealing pit and 10-foot high berm onto these lands. For these reasons, as I explain more fully below, the County must conduct a proper hydrologic analysis that addresses the potential cumulative watershed effects of Syar’s project.

IV. NEW FIELD DATA CONTRADICTS LSCE’S MODEL.

16. As background for this testimony I reviewed the environmental and technical documents prepared by Syar and the County for this project and conducted a field investigation on March 12, 2005. I also developed a database of the aerial photography and topographic maps, and compiled a georectified GIS layer of the parcels on the west side of the Russian River south of Healdsburg. Then, on April 6 and 11, 2005 at my further direction, Curtis and Associates Surveyors and Luciani Pump collected further field data.

17. As a result of my investigations, I have determined that several basic assumptions used by the County and Syar to assess the environmental impact of the proposed wastewater disposal project in Pit V are incorrect. In conducting my analysis, I assumed that over the next five years Syar's Phase VI pit was to be excavated as proposed surrounded by a 10-foot high flood-protection berm, and that the excavations of Pit V and Pit VI are as specified by Syar in areal extent and depth.

18. The issue of the County's proposed open-space conservation easement on Pits V and VI and its impact on the Healdsburg wastewater disposal options is integrally related to the local groundwater conditions. Critical in the assessment of the proposed options are the analyses by Luhdorff and Scalmanni Consulting Engineers ("LSCE") conducted both for Syar and for the City of Healdsburg. These analyses and subsequent reports all are based on a groundwater hydrologic model constructed by that firm to assess impacts of terrace pit mining on groundwater flow paths and elevations of seasonal water tables. I have criticized the findings of LSCE based on its MODFLOW groundwater computer modeling in the past but have been limited in my critical reviews by the absence of the data set upon which the MODFLOW model was constructed by LSCE. The monitoring data that LSCE claims support its model are critical if the validity of that model is to be verified. The Regional Water Quality Control Board's review (by its consultant, GeoTrans) observed that the LSCE model must be based on accurate input data and proper methodology to be useful. The LSCE model fails both tests, as we explain below.

19. LSCE's model is based on the fundamental assumption that the groundwater flow gradients on the west side of the Russian River in the vicinity of the Healdsburg wastewater disposal facilities are distinctly different than those on the east side of the Russian River. LSCE assumes that the west side flow of groundwater through the terrace gravels is primarily north-to-

south, while that on the east side is primarily east-to-west. This assumption underlies Syar's hydrologic maps such as the LSCE Figure 3-10 to its 1997 Model Report referenced above and reproduced as Figure 4 below, and LSCE's Figure 4 map titled "*Simulated Contours of Equal Ground-Water Elevation; Interim Project Discharges to 20-acre Phase V Pond, Middle Reach of the Russian River*" that appears in LSCE's previous reports for Syar assessing Phases VI and V and other originally planned terrace mining excavation impacts. On prior versions of that map, the locations of the monitoring and other wells upon which the MODFLOW groundwater flow model is based are plotted.

20. Only a very limited number of wells west of the Syar pits are included in LSCE's monitoring network and upon which its model is ostensibly based. Those wells, S-8 and P-16, become critical for contouring the groundwater surface elevation that is then the fundamental basis of the MODFLOW model that calculates flow direction for regional groundwater. Yet S-8 is not included in LSCE's reported plots. Although LSCE has not released its monitoring data, it has included in its reports limited plots of groundwater elevations (ft-msl) of Middle Reach Russian River irrigation and monitoring wells that have been measured from time to time. These plots span a period of time from 1975 through 2000, with only sporadic subsequent data. The absence of any systematic collection of data points since 2000, to reflect conditions following excavation of Pit V, is a severe shortcoming. This omission precludes use of LSCE's inadequate data to predict the impacts of Pits V and VI.

21. Putting aside LSCE's fatal omission of essential data since 2000, close inspection of LSCE's reported data, as depicted in the groundwater contour maps on which its reports are based, reveals an even more profound error. The map is clearly contrary to the available groundwater data. Attached as Figure 4 is a photocopy of the LSCE figure that shows its

postulated groundwater elevation contours. This contour map is directly contradicted by the field data I recently gathered from local wells, as discussed below.

22. LSCE's groundwater contour maps are also contradicted by its own data. By identifying apparent near-simultaneous points on the LSCE data plots from Syar's various submissions to Sonoma County, one can establish some of LSCE's water table elevations at some times. These data do NOT coincide with or support the general contours of water table surface elevation that are predicted from the simulated hydraulic head plotted in the maps accompanying the many LSCE reports. While the calculated elevations might not be expected to always coincide with actual measured elevations due to local discontinuities in permeability, the general direction of flow should always be down the gradient of the plotted contours of groundwater head. That is the fundamental assumption on which the MODFLOW model is based. The season of measurement is also critical. The limiting conditions for impacts to adjacent parcels is in the springtime and early summer when water tables are at their highest. These are the times that I measured and found the generalized LSCE data in error. The new EIR must address groundwater conditions during all four seasons.

23. It is apparent that LSCE's MODFLOW model is not based on sufficient data on the west side of Syar's excavations to support the model's conclusions. For example, in the December, 2004 groundwater elevation data plotted in the John Perry letter of January 17, 2005 (referred to as the LSCE report in Syar's January 19, 2005, letter to Michael Sotak), only *one* well (P-12) is arguably consistent with the predicted MODFLOW flow model.

24. The next nearest plotted well (P-16), however, is *higher than the level LSCE predicts by 16 feet*. Moreover, to determine where the observed groundwater comes from and where it goes requires both data from the wells within the zone of influence of Pits V and VI, and

accurate water table elevations up to several thousand feet laterally – both upslope and downslope – from the ponds. The LSCE models lack this critical foundation, and indeed, are *contradicted* by the actual groundwater elevations I have recently measured in this area, as summarized below.

25. I have interviewed property owners west of Syar Pit V and adjacent proposed Pit VI and they have told me that their wells have not been monitored by LSCE or Syar. This was very surprising to me because data from those wells would be necessary to validate the MODFLOW model and to predict the impacts of the various options recently proposed for the Healdsburg wastewater disposal. On March 12, 2005, I measured the static water surface elevations in the domestic wells of Scott Adams and James Love. This was done when the wells were not being pumped and probably represent a springtime water table elevation near the seasonal maximum for the 2005 water-year. I also inspected the irrigation wells of Seghesio Vineyards and Scott Adams, and observed the existing and newly installed wells of Joan Palmer, the existing well of Bommersbach/Olney, and the Seghesio domestic well. The locations and ground surface elevations of these wells are shown in Figure 5. All these wells are important for establishing the flow directions of groundwater west of the Syar pits and the Healdsburg wastewater facilities.

26. The LSCE Figure 4 map in the Healdsburg Wastewater EIR indicates the locations of the Seghesio irrigation well at the southwest corner of Pit V and a nearby well marked “Domestic Well”. That domestic well is the Love’s (see Plate 1 and Figure 5 for locations). On March 12th, the static water table in the Love well was 18.4 ft below the ground surface (bgs), which surface is about 79 feet above mean sea level (msl). Thus, at that time of the year, the water table was about 60.6 feet above msl adjacent to Pit V. I then measured the

water table elevation in the Scott Adams domestic well, which is situated 810 ft S 35 W from the Love well and should have a water elevation about 1 foot lower according to the MODFLOW model. A compass and tape level survey indicated that the Adams well water table was then at least 3 feet *higher* – not lower – than that in the Love well.

27. Fundamentally, this means that in the springtime after water tables are recharged, flow direction is from the west to the east toward the Russian River in the Pit V and Pit VI area. If the water levels of the monitoring wells shown in the LSCE figures are plotted as interpolated from their point-graphs, a general pattern emerges that is quite different from the LSCE groundwater contour maps. These monitoring well data show that groundwater is higher as one moves west from the sites of Pit V and Pit VI, and flows to the east toward the swale along the site of the proposed berm that will surround proposed Pit VI on Syar lands. This directly contradicts the LSCE MODFLOW contour maps, which show groundwater elevations on the valley floor west of the Russian River roughly the same along east-west contours.

28. On April 6, 2005, at my direction, Luciani Pump and Drilling again sounded the wells. They found that the water in the Love well had risen slightly, to 17.92 feet bgs, on that date. They measured the Adams domestic well at 18.67 feet bgs, and measured the Bommersbach/Olney well west of the Adams well and found the static water level to be only 0.33 feet bgs. They also measured the two Soracco irrigation wells south of the Adams and adjacent Syar parcels and found that their static water levels were 21.79 feet bgs (12-inch well) and 22.25 feet bgs (10-inch well).

29. On April 11, 2005, at my further direction, Curtis and Associates Surveyors of Healdsburg surveyed the well locations and tops of the casings. The Love well casing elevation was determined to be 81.39 ft msl, and the ground 78.89 feet msl. The Adams domestic well cap

was measured at 83.89 feet msl with the ground surface at 83.06 feet. The Bommersbach well head was 83.34 ft msl and the ground 81.59 ft. On the Soracco vineyards to the south the 12-inch well cap was measured at 81.80 msl with the ground at 79.51 ft, and the 10-inch well was measured at 82.13 ft with the ground at 81.38 ft.

30. These measurements thus confirm the following groundwater levels as of April 6, 2005: Love – 60.97 ft msl; Adams – 64.39 ft msl; Bommersbach – 81.26 ft msl; Soracco 12" – 57.72 ft msl; Soracco 10" – 59.13 ft msl. Thus, my measurements on March 12th and the Luciani measurements on April 6th document a *clear eastward groundwater gradient that directly contradicts the published MODFLOW calculated water surface elevations reported by LSCE.*

31. The reason why groundwater elevations are higher to the west is apparent. The Bommersbach/Olney well is located at the base of an alluvial fan below the VanNoy Pond/Palmer Ridge watershed. Consequently, in the springtime, water table elevation here is almost at the ground surface (0.33' bgs on April 6). The water table elevation on the west side of the valley at the Bommersbach well at about 81.3 ft drops to about 64.4 ft at Adams and 61.0 ft at Love, while the southward gradient is much less steep with the Soracco water tables 3000 or more feet south at 57.7 and 59.1 ft. Rather than being about *1 foot lower* as predicted in the MODFLOW data set, the Adams well was *3.3 feet higher* than the Love water surface elevation. The MODFLOW contours suggest that the Bommersbach well level ought to be at about 56 ft but it is in fact *more than 81 feet* in the spring season – *25 feet higher than the LSCE reports assume.*

32. These documented discrepancies between groundwater elevations as predicted by the MODFLOW reports, and as actually measured in the field, confirm that the MODFLOW model is not based on accurate limiting field data. Because it is not based on accurate data, it is

useless to predict groundwater elevations in the future. Accordingly, the County must conduct a comprehensive groundwater study in the area to develop a sufficient data base from which to construct an accurate model to predict future groundwater conditions. Without accurate data and a proper model, the impacts of the proposed 5-year extension to excavate Pit V cannot be accurately predicted.

V. UNLESS A FLOODWAY IS CONSTRUCTED AND ADDITIONAL REMEDIAL MEASURES ARE TAKEN, THE PIT VI BERM WILL LIKELY CAUSE ADDITIONAL FLOODING OF ADJACENT LANDS.

33. The observed eastward gradient of groundwater elevations exists because primary recharge to the westside terrace gravels is from local precipitation and from runoff from the west. Local seasonal rainfall averages about 48 inches and to that is added runoff from the bedrock areas west of Westside Road. The primary side streams that contribute to the terrace recharge locally are Mill Creek (which is separated hydrologically by a slight rise from the lands to the south immediately adjacent to the Syar Pits site), and an unnamed stream that originates above what is locally called the Van Noy Pond and then flows in a channel east of Westside Road between the Bommersbach/Olney and Palmer parcels. That small watershed on the Palmer Ridge Ranch, Van Noy, and Rabbit Ridge properties has an area of about 290 acres.

34. Forty-eight inches of winter precipitation will recharge an open, unconfined and freely permeable ground surface to raise the water table in the terrace gravels by about 26.7 feet, assuming 15 percent pore volume in the gravel (if the pore volume were 20 percent, 1 foot of rain would saturate 5 feet of aquifer). Because the springtime water tables are higher than that but below the ground surface, we can infer that some of that water must flow off the land and/or that the shallow groundwater drains away downgradient faster than the pores will fill.

35. Observations on site and discussions with neighbors Bommersbach, Olney and

Love indicate that water saturates the ground “several times” during a winter season and that overland flow then occurs. I inspected the drainage system installed by Scott Adams on his parcel that carries surface water via pipe and sump pump from a small artificial ditch on the west boundary of his parcel eastward to empty into a natural swale near his eastern border with Syar. The natural drainage swale defined by the 80-foot msl contour on the US Geological Survey Healdsburg Quadrangle 1:24,000 map lies along the west edge of Syar’s lands directly adjacent to the proposed Pit VI flood berm. When I visited the site in March, a series of hay bales marked that boundary and mud cracks indicated that water ponded there this past winter. If we add the 1160 acre feet of water that flow over the surface onto the Bommersbach/Olney and Adams parcels from the aforementioned Van Noy/Palmer watershed (estimated based on average rainfall and watershed area) and the natural channel recharge that would be expected from Mill Creek of unknown volume, we would expect substantial mounding of groundwater flowing from west to east along the proposed western boundary of Pit V and proposed Pit VI. This explains the observed water table elevations at LSCE monitoring well P-16 and in the newly observed Love and Adams well elevations. If we accept the LSCE monitoring data for P-12 and the LSCE data points in and immediately adjacent to Syar’s Pits, then we must develop a groundwater flow model that looks quite different than that used by LSCE for its MODFLOW reports and analyses. Instead of flow that will pass southward around the Syar Pits, we now see that flow for much of the year will flow east directly into or against the Pits. If Pit VI is excavated and sealed and a perimeter berm is constructed as proposed, that water must rise to the surface and can then only flow southward across the Adams and Palmer lands and onto the Soracco vineyard parcels. Thus, the Love, Adams and Soracco lands will likely be impacted by additional surface water and as a result may *remain saturated in both winter and spring*.

36. These resulting changes in groundwater flow dynamics would also impact the options for the Healdsburg wastewater disposal in Pit V, modifying both pollutant transfer and infiltration capacity. In my professional opinion, based on these new data and the prior critique of the LSCE work by the independent consultant retained by the Regional Water Board, Geotrans, a reanalysis should be conducted of the LSCE MODFLOW model results using as many wells west of the Pit V site as possible. Syar shows an S-8 monitoring well on its maps located at the southwest corner of its proposed Pit VI pond. Those data have never been brought forward and are not apparently part of the MODFLOW data set. I observed a well in that location and if it is available, those data should be considered. Similarly, the aforementioned irrigation and domestic wells located west of Syar's lands can be potential monitoring sites with sufficient notice to ensure that the wells are not being pumped. The Seghesio irrigation well may be useful also in non-irrigation season. The Bommersbach/Olney well, the Soracco wells, the Love well, and the Adams wells can also be potential monitoring sites with sufficient notice to insure that the wells are not being pumped.

37. Because Syar proposes to continue excavating for 5 more years, sealing off eastward groundwater flows to a depth of 90 feet, surface water that today accumulates in the low swale between Syar's west parcel boundary and its neighbors Love, Adams, Palmer and Soracco will pond to substantially greater depth. The historic downgradient groundwater flow west to east toward Syar's land and the Russian River would be intercepted by future pit-wall sealing. That water will then have to rise to the surface and flow over the surface to the south and southwest, directly onto the Love, Adams, Palmer and Soracco parcels. *This will cause high water tables extending into late spring and summer that would be expected to reduce vineyard production and grape quality (and potentially damage wells) on the Love, Adams, Palmer and*

particularly Soracco vineyard parcels.

38. Because eastward-flowing ground and surface water will pond against the west side of the flood berm to be constructed around Pit VI, and then be diverted southward toward the Soracco vineyards, it follows that the proposed groundwater outflow from Pit V to the west will be minimal or non-existent in winter and spring. If Pit V is ever used for Healdsburg's wastewater, as was proposed in the past – or is contaminated by wastewater overflowing from the Basalt Pond as could occur during high flows on the Russian River – that wastewater would then be forced to flow east toward the Russian River or south into Pit VI. This scenario casts doubt on the advisability of reducing the height and width of the septum between Pit V and VI as proposed by Syar for its Pit VI expansion. Any wastewater discharged into Pit V will infiltrate and contaminate the groundwater in Pit VI, bringing many more wells into the zone of wastewater influence. Moreover, the redirected flow of wastewater will be eastward to the Russian River, *directly upstream of the City of Windsor's wells.*

39. In conclusion, based on my observed field data, the LSCE MODFLOW model is useless to predict wastewater contamination and flood impacts, because it is not based on accurate and complete groundwater data. Further, as I previously testified, I do not find the LSCE responses to the GeoTrans critique responsive to the identified problems with the MODFLOW model. A model is only as good as its input data, and where that is inadequate, it makes little sense to simply state that new inadequate data corroborate old inadequate data. Proper evaluation of Syar's proposed 5-year extension requires knowledge of both high and low seasonal groundwater levels adjacent to those pits. The LSCE MODFLOW model is not accurate for that purpose.

40. The 1994 ARM Plan EIR does not consider the impacts of global warming.

Substantial, credible, recent scientific research has documented the fact that as global warming proceeds at an accelerated rate, climatic perturbations such as Hurricane Katrina will increase in frequency and severity. This means that flooding along the Russian River will likewise increase in frequency and severity. The EIR should examine the impacts of global warming on Syar's proposed excavation, particularly with regard to (1) impacts of more frequent and severe floods on Syar's Pond VI and adjacent ponds; (2) the likelihood for increased sedimentation of these ponds due to "pit capture" from high flows on the Russian River; (3) the potential resulting loss of "engineered" benches and other topographic configurations adopted as "mitigation" for Syar's ponds; (4) the likelihood of increased evaporation of groundwater through Syar's ponds during drought periods; and (5) the impact of all of the above on the flora and fauna of the Russian River, including its recently-listed chinook and coho salmon and steelhead.

41. Concerns that I and others have expressed regarding the vulnerability of Syar's ponds to "pit capture" by the Russian River during flood stage were recently confirmed during the December 31-January 2 flooding of the river. As documented in Figure 7, prepared by the United States Geological Survey, this flood has a recurrence interval of roughly 10 years. Put another way, since 1940, five floods have been more severe. The EIR should examine whether floods of this magnitude will become more commonplace (and severe) as a result of global warming, and assess the impact of Syar's excavation on this changing river system.

42. The effects of the recent Russian River flood on the Syar ponds is depicted in Photos 1-4, attached hereto. Although these photographs were taken after the peak flood stage had subsided, they show collapsed levees between the Basalt Pond and Ponds, I, II, IV, and No Name. It is apparent that had the flood stage been a few feet higher, river waters would have

breached the levees separating these ponds from Ponds V and VI. Because flood waters carry high volumes of sediment, when flood waters breach protective levees and enter ponds such as these, substantial quantities of sediment are deposited on the sides and bottom of the pits, greatly accelerating the rate at which these pits self-seal and prevent groundwater movement. These impacts of “pit capture” should be examined in the new EIR.

43. The EIR should also examine the substantial body of scientific literature which has developed during the last decade regarding the unique ecological function of alluvial deposits underlying and adjacent to rivers. Two examples of this emerging body of science are annexed as Attachment 1 (Trush, McBain and Leopold, *Attributes of an Alluvial River and Their Relation to Water Policy and Management*, Proceedings of the National Academy of Sciences of the United States of America, Vol. 97, No. 22 (Oct. 24, 2000), pp. 11858-11863) and Attachment 2 (Fraser and Williams, *Seasonal Boundary Dynamics of a Groundwater/Surface-Water Ecotone*, Ecology, Vol. 79, No. 6 (1998), pp. 2019-2031). These pioneering studies demonstrate that alluvial deposits such as those Syar proposes to excavate provide nutrients essential to a healthy riverine ecosystem. These nutrients feed bacteria and other microscopic organisms that ultimately feed insects that are consumed by fish and other wildlife. The impacts of Syar’s proposed 5-year extension of gravel mining on this recently-discovered ecological system should be examined.

44. In summary, the 1994 ARM Plan EIR is profoundly inadequate to address the impacts of Syar’s proposed 5-year extension of gravel mining. The EIR to be prepared for Syar’s mining activity should address the potential impacts I have described, and answer the questions I have raised, in the foregoing testimony.

I declare under penalty of perjury that the foregoing facts are true of my personal knowledge and reflect my best professional judgment, and that I am competent to, and if called would so testify.

Executed on January 25, 2005, in Soquel, California.

/s/ Robert R. Curry, Ph.D.
ROBERT R. CURRY, Ph.D.

Figure 1. Location map: a portion of Figure 2a from: Syar Phase VI: Subsequent Mitigated Negative Declaration of 3-18-05

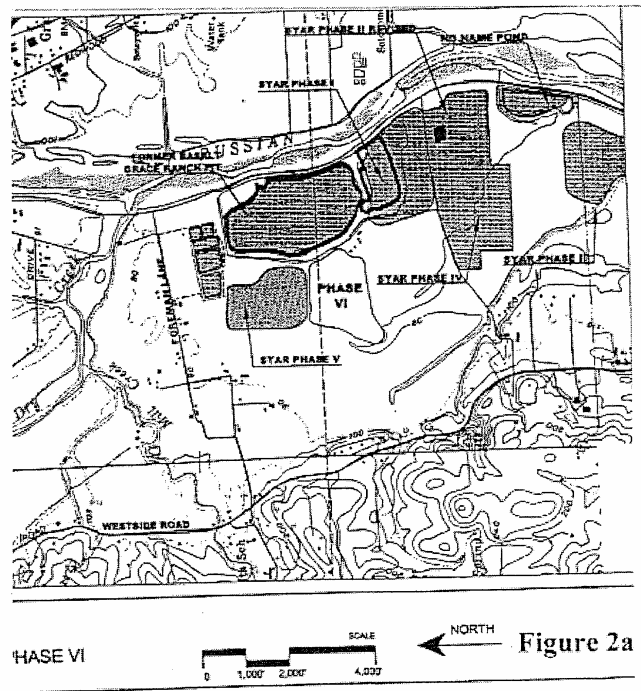
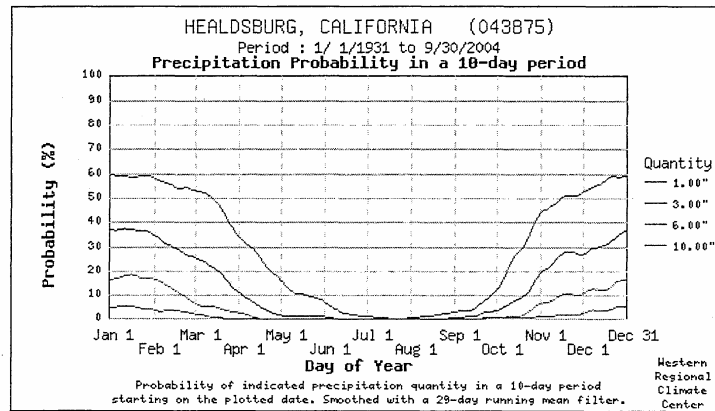


Figure 2. Healdsburg 10-day cumulative precipitation probability. A 3-inch storm period will saturate the ground adjacent to Pond V and result in surface flow under most common conditions. There is a 20-35% probability of occurrence of such rainfall for any 10-day period between about Nov 1 and March 15, or about 3.7 such occurrences in an average winter.



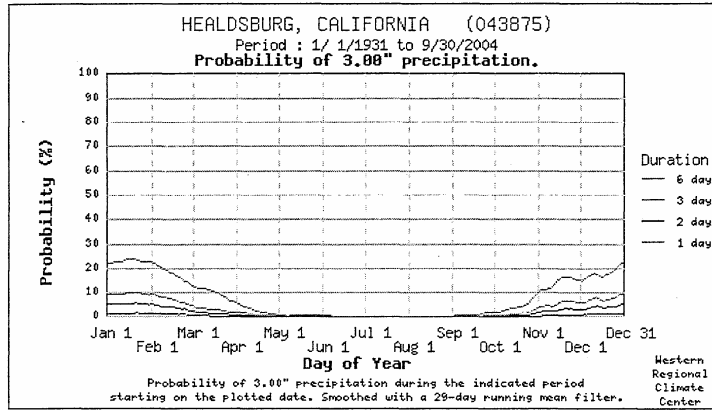
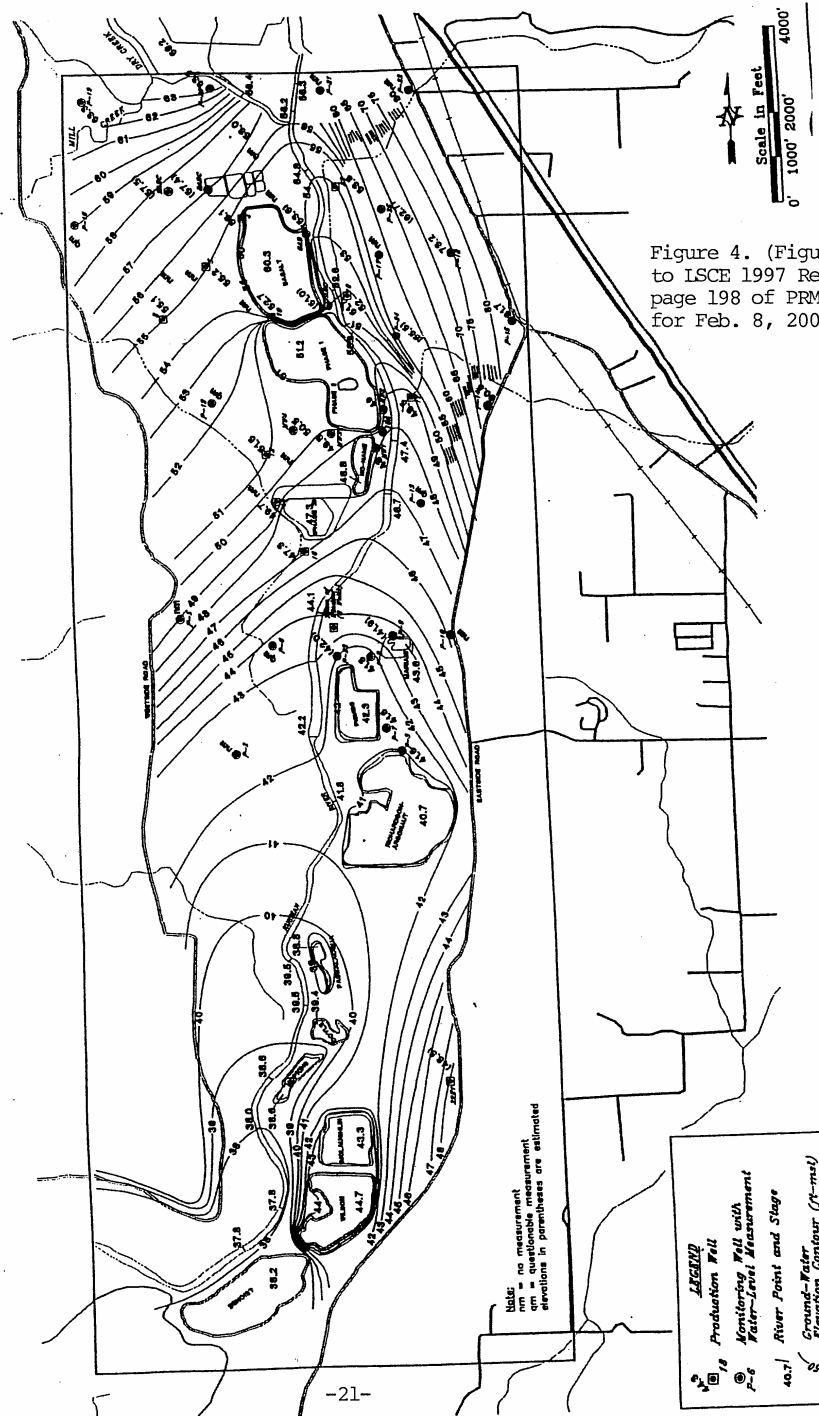


Figure 3. Healdsburg 3-inch rainfall probability for 1-6 consecutive days that would be expected to cause surface flooding to private parcels adjacent to Syar berms around Phase V and VI pits. Multiply the probability of the top line by 5 (30 days divided by 6 days) to get the probability in any given month.



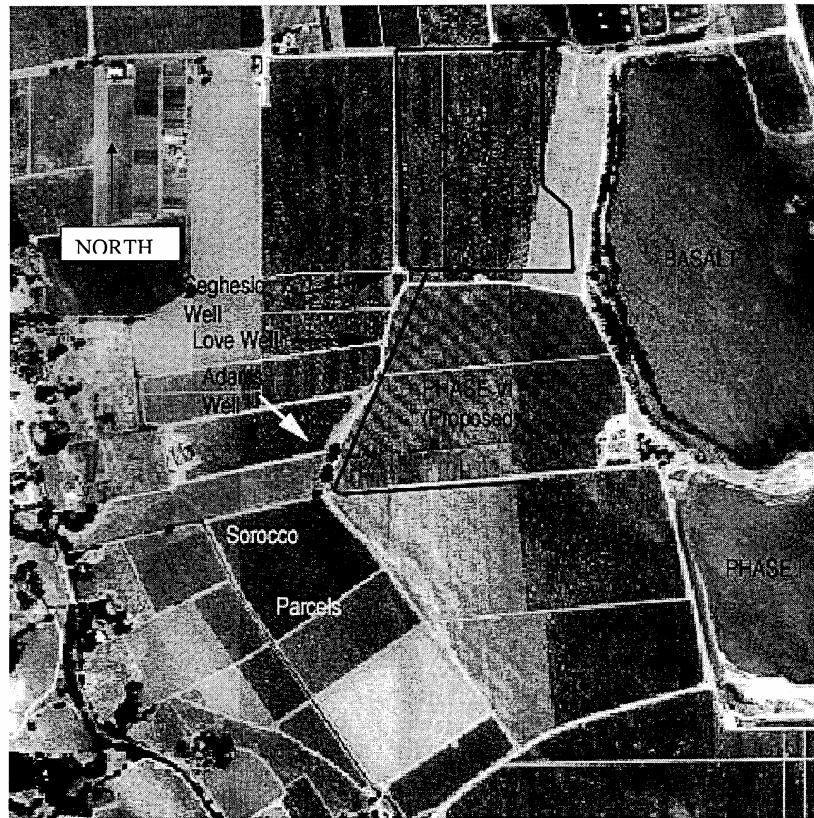


Plate 1. July 11, 1993 aerial photo showing newly measured wells in relationship to approximate Syar pit locations

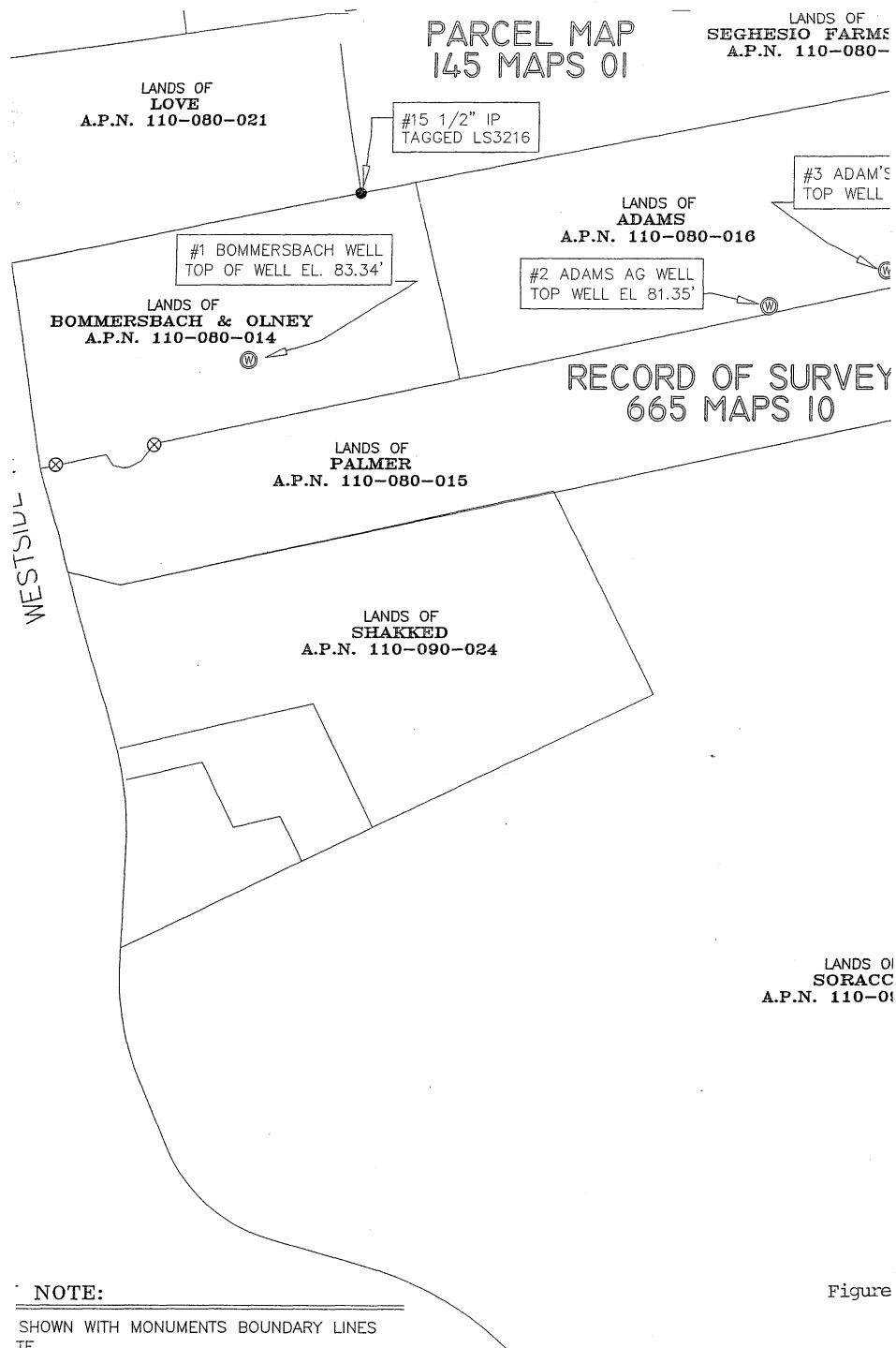
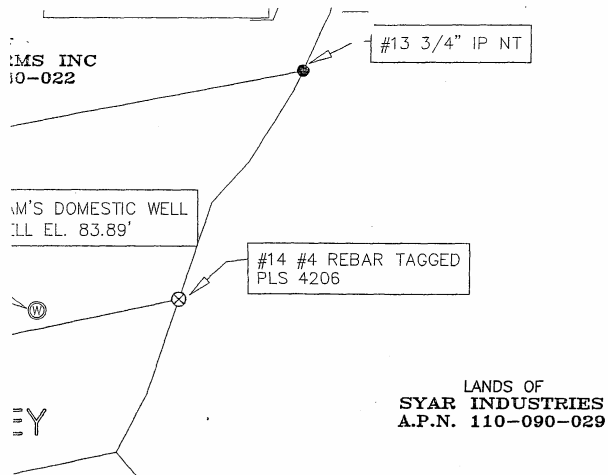
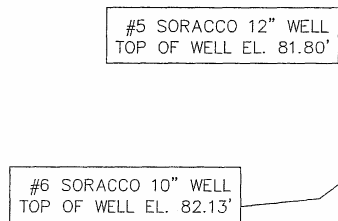


Figure 5



FIELD T1	
NO.	BE/ DIS
#15 IP	
#1 WELL	S 33°53'53"
#13 IP	
#2 WELL	N 14°43'13"
#14 RB	
#3 WELL	S 79°36'20"
#4 WELL	S 85°23'58"
#5 WELL	S 30°52'24"
#6 WELL	S 21°54'16"

OF
CCO
-090-006



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Figure 6

**Highest Historical Peak Streamflow
For USGS 11467000**

at Guerneville Date	Streamflow (cfs)
1986-02-18	102,000
1995-01-09	93,900
1964-12-23	93,400
1955-12-23	90,100
1940-02-28	88,400
1997-01-01	82,100
1966-01-05	77,000
1974-01-17	74,000
1970-01-24	72,900
1983-01-27	71,900

Healdsburg State data near Healdsburg

Historical Crests (Not official USGS crest values)

- (1) 30.8 ft on 12/01/1937
- (2) 30.0 ft on 02/28/1940 (67000 cfs)
- (3) 27.0 ft on 12/23/1964 (71300 cfs)
- (4) 26.23 ft on 01/09/1995 (73000 cfs)
- (5) 26.16 ft on 12/22/1955 (65400 cfs)
- (6) 25.81 ft on 02/17/1986 (71100 cfs)
- (7) 25.45 ft on 01/21/1943 (53300 cfs)
- (8) 24.7 ft on 01/01/1997 (65930 cfs)
- (9) 24.62 ft on 01/16/1974 (64700 cfs)
- (10) 24.18 ft on 01/26/1983 (62700 cfs)
- (11) 22.96 ft on 02/06/1942 (43200 cfs)
- (12) 22.95 ft on 03/09/1995 (58400 cfs)
- (13) 22.68 ft on 01/17/1954 (53700 cfs)
- (14) 22.35 ft on 02/25/1958 (50900 cfs)
- (15) 22.08 ft on 01/24/1970 (53500 cfs)

near Healdsburg

Flood Stage: 19 Feet

Latest Stage: 5.59Ft

Current Warnings/Statements/Advisories:

None currently.

Cc
the Russi

NWS San

Flood Categories (in feet)	Historical Crests
Major Flood Stage: 24	(1) 30.8 ft on 12/01/1937
Moderate Flood Stage: 20	(2) 30.0 ft on 02/28/1940 (67000 cfs)
Flood Stage: 19	(3) 27.0 ft on 12/23/1964 (71300 cfs)
Action Stage: 15	(4) 26.23 ft on 01/09/1995 (73000 cfs)
	(5) 26.16 ft on 12/22/1955 (65400 cfs)
	Show More Historical Crests

Figure 7

at Guerneville
Flood Stage: 32 Feet
Latest Stage: 10.99Ft

Current Warnings/Statements/Advisories:
None currently.

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Collaborative Agencies

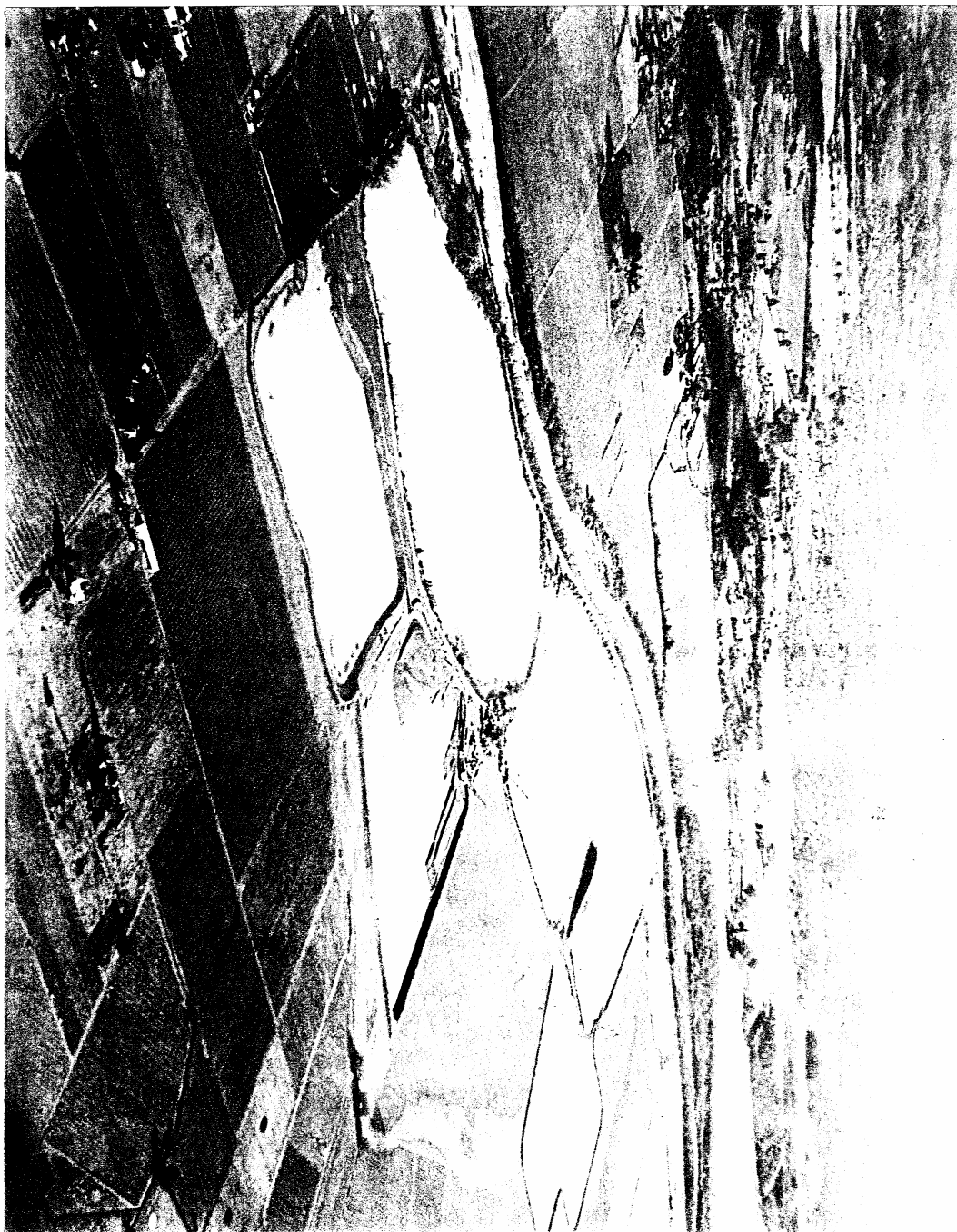
 Collage

Flood Categories (in feet)		Historical Crests	
Major Flood Stage:	40	(1) 48.8 ft on 02/18/1986 (102000 cfs)	
Moderate Flood Stage:	38	(2) 48.0 ft on 01/10/1995 (93900 cfs)	
Flood Stage:	32	(3) 47.62 ft on 12/23/1955 (90100 cfs)	
Action Stage:	29	(4) 47.35 ft on 12/23/1964 (93400 cfs)	
		(5) 46.87 ft on 02/28/1940 (88400 cfs)	
		Show More Historical Crests	

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11467000 GUERNEVILLE 1,338 32.0 5 2006- 05:30:00 85,800 44.21 10 10 6 65 102,000
CA 01-01 (1986)
http://water.usgs.gov/cgi-bin/wwdp?state_nm=ca

PHOTOGRAPHS 1–4









Attributes of an Alluvial River and Their Relation to Water Policy and Management



William J. Trush; Scott M. McBain; Luna B. Leopold

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ATTACHMENT 1

Attributes of an alluvial river and their relation to water policy and management

William J. Trush^{*†}, Scott M. McBain[‡], and Luna B. Leopold[§]

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Contributed by Luna B. Leopold, August 15, 2000

Rivers around the world are being regulated by dams to accommodate the needs of a rapidly growing global population. These regulatory efforts usually oppose the natural tendency of rivers to flood, move sediment, and migrate. Although an economic benefit, river regulation has come at unforeseen and unevaluated cumulative ecological costs. Historic and contemporary approaches to remedy environmental losses have largely ignored hydrologic, geomorphic, and biotic processes that form and maintain healthy alluvial river ecosystems. Several commonly known concepts that govern how alluvial channels work have been compiled into a set of "attributes" for alluvial river integrity. These attributes provide a minimum checklist of critical geomorphic and ecological processes derived from field observation and experimentation, a set of hypotheses to chart and evaluate strategies for restoring and preserving alluvial river ecosystems. They can guide how to (i) restore alluvial processes below an existing dam without necessarily resorting to extreme measures such as demolishing one, and (ii) preserve alluvial river integrity below proposed dams. Once altered by dam construction, a regulated alluvial river will never function as before. But a scaled-down morphology could retain much of a river's original integrity if key processes addressed in the attributes are explicitly provided. Although such a restoration strategy is an experiment, it may be the most practical solution for recovering regulated alluvial river ecosystems and the species that inhabit them. Preservation or restoration of the alluvial river attributes is a logical policy direction for river management in the future.

Since the 1990s, the physical and environmental consequences of river alteration and management have been openly questioned. Continued increases in flood losses, both financial and human, and the unanticipated and unwanted results of dams and channel straightening, invite reevaluation of river management. Reevaluation has even led to removing existing dams (e.g., Butte and Clear creeks in California, Elwha River in Washington), as well as implementing experimental releases of high flows (1, 2).

Historically, river policymakers and resource managers have been less attentive to a growing body of experience, experiment, and theory concerning geomorphic processes that form and maintain alluvial river ecosystems. There are several commonly known concepts that govern how healthy alluvial channels work that we have compiled as attributes of alluvial river integrity. These attributes can guide how to (i) restore alluvial processes downstream of an existing dam without necessarily resorting to extreme measures such as demolishing one, and (ii) preserve alluvial river integrity below proposed dams. This set of attributes is not a classification system or a substitute for individual study and observation on a river. It provides a minimum checklist of critical geomorphic and ecological processes derived from field observation and experimentation, a set of hypotheses to chart and evaluate strategies for restoring and preserving alluvial river ecosystems. At the ever-present risk of oversimplification, the attributes also can help policymakers appreciate many of the complex requirements of alluvial river ecosystems.

Alluvial river ecosystems persist through a complex, interacting array of physical and biological processes. For any impetus

imposed on the river ecosystem (e.g., a recommended flow release), we should expect a response (e.g., scouring sand from a pool). The significance of an impetus will depend on an appropriate threshold beyond which a specific response is expected. A process, therefore, is comprised of an impetus and an expected response. To use the alluvial river attributes as guidelines for recovering or preserving critical processes, one must consider how the magnitude, duration, frequency, and timing of an impetus will exceed a threshold to produce a desired response. Rarely, however, is a single impetus imposed on a river ecosystem associated with a single response.

Floods are primary impetuses for all alluvial river morphology. An increase in discharge may initiate bed surface movement and bank erosion, once the force exerted by the flood event (the impetus) has passed some threshold for movement or erosion. This threshold may require a specific flow magnitude and duration before producing a significant morphological response. The timing and frequency of the flood also may have profound effects on a species or a population. Mobilizing sand from a pool in January may smother salmon eggs incubating in the downstream riffle. The impetus, therefore, cannot be prescribed as a simple measure of force, nor can the total reaction be as succinctly quantified or even fully anticipated. It is with this backdrop of uncertainty that the attributes were compiled.

The Alluvial River Attributes

The alluvial river attributes (3) can help river managers identify desired processes, then help prescribe necessary impetuses based on useful empirical relationships and thresholds developed by river geomorphologists and ecologists. All of the concepts deriving the alluvial attributes have been described among a wide range of professional journals, technical books, and agency reports (reviewed in ref. 2), but their compilation has not been previously published. They may not apply equally to all alluvial river ecosystems. Some rivers may not be capable of achieving certain attributes because of overriding constraints, e.g., a river passing through an urbanized corridor often is not free to migrate. These constraints do not eliminate the attributes' usefulness; knowing what might remain broken should influence what can be repaired.

Attribute No. 1. The primary geomorphic and ecological unit of an alluvial river is the alternate bar sequence. Dynamic alternating bar sequences are the basic structural underpinnings for aquatic and riparian communities in healthy alluvial river ecosystems.

The fundamental building block of an alluvial river is the alternate bar unit, composed of an aggradational lobe or point bar, and a scour hole or pool (Fig. 1). A submerged transverse bar, commonly called a riffle, connects alternating point bars. An alternate bar sequence, comprised of two alternate bar units, is a meander wavelength; each wavelength is between 9 and 11 bankfull widths (4). The idealized alternate bar sequence is

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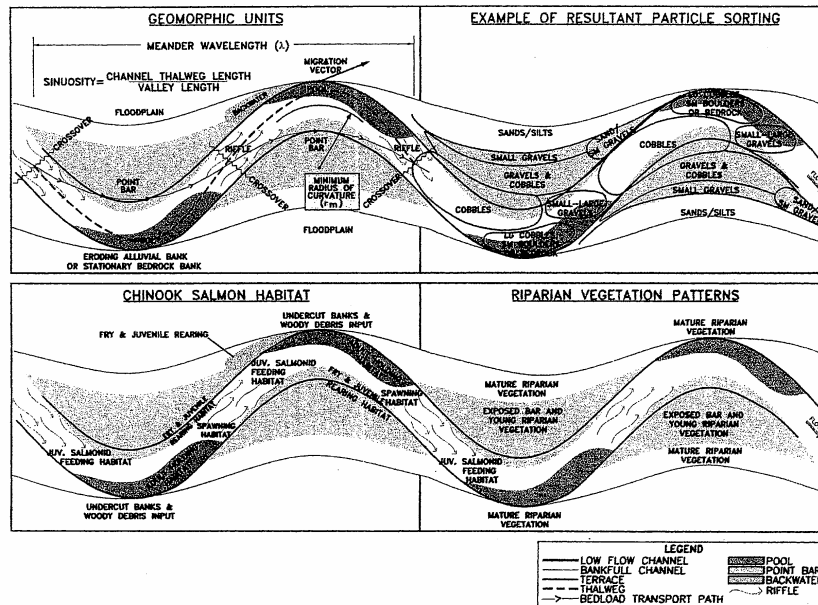


Fig. 1. An idealized alternate bar sequence showing geomorphic units, particle-sorting trends, typical salmonid habitats, and riparian vegetation succession patterns.

rarely found in nature, because natural geomorphic variability (e.g., valley width contractions, bedrock exposures, etc.) perturbs the idealized channel form shown in Fig. 1. Floods flowing through alternating bar sequences frequently rearrange the bar topography, producing diverse, high-quality aquatic and terrestrial habitat.

Attribute No. 2. Each annual hydrograph component accomplishes specific geomorphic and ecological functions. Annual hydrograph components (including winter storm events, baseflows, snowmelt peaks, and snowmelt recession limbs) collectively provide the impetus for processes that shape and sustain alluvial river ecosystems. These components are uniquely characterized by year-to-year variation in flow magnitude, duration, frequency, and timing.

Hydrograph components are seasonal patterns of daily average flow that recur from year to year. For many rivers in the western U.S., these hydrograph components include summer baseflows, rainfall- and rain-on-snow-generated floods, winter baseflows, snowmelt peak runoff, and snowmelt recession (Fig. 2). Each annual hydrograph component can be characterized by its interannual variability in flow magnitude, duration, frequency, and timing. A subset of all processes needed to create and sustain alluvial river ecosystems is provided by each hydrograph component. Eliminate or alter the interannual variability

of the hydrograph components, and the ecosystem is invariably altered.

Attribute No. 3. The channelbed surface is frequently mobilized. Coarse alluvial channelbed surfaces are significantly mobilized by bankfull or greater floods that generally occur every 1–2 years.

As streamflow rises throughout a winter storm and during peak snowmelt, a geomorphic threshold for mobilizing the channelbed surface is eventually exceeded. This flow threshold typically occurs over a narrow range of streamflow and varies spatially, depending on the morphology, grain size, and location of sediment deposits (Fig. 3). In general, grains on the channelbed surface are mobilized many times a year, but sometimes not at all in other years, such that, over the long-term, the streambed is mobilized on the order of once a year. The duration of channelbed mobilization is a function of the duration of the high flow, which is typically on the order of days.

Attribute No. 4. Alternate bars must be periodically scoured deeper than their coarse surface layers. Floods that exceed the threshold for scouring bed material are needed to mobilize and rejuvenate alternate bars. Alternate bars are periodically scoured deeper than their coarse surface layer, typically by floods exceeding 5- to 10-year annual maximum flood recurrences. Scour is generally followed by redeposition, often with minimal net change in the alternating bar topography.

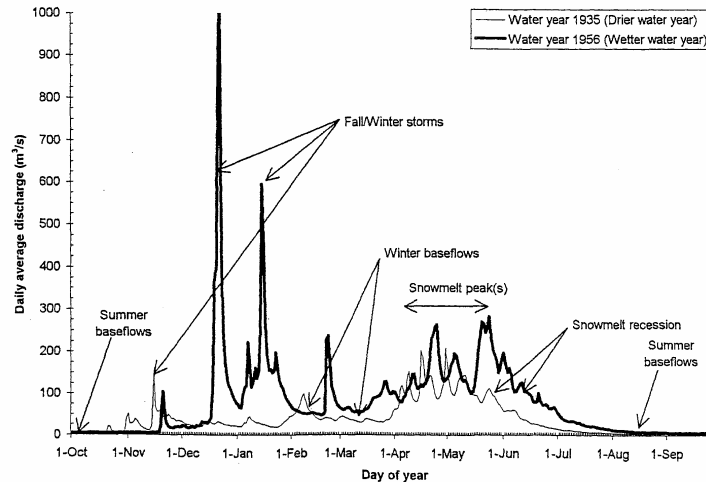


Fig. 2. Hydrograph components of an annual hydrograph by using 1956 (wetter year) and 1935 (drier year) unimpaired flows on the Trinity River in California.

Complex alternating bar sequences are partly created and maintained by providing the natural frequency and intensity of bed scour dependent on discharges that vary in magnitude and duration. During the rising limb of a hydrograph, after the bed surface begins to move, the rate of gravel transport rapidly increases and the bed surface begins to scour. The degree of scour can be significant, up to several feet deep. Infrequent, wet years typically generate storms with a high magnitude and long duration; scour depth will be substantial. On the receding limb of a flood hydrograph, gravel and cobbles redeposit, often resulting in no net change in channelbed elevation after the flood.

Attribute No. 5. Fine and coarse sediment budgets are balanced. River reaches export fine and coarse sediment at rates approximately equal to sediment input rates.

Although the amount and mode of sediment stored may fluctuate within a given river reach, channel-wide morphology is sustained in dynamic quasiequilibrium when averaged over many years. The magnitude and duration of high flows surpassing a flow threshold for channelbed mobility are critical for balancing the sediment budget. Chronic channelbed aggradation and/or degradation are indicators of sediment budget imbalances. A balanced coarse sediment budget implies bedload continuity; that is, the coarser particle sizes comprising the channel bed must be transported through alternate bar sequences.

Attribute No. 6. Alluvial channels are free to migrate. During lateral migration, the channel erodes older flood plain and terrace deposits on the outside bend whereas it deposits sediment on the bar and flood plain of the inside bend. Although outer and inner bend processes may be caused by different hydrograph components, the long-term result is maintenance of channel width.

Channel migration is one of the most important processes

creating diverse aquatic and terrestrial habitats: Sediment and woody debris are delivered into the river and flood plains are rebuilt on the inside of the meander. That the stream has occupied numerous locations in its valley is evidenced by direct observations of its movement over time, and by indirect evidence obtained if one digs deeply enough into the flood plain. Gravel and cobbles laid down by the river many years before will be found. The channel does not typically migrate during periods of low flow, but migrates during flows approaching and exceeding bankfull discharge. Shear stress on the outside of bends exceeds that necessary to erode the materials on the outside of the bank. In lower gradient reaches of alluvial rivers, migration tends to be more gradual.

Attribute No. 7. Flood plains are frequently inundated. Flood plain inundation typically occurs every 1–2 years. Flood plain inundation attenuates flood peaks, moderates alternate bar scour, and promotes nutrient cycling.

As flows increase beyond that which can be contained by the bankfull channel, water spreads across the flatter flood plain surface. The threshold for this process is the bankfull discharge. This first threshold allows flow simply to spill out of the bankfull channel and wet the flood plain surface; a slightly larger discharge is required to transport and deposit the fine sediments that are in suspension. Flood plain inundation also moderates alternate bar scour in the mainstem channel by limiting flow depth increases within the bankfull channel during floods. As water covers the flood plain, flow velocity decreases. Sediment begins to settle, causing fresh deposits of fine sands and silts on the flood plain. This deposition promotes riparian vegetation regeneration and growth.

Attribute No. 8. Large floods create and sustain a complex mainstem and flood plain morphology. Large floods—those exceeding 10- to

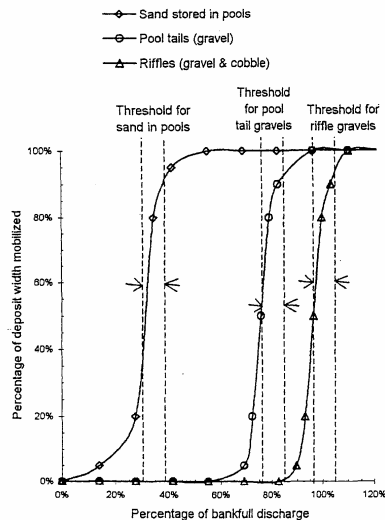


Fig. 3. Conceptual bed mobility thresholds, showing the narrow range in discharge that initially mobilizes the surfaces of selected alluvial features.

20-year recurrence events—reshape and/or redirect entire meander sequences, avulse mainstem channels, rejuvenate mature riparian stands to early successional stages, form and maintain side channels, scour flood plains, and perpetuate off-channel wetlands, including oxbows.

A still larger flow threshold than floodplain inundation is one that scours the flood plain. The streamflow necessary to surpass this threshold is typically many times the bankfull flow because shear stress on the vegetated flood plain surface must be high enough to cause scour. Infrequent large floods are critical for sustaining channel complexity because they change river location and morphology on a large scale and prevent riparian vegetation from dominating the river corridor.

Attribute No. 9. Diverse riparian plant communities are sustained by the natural occurrence of annual hydrograph components. Natural, interannual variability of hydrograph components is necessary for woody riparian plant life history strategies to perpetuate early and late successional stand structures.

Native riparian plant communities characteristic of alluvial river ecosystems are adapted to, and thus sustained by, a constantly changing fluvial environment. The magnitude and duration of annual hydrograph components needed for alternate bar scour, channel migration, floodplain inundation and scour, and channel avulsion provide necessary substrate conditions for successful seedling establishment and stand development. The timing and frequency of annual hydrograph components must coincide with seasonally dependent life history requirements, such as the short window of time when riparian plants are dispersing seeds. A sustainable supply of large woody debris

from the riparian zone ultimately depends on variable age classes of woody riparian vegetation and a migrating channel.

Attribute No. 10. Groundwater in the valley bottomlands is hydraulically connected to the mainstem channel. When flood plains are inundated, a portion of surface runoff from the watershed is retained as groundwater recharge in the valley bottomlands.

The river corridor is hydraulically interconnected. Groundwater in the floodplain is closely connected to mainstem flows (5) and can be periodically recharged by mainstem flooding. Avulsed meander bends often create oxbow wetlands, which retain direct hydraulic connectivity to mainstem surface flows.

The alluvial river attributes can be used to recommend flow releases and other management activities below an existing dam. Although this strategy is being considered in other locations, we will use the Trinity River in Northern California as an example, where the recovery of Pacific salmon and steelhead trout is being linked with the overall goal of restoring an alluvial river ecosystem.

The Trinity River at Lewiston

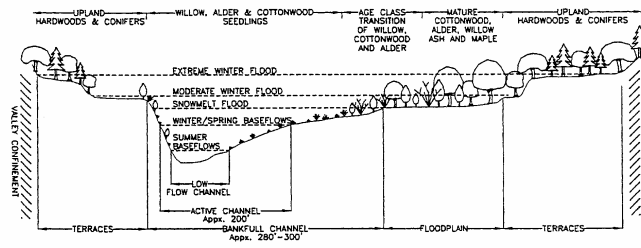
The mainstem Trinity River in northern California was once an alluvial river capable of constantly reshaping its channelbed and banks. In 1963, the U.S. Bureau of Reclamation constructed a large storage reservoir and diversion tunnel to store and divert up to 90% of the natural streamflow from the Trinity River into the Sacramento River for power generation and agricultural/municipal water supply (6). Historically, Trinity River daily flows varied from less than 2.8 m³/s baseflows in dry summers to near 2,800 m³/s floods in wet winters. Snowmelt peak runoff and its recession limb were two critical annual hydrograph components generated upstream of Lewiston (Fig. 2). In wet years, snowmelt runoff typically peaked at 340 m³/s or higher in late June or July, whereas in dry years the peak would only be 110 m³/s or lower in mid-May through mid-June (7). Together they provided the magnitude and duration of flows needed to balance the sediment budget and accomplish a wide range of physical and biological processes. Both hydrograph components theoretically could have occurred at any time of the year and still have balanced the sediment budget. But seasonal timing of snowmelt runoff was critical to ecological processes.

Peak snowmelt runoff was an important environmental cue for juvenile salmonids to begin their migration to the Pacific Ocean (2). Amphibians needed snowmelt runoff to keep oxbow wetlands inundated. If the snowmelt recession limb did not extend into early June, the wetland might have dried out before amphibians could complete their aquatic life history stage. Interannual variability of timing, magnitude, and duration of snowmelt recession limbs determined whether a particular oxbow wetland could sustain an amphibian population. Successful cottonwood regeneration on freshly deposited floodplains also required specific snowmelt peaks and recession limbs to create favorable moisture conditions for seedling germination, as well as the absence of extreme winter storm events the following year to prevent seedling loss.

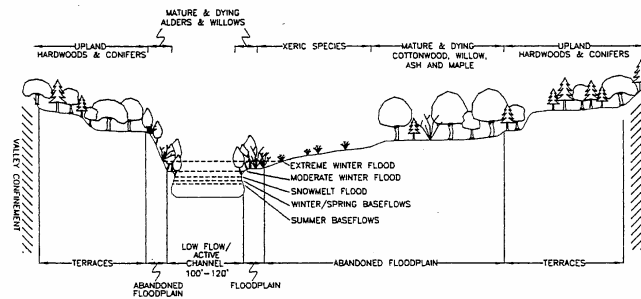
After the dam was completed, flows were kept nearly constant at 4.2 m³/s; river managers thought that 4.2 m³/s would provide ideal hydraulic conditions for chinook salmon spawning. What river managers did not foresee was that by eliminating hydrograph components they would set in motion a chain of predictable events. Seedlings, no longer scoured away by frequent winter and snowmelt floods, rapidly encroached onto the alternate bars. Prominent berms of freshly deposited sand and silt accumulated along the channel margins within the maturing dense riparian vegetation (Fig. 4), effectively isolating the floodplain from the mainstem river. High shear stresses of infrequent high flow events were then concentrated in the channel's center.

APPLIED PHYSICAL SCIENCES

A) PRE-TRD CONDITIONS



B) PRESENT DAY CONDITIONS: RIPARIAN BERM FULLY DEVELOPED WITH MATURE VEGETATION



C) DESIRED FUTURE CONDITIONS: SCALED DOWN CHANNEL MORPHOLOGY WITH FLOODPLAINS AND NATURAL RIPARIAN REGENERATION

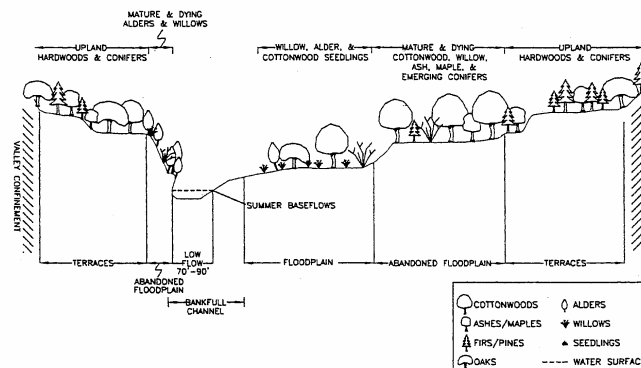


Fig. 4. Evolution of channel geometry and riparian vegetation in response to flow and sediment regulation from the Trinity River Division of the Central Valley Project in California, 1963-1999.

The river's complex alternate bar morphology was quickly transformed into a smaller, confined rectangular channel (Fig. 4) now unable to meander. Floodplains were abandoned. Cumulatively, this flume-like morphology and floodplain isolation greatly reduced habitat quantity and complexity important to numerous aquatic and riparian species.

Salmon populations were immediately and significantly affected. With most of their primary spawning and rearing habitat upstream of an impassable dam, the mainstem channel below Lewiston became the primary habitat provider. When young salmon emerge from spawning gravels as fry, their immediate habitat preference is for gently sloped, low velocity, exposed cobble areas typically found along predam alternate bar margins. In contrast, the vertical banks of the postdam channel allow excessive velocities to extend up to the banks' edges. Although the constant 4.2 m³/s dam release temporarily accommodated spawning habitat needs, fry rearing habitat became a limiting factor to salmon production because of this rapid change in channel shape.

Was the widespread habitat loss in the Trinity River predictable? Managers who expected that spawning habitat would be preserved below the dams ignored the sediment budget (*Attribute No. 5*). Trinity and Lewiston dams prevent all bed material from passing downstream; the only sources for spawning gravels are downstream tributary inputs, minor flood plain scour, and occasional gravel introductions. The snowmelt peak and recession hydrograph components were completely eliminated (*Attribute No. 2*), even though this river ecosystem had been dominated by snowmelt runoff. Of the planned flow releases greater than 4.2 m³/s, all were well below the threshold for mobilizing the channelbed (*Attributes Nos. 3 and 4*), routing bed load (*Attribute No. 5*), or inundating the floodplain (*Attributes Nos. 7, 8, and 10*). Consequently, seedlings escaped being scoured and encroached onto the predam alternating bars (*Attribute No. 9*). Loss of the alternate bar morphology (*Attribute No. 1*) was inevitable; so was the loss of habitat created by it.

Was the widespread habitat loss on the Trinity River preventable? Anadromous salmonids cannot pass upstream of Lewiston Dam, therefore their habitat will never be completely replaced unless both dams are removed. The mainstem Trinity River below Lewiston Dam cannot be brought back to its original dimension. But a scaled-down alluvial channel morphology in equilibrium with its constrained sediment budget, reduced hydrograph components, and occasional bed material introductions could greatly restore habitat abundance and quality.

A new restoration approach for the Trinity River that is guided by the alluvial attributes is in its final planning stages. An environmental impact statement/report (6) includes this new restoration strategy, developed by the U.S. Fish and Wildlife Service and Hoopa Valley Tribe (2), as one fishery restoration alternative. The management goal would be to rebuild and maintain a self-sustaining alternate bar morphology and riparian community by using the attributes as a blueprint. Planned releases from Lewiston Dam would provide snowmelt peak and snowmelt recession hydrograph components (*Attribute No. 2*) to recreate physical processes that will recover an alluvial channel morphology (*Attributes Nos. 1, 3, 4, and 6–8*) and sustain off-channel wetlands (*Attribute No. 10*). The sediment budget would be balanced by releasing appropriate hydrograph components with sediment transport capacities commensurate with sediment inputs (*Attribute No. 5*). If transport capacities exceed supply, as might occur during large flood releases in wet years, bed material would be introduced into the mainstem to compensate. Riparian berms on segments of fossilized alternating bars (in the upper 64 km) would be mechanically cleared as a precursor to reestablishing dynamic alternating bars (*Attribute No. 9*).

Conclusion

Society is embarking on a grand experiment. Recent dam removals are merely forerunners of a much larger task ahead. Many more dams will remain than are removed. In practice, we must rely on the crucial assumption that native species have evolved with the natural flow regime. Violating this assumption often results in consequences that can be highly significant and difficult to reverse. The intent to recover alluvial river ecosystems below dams, as proposed for the Trinity River in northern California, will be controversial. To obtain the societal benefits of water diversion, flood control, and hydropower generation, rivers will continue to receive less flow and sediment than under unimpaired conditions. But if important attributes are provided to the greatest extent possible, alluvial river integrity can be substantially recovered. The compromise will be a smaller alluvial river; it may not recover its predam dimensions, but it would exhibit the dynamic alternate bar and floodplain morphology of the predam channel. Although a restoration strategy guided by the alluvial attributes is an experiment, it may be the most practical direction toward recovering regulated alluvial river ecosystems and the species that inhabit them.

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Seasonal Boundary Dynamics of a Groundwater/Surface-Water Ecotone

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SEASONAL BOUNDARY DYNAMICS OF A GROUNDWATER/ SURFACE-WATER ECOTONE

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Abstract. Interstitial water, faunal samples, and hydrogeological data were collected beneath a riffle on the Speed River, southern Ontario, Canada. The purpose was to identify the location and seasonal fluctuation of the hyporheic/groundwater interface and to examine several aspects of water mass chemical signatures and the dynamics of the interstitial fauna. Concentration discontinuities in several water chemistry parameters delineated the chemical boundary between the true groundwater and hyporheic habitats. The groundwater mass was characterized as having higher levels of ammonium, alkalinity, and conductivity, and lower nitrate levels. Differences in water chemistry between the hyporheic and groundwater zones persisted throughout the year, though no single variable differed quantitatively between these two zones on all occasions. The location of the chemical discontinuity varied seasonally. Whereas hyporheic and groundwater faunal subunits of the interstitial community were identified and the location of the subunits coincided with the chemical breaklines, response to shifts in the position of the hyporheic/groundwater interface was taxon rather than subunit based. Fauna therefore provided poor spatial resolution in terms of pinpointing the location of the interface. Boundary fluctuation coincided with extremes in seasonal discharge patterns and was regulated by the relative strength of the upward force of baseflow and the downward force of advecting surface water. Identifying patterns of fluctuation of the hyporheic/groundwater interface, and consequently hyporheic habitat volume, may have important consequences for the storage, retention, and cycling of nutrients in lotic ecosystems.

Key words: ecotone; freshwater invertebrates; groundwater; hyporheic zone; hyporheic/groundwater interface; water chemistry.

INTRODUCTION

Through initiatives cosponsored by the International Unions' Scientific Committee on Problems of the Environment (SCOPE) and UNESCO's Man and the Biosphere Programme (MAB), the characterization of landscape boundaries, or ecotones (sensu Holland 1988), has become an important research objective. It is now widely recognized that ecotones function as regulatory sites in the movement of nutrients (e.g., Lowrance et al. 1984), organic materials (e.g., McArthur and Marzolf 1986), and biotas (e.g., Ward and Palmer 1994) across landscapes. Concomitantly, there has developed a body of literature concerning the importance of ecotone management (see review in Di Castri et al. 1988, Naiman and Decamps 1990, Holland et al. 1991). While ecosystem boundaries often are defined by conspicuous changes in ecosystem characteristics (e.g., transition zone from forest to grassland), the ecotone between the surface and subsurface environments in lotic ecosystems, the hyporheic zone, is not precisely delineated as it cannot be reduced to a simple physical boundary (Gibert 1991).

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Early attempts to describe the spatial extent of hyporheic zones were based largely on the vertical and lateral distributions of epigeal (derived from the surficial river bed environment) or hypogean (derived from the true groundwater environment) fauna. Where hypogean taxa were absent or poorly developed, studies focused on the depth of penetration of epigeal fauna. Both Coleman and Hynes (1970) and Williams and Hynes (1974) suggested that the hyporheic zone extended deep into the substratum (30–70 cm) beneath a riffle on the Speed River, Ontario, Canada, as they collected high numbers of typical epigeal taxa there. Where hypogean taxa were more populous, others have attempted to demarcate hyporheic limits based on epigeal–hypogean associations (e.g., Danielopol 1989, Ward 1989, Bretschko 1991). In these studies, the distinction between the hyporheic zone and the true groundwater zone was less clear, however, as hypogean–epigeal associations were often more spatially complex.

More recently, a few studies have heeded Hynes' (1983) plea to more actively integrate the principles of groundwater science into studies of river ecology and have attempted to delineate hyporheic zones using hydrogeological and chemical measures. Based on work with conservative tracer injections, Triska et al. (1989)

suggested a functional means by which the spatial extent of the hyporheic zone could be identified. Their two-component hyporheic zone included the surface region (the area beneath the bed surface that was chemically indistinguishable from the channel water, containing >98% advected channel water) and the interactive zone (characterized by <98% but >10% advected channel water). Williams (1989) identified several chemical discontinuities in two Canadian rivers, with break lines occurring from the river margin obliquely downwards under both the river bed and bank. He proposed that these discontinuities were indicators of the position of the hyporheic/groundwater interface. Using depth-to-groundwater temperature (i.e., the depth at which water temperature is isothermal with true groundwater) as an indicator of the location of the hyporheic/groundwater interface, White (1993) generated a three-dimensional model of the hyporheic zone beneath a 9 m long pool-riffle-pool sequence. These more recent studies are unique, as they represent the first explicit attempts to identify parameters that define the location of the hyporheic/groundwater interface. Yet, they provide no data to describe how the interface may shift in response to changes in relative inputs of the various sources contributing to flow in rivers. Temporal fluctuation in the volume of hyporheic interstices is likely to affect the retention and processing of material exchanged between the surface and subsurface environments. Accordingly, there is a need to identify patterns of hyporheic volume fluctuation in order that a more holistic interpretation of: (1) the nature and causes of the changes in water chemistry; and (2) the quantification of the import, export, and transformation of dissolved and particulate organic matter, which occur during exchange between contiguous groundwaters and streams, can be acquired (Williams 1993).

The goal of this study was to examine seasonal boundary fluctuation of the hyporheic/groundwater interface by quantitatively assessing the biotic and abiotic parameters beneath a stream riffle. Specifically, we were interested in the following aspects of hyporheic/groundwater dynamics: (1) do the hyporheic and groundwater zones have distinct and distinguishable chemical signatures and therefore could chemical discontinuities identified in the subsurface delineate the location of the hyporheic/groundwater interface?; (2) is the subsurface community divisible into a number of subunits whose relative positions identify the location of the hyporheic/groundwater interface?; (3) does faunal subunit distribution track seasonal shifts in the position of the hyporheic/groundwater interface?; and (4) is hyporheic/groundwater interface fluctuation related to the relative strengths of the upward force of baseflow and downward force of advected channel water?

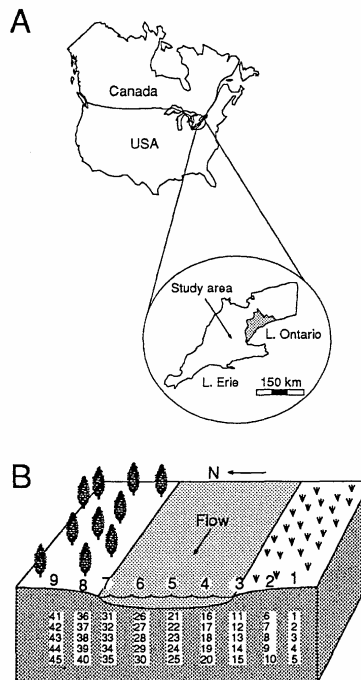


FIG. 1. Study site at the Speed River, Ontario, Canada. (A) North America with inset showing southern Ontario (shaded area is Metropolitan Toronto). (B) Orientation of sampling stations (numbers 1–9 across the river and sample site numbers 1–45). At each station fauna, interstitial water samples, and hydrogeological data were collected at each of five depths (20, 40, 60, 80, and 100 cm below the surface of the river bed, corresponding to numbers 1–45).

MATERIALS AND METHODS

The study area

The study was conducted near the source of the Speed River, southern Ontario, Canada (Fig. 1). The Speed flows through gently undulating hills, drumlin fields, glacial spillways, and swampy depressions with an average gradient of 2 m/km (Ontario Department of Planning and Development 1953, Chapman and Putnam 1984). Bedrock in this region belongs to the Guelph dolomite horizon and soils are grey-brown podzols and humic gleysols intermixed with outwash sand, gravels, and coarser glacial tills (Hoffman et al. 1964). Approximately 80% of the watershed is used for mixed farming, although floodplains of the upper course are

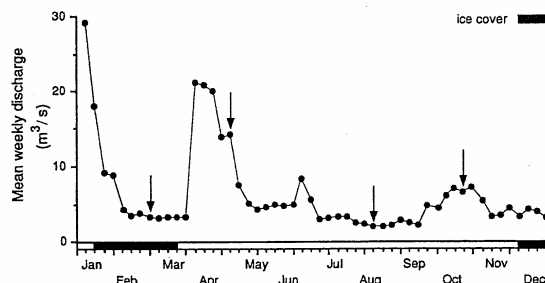


FIG. 2. Mean weekly discharge for the Speed River, 1993. Arrows indicate commencement of sampling period. Data were provided by the Water Survey of Canada, Environment Canada, Guelph, Ontario, Canada.

largely wooded, reforested, or maintained as rough pastures (Bishop and Hynes 1969).

The main sampling area, the Rowan Farm study site (43°43'54" N, 80°16'24" W), consisted of a 40-m riffle and the adjacent riparian corridor. Along this reach, river width varied from 4 to 6 m and water depth ranged from 7 to 12 cm during baseflow conditions to 70 cm at the height of spring run-off. Typically, the seasonal discharge pattern along this portion of the Speed River is characterized by extended periods of high flow during the spring and fall and low flow during the summer and winter (unpublished data; Water Survey of Canada, Environment Canada, Guelph, Ontario, Canada).

To a depth of 30 cm, the substrate is composed primarily of gravels (<10 cm diameter) intermixed with silts and sands together with a few larger dolomite slabs. Below 30 cm, substrate heterogeneity is low and substrate composition is dominated by medium and fine sands (sensu Cummins 1962). The subsurface sediment profile has been described in detail by Stocker and Williams (1972). Riparian vegetation is dominated by eastern white cedar (*Thuja occidentalis* L.) and paper birch (*Betula papyrifera*) mixed with willow (*Salix* sp.) along the north bank of the river and by goldenrod (*Solidago* sp.) and various grasses along the south bank.

Data collection

Sampling program.—As sampling effort was directed towards monitoring seasonal trends, biological, chemical, and hydrogeological data were collected during a single week-long sampling period per season from winter 1992–1993 through fall 1993. The exact time of sampling was based on seasonal river discharge extremes (Fig. 2). Spring and fall sampling commenced immediately following the peaks of seasonal discharge (29 April through 4 May and 27 October through 1 November, respectively). Summer and winter sampling occurred during the period when baseflow accounted for the greatest proportion of stream discharge (18 Au-

gust through 23 August and 27 February through 4 March, respectively).

All data were collected from nine permanently installed sampling stations positioned at the head of the riffle in a transect across the river and into the adjacent banks (Fig. 1B). The sampling device, the colonization corer, combines aspects of an artificial substrate sampler (after Panek 1991) and a bundle piezometer (Cherry 1983), which made it possible to collect faunal samples, interstitial water samples, and potentiometric head measurements at 0.2-m intervals between 0.1 and 1.1 m below the river bed surface. A detailed description of the colonization corer can be found in Fraser et al. (1996) and its performance, in comparison with other hyporheic samplers, is reported in Fraser and Williams (1997).

Macroinvertebrates.—Internal acrylic colonization sleeves, filled with sterilized Speed River sediment to specifications that mimicked the vertical sediment particle distribution of the river bed, were placed within the permanent standpipes. Following a minimum colonization period of 9 wk, the sleeves were removed from the corer with the aid of a tripod and winch. Both benthic (Mason et al. 1973, Lamberti and Resh 1985) and hyporheic (Coleman and Hynes 1970, Boulton et al. 1991) substrate colonization studies indicate that this is a sufficient time for levels of both organic matter and fauna to return to natural levels. As the sleeves were withdrawn they were wrapped in plastic film to prevent the loss of invertebrates. The sleeves were immediately cut into 20-cm sections (volume = 125 mL), and the sediment from each section was transferred to plastic sample jars. Samples corresponding to depths 20, 40, 60, 80, and 100 cm below the surface of the river bed thus were obtained from each station. These samples included sediment ± 10 cm from the depth indicated (e.g., 20-cm sample = 10–30 cm). In the field, all samples were preserved and stained using a mixture of 10% formalin and rose bengal. In the laboratory, each sample was floated with saturated calcium

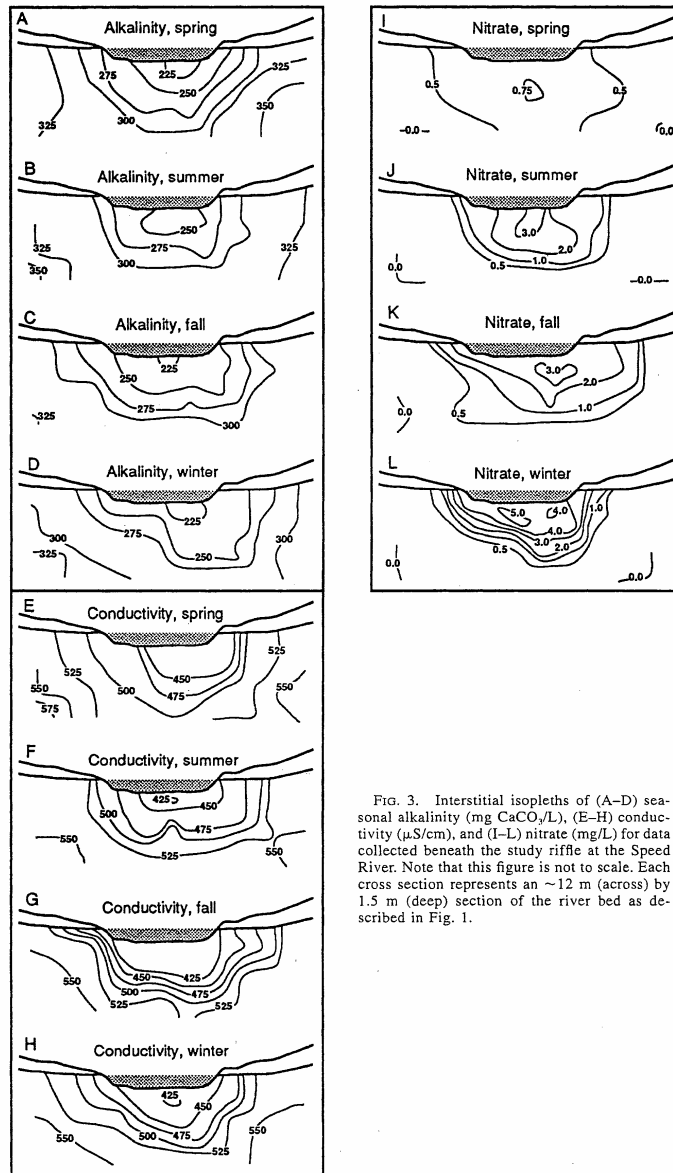


FIG. 3. Interstitial isopleths of (A–D) seasonal alkalinity (mg CaCO₃/L), (E–H) conductivity (μS/cm), and (I–L) nitrate (mg/L) for data collected beneath the study riffle at the Speed River. Note that this figure is not to scale. Each cross section represents an ~12 m (across) by 1.5 m (deep) section of the river bed as described in Fig. 1.

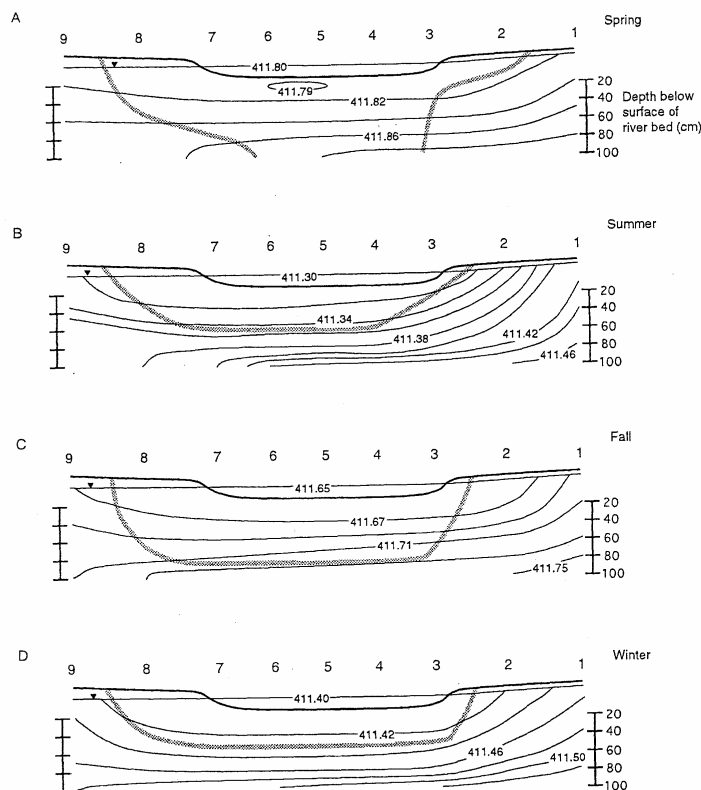


FIG. 4. Hydraulic head distribution for a 1.5×12 m cross section of the Speed River study site for (A) spring, (B) summer, (C) fall, and (D) winter. Stream cross section is as described in Fig 1. Hydraulic head contours join points of equal water-level elevation in meters above sea level (ASL). Contour interval is 0.02 m. Thick, grey lines represent the approximate location of the hyporheic/groundwater interface as determined by the TWINSPAN analysis and water chemistry data.

chloride to separate flocculent (organic) from nonfloculent material, washed through a $53\text{-}\mu\text{m}$ mesh net, and hand-sorted under $10\text{--}40\times$ magnification with the aid of a dissecting microscope. The nonfloculent portions of the samples were visually inspected for cased caddisflies, bivalves, and other invertebrates not likely to be separated during floating.

Chemical measurements.—High-density polyethylene bottles were prepared according to a four-step protocol: (1) detergent wash; (2) 24-h 10% nitric acid soak; (3) distilled water rinse ($7\times$); (4) de-ionized water rinse ($5\times$). Each of the colonization corer water sampling tubes was cleared and allowed to refill prior to sam-

pling. Triplicate water samples were pumped peristaltically through plastic tygon tubing from each of the 45 tubes as well as from the river itself. Each bottle was overfilled with at least two equivalent bottle volumes prior to sealing and storage at 4°C until analysis could be performed. Cation and anion samples were filtered on site through $0.2\text{-}\mu\text{m}$ mesh cellulose filters with the aid of a hand-operated vacuum pump, and cation samples were acidified with ultrapure nitric acid (Ultrex II) to a pH of 2. Field and laboratory blanks and standards of known concentration were prepared in order to confirm the integrity of results derived from the analytical methods used.

Conductivity, temperature, pH, and dissolved oxygen were measured in the field using an ICM Water Analyzer, Series 51100 (Industrial and Chemical Measurement Incorporated, Hillsboro, Oregon, USA). Alkalinity (CO_3^{2-} and HCO_3^- concentrations) was determined in the laboratory within 24 h of collection, using the color change standard method (APHA 1985). Biological oxygen demand was measured as the difference between the initial dissolved oxygen concentration (meter reading) and the dissolved oxygen level (modified Winkler method; APHA 1985) following 24 h of air incubation at 20°C in the dark. Major ion concentrations were determined by high performance liquid chromatography using a Dionex 4000 Ion Chromatograph (Dionex Corporation, Sunnyvale, California, USA). All analyses were done in triplicate.

Sample quality was assessed by determining "correctness." Correctness was evaluated based on the assumption that water is a neutral substance and therefore the cation milliequivalent sum should equal the anion milliequivalent sum. The following formula was used to calculate the charge-balance error (E):

$$E (\%) = [(\sum \text{zm}_c - \sum \text{zm}_a) / (\sum \text{zm}_c + \sum \text{zm}_a)] \times 100 \quad (1)$$

where zm_c is the molality of cation species and zm_a is the molality of anion species (WATSPEC; Wigley 1977). Samples with $E > 10\%$ suggested that the chemical analyses likely contained inaccuracies (Freeze and Cherry 1979, Hem 1989) and therefore were not included in further data analyses. In cases where a sample was eliminated from further data analyses the mean value was based on the values of the remaining samples. Less than 3% of the total number of samples collected were eliminated and in no instance was it necessary to discard more than one in three samples from a triplicate.

Hydrogeology.—Water-level measurements were made in each water-sampling tube using an electric water-level indicator. Measurements were repeated 6 times over the duration of each week-long seasonal sampling period. The head data were contoured to depict potential groundwater flow for a vertical cross section of the study site, ~12 m across by 1.5 m deep. Equipotential lines join points of equal hydraulic head and, assuming isotropicity of the medium through which flow occurs, flow is perpendicular to these lines. The velocity of flow is proportional to the hydraulic gradient (i), the change in water-level elevation between two points over the distance through which the change takes place (Freeze and Cherry 1979).

Data analysis

Ordination and classification techniques were used to identify potentially important environmental variables and taxa, and to assess the degree of similarity among sampling sites (Furse et al. 1984, Wright et al. 1984). Species assemblages were ordinated using Cor-

respondence Analysis (CA) and the program CANOCO (ter Braak 1986, 1988) applied to a single, combined-seasons invertebrate data set. This allowed analysis of the spatial and temporal data simultaneously. In CA, sites are arranged into an objective order, those with similar taxonomic composition occurring most closely together. The relative strengths of the ordination axes are given by eigenvalues and the relative importance of each axis, in explaining variance in the data set, is expressed as the ratio of an eigenvalue to the sum of the eigenvalues for all axes combined. Axes are measured in standard deviations and are a measure of taxon turnover. A complete turnover in taxa can be expected in 4 sd (Hill 1979). A sizeable proportion of the specimens collected were first- or early-instar larvae that were difficult to identify to the genus or species level. Consequently, so as not to complicate the data set with multilevel taxonomic identifications, the family level was used for ordination. We acknowledge that patterns in hyporheic faunal distribution have been shown to occur at fine taxonomic levels (e.g., Williams 1989, Vervier and Gibert 1991); however, in this study identification to these levels proved impractical. CA axes were related to measured environmental variables using multiple linear regression (SPSS 6.1.3; Norusis 1995). Although linear tests may not recognize cyclical or seasonal patterns, this methodology has been used successfully in previous studies with similar objectives (e.g., Omerod and Edwards 1987, Grown and Davis 1994).

Classification of sites was made by two-way indicator species analysis (TWINSPAN, Hill 1979) following conversion of quantitative taxon abundance data into a qualitative format. Conversion was accomplished by categorizing each taxon and its abundance level into individual units termed pseudospecies. In the analysis, taxa with high abundance, for example, are included not only at the appropriate pseudospecies abundance level, but also at all lower levels. As a result any given taxon may be present in a data set numerous times (Furse et al. 1984). Further details pertaining to this and advantages associated with TWINSPAN are given by Furse et al. (1984) and Wright et al. (1984). Based on cursory examination of our invertebrate density data, we applied three logarithmic abundance categories (each with a corresponding pseudospecies) to family-level identifications. Abundance categories 1 and 2 correspond to pseudospecies for which 1–9 and 10–99 individuals, respectively, were collected. Abundance category 3 corresponds to pseudospecies for which >100 individuals were collected. We elected to use three pseudospecies per taxon as we thought this adequately reflected the difference between rare and abundant families. The analysis was arrested following three dichotomies as beyond this level groupings were likely to be too small to be meaningful.

For TWINSPAN site groups (first TWINSPAN dichotomy only), mean values of individual chemical pa-

TABLE 1. Mean hydraulic gradient (i , cm/cm) between the surface of the river bed and a depth of 1 m below the bed surface in the Speed River, February 1993 through October 1993. River cross section is divided into two sections—midriver to Station 1 and midriver to Station 9.

Sampling period	Midriver to Station 1	Midriver to Station 9
Spring	0.08	0.04
Summer	0.16	0.07
Fall	0.10	0.06
Winter	0.12	0.08

rameters that were significantly correlated with CA axes 1 or 2 (and therefore presumably related to differences in macroinvertebrate assemblage) were calculated. Means were compared using t tests (SPSS 6.1.3; Norusis 1995) following appropriate transformations to fulfill the assumptions of normality (Wilk-Shapiro) and homoscedasticity ($F_{\max}$).

For the multiple regression, an α level of $P < 0.05$ was used as the critical value for statistical significance. For the comparisons of TWINSPAN site group means, α was corrected for multiple tests using the Bonferroni method ($P < \alpha/n$, where n is the number of null hypotheses tested; Sokal and Rohlf 1981). We deemed it appropriate to use $P < 0.05$ in the regression analysis, as this was employed purely as an exploratory tool to identify potentially important environmental variables. A more rigorous level of significance was adopted for the subsequent comparison of TWINSPAN site group means, which validated only those variables, identified by the regression analysis, likely to be of biological significance.

RESULTS

Macroinvertebrates

In total, 28 different taxa were identified (the majority to family) from samples obtained at the Speed River. These included representatives of both the "occasional" (the larvae of benthos that occupy the hyporheic habitat for a portion of their life cycle) and "permanent" (animals that complete their entire life cycle in the hyporheic habitat) hyporheos (sensu Williams and Hynes 1974), though the former were far more numerous than the latter. Total density was highest during the fall and winter (>100 animals per liter of sediment) and lowest during the summer (<50 animals per liter sediment). Total density decreased with depth below the river bed and was lower also outside the active river channel. Of the aquatic insect larvae identified, chironomids were most abundant and were found regularly to depths of 60 cm below the river bed, though specimens were found to 80 and 100 cm below the bed during the spring and fall. Larvae of other aquatic insects (e.g., Ephemeroptera, Trichoptera, Plecoptera) typically penetrated to only 20 cm below the bed surface though they, like the chironomids, were

found deeper during spring and fall. Lumbricid oligochaetes and hyalellid amphipods were the only taxa that seemed particularly limited in terms of their spatial distribution. Lumbriculidae were found only outside the limits of the active river channel and Hyalellidae were found only deep (60–100 cm) below the bed surface.

Water chemistry

Interstitial water was characterized as calcium-bicarbonate, which is typical for both this river system (e.g., Williams and Hynes 1974) and this region (e.g., Hill 1990). Over the study period, water temperature ranged from 22–24°C to 2–0°C in the interstices near the surface of the river bed and changed in near-uniform increments to 6–8°C deep below the bed and under the river banks. Not surprisingly, dissolved oxygen decreased with depth below the river bed, although there were differences among seasons in terms of the depth of detectable levels of oxygen. During spring and fall oxygen was detectable regularly to 80 cm below the bed surface, but it was rarely detectable below 60 cm during summer and winter.

Severe spatial concentration gradients were evident for three water chemistry parameters (alkalinity, conductivity and nitrate), and these data are summarized in Fig. 3. At all sampling times, near-surface interstitial water had lower levels of both alkalinity (Fig. 3, A–D) and conductivity (Fig. 3, E–H) than the groundwater. Although alkalinity and conductivity levels generally decreased with depth, this trend was not uniform. Chemical discontinuities occurred landwards from each of the river margins down beneath the channel. In summer and winter these breaklines occurred near the river margins and at shallow depths under the river bed; they extended farther landwards and deep beneath the bed in the spring and fall. Similar spatial and temporal patterns were observed for nitrate (Fig. 3, I–L). Nitrate levels peaked in the shallow interstices directly beneath the river bed in the summer and winter with this area extending deeper and landward in the fall but, unlike the latter two parameters, not during the spring.

TABLE 2. Correspondence analysis summary for the ordination of the combined, all-seasons data set. Only the values for the first four ordination axes are given.

Axis	Eigenvalue	Cumulative % variance explained	Length (sp)
1	0.287	35.2	2.28
2	0.103	47.8	1.16
3	0.048	48.4	0.94
4	0.037	48.9	1.01

Note: Variance explained by each axis is the ratio of its eigenvalue to that of the total inertia (i.e., all ordination axes combined).

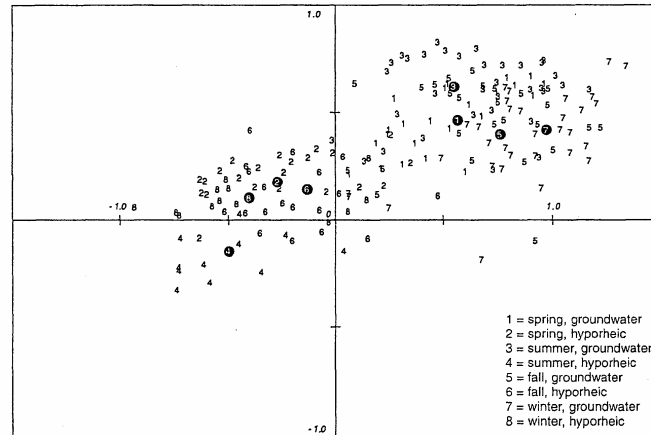


FIG. 5. CA Axis 2 vs. CA Axis 1 for the combined seasons taxonomic data. Data points are numbered according to level-1 TWINSpan groups. Solid circles with numbers represent the mean x, y coordinates for the corresponding TWINSpan level-1 groups.

Hydrogeology

Interstitial water flow within the component of the flow system sampled appeared to be typical of an effluent river (sensu Williams 1989) (Fig. 4). Measured hydraulic potential, or head, beneath the river was greater than that of the water level of the river, indicating that net water movement was generally upwards into the channel. In only one instance was this not the case: during the spring sampling period, the river head was greater than the head 20 cm below the bed surface at midriver, indicating the potential for net water flow into the interstices (Fig. 4).

From spring through fall, between 60 and 100 cm below the surface of the river bed, at sampling stations 7, 8, and 9, the head data indicated that flow was virtually horizontal across the river rather than vertical into the river. The head data also indicated that the relative upward force of baseflow varied among sea-

sons and within seasons across the transect. There was substantial seasonal variation in the hydraulic gradient (i) between the river and the subsurface (Table 1), i was greatest for the summer and winter sampling periods. Periods of high i were coincident with times of the year when discharge in the river was dominated by baseflow. For individual seasons, the head distribution was asymmetrical across the river (Table 1). For all seasons, i was greater from midriver to the south bank than from midriver to the north bank.

Ordination and relationship with measured environmental parameters

The primary and secondary ordination axes, which together explained nearly 50% of the variance in the data set, were 2.28 and 1.16 SD in length and represented changes in taxonomic composition of ~85 and 55%, respectively (Table 2). Grouping of sampling sites was readily evident (Fig. 5) and corresponded well with the distinction between groundwater and hyporheic sites generated by the level-1 TWINSpan dichotomy. The ordination displayed a much stronger distinction between hyporheic and groundwater community subunits vs. seasonal changes in faunal composition. This is likely the result of the level of taxonomic identification used, as seasonal changes in the major taxa are more conspicuous at the genus level (Williams and Hynes 1974).

Water chemistry parameters significantly correlated with either CA Axis 1 or 2 scores are listed in Table 3. Alkalinity and conductivity were the most highly

TABLE 3. Results of the multiple linear regression (correlation coefficients) between CA axes 1 and 2 and measured environmental parameters for which there was one significant correlation ($P < 0.05$).

Variable	Axis 1	Axis 2
Alkalinity	0.364***	...
Conductivity	0.323***	...
Dissolved oxygen	-0.195*	...
Nitrate	-0.163*	-0.181*
Sodium	...	0.161*

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$. Ellipses indicate that the correlation was not significant.

correlated with Axis 1. Other variables significantly correlated with Axis 1 included dissolved oxygen and nitrate (Table 3). Variables significantly correlated with Axis 2 included nitrate and sodium (Table 3).

Classification

The two site groups generated at TWINSpan level 1 were characterized as either groundwater or hyporheic sites for each seasonal invertebrate data set (Fig. 6). Comparison of the TWINSpan classification scheme and the CA axes suggested that site group membership was strongly related to water conductivity and alkalinity. During all seasons, groundwater sites were characterized by higher conductivity and alkalinity levels, though statistical differences between mean levels of conductivity and alkalinity were found only for spring and fall and spring, respectively (Table 4). Nitrate concentration was also a strong indicator of group membership. The mean nitrate concentration of hyporheic sites was significantly greater than that of groundwater sites during summer, fall, and winter (Table 4). A small degree of seasonal variation in site group membership was evident. For the fall, and especially the spring, sampling periods, the boundary between the hyporheic and groundwater site groups was located deeper beneath the river bed and farther into the banks. Density and diversity were generally higher in the hyporheic zone, although many of the numerically dominant taxa were found also in groundwater sites. Taxa that were particularly diagnostic of hyporheic sites included the Ephemeroptera (Caenidae, Ephemerellidae), Plecoptera, and Trichoptera (Helicopsychidae, Hydropsychidae) (Fig. 7). Taxa that were diagnostic of groundwater sites included the Amphipoda (Hyalinellidae) and Oligochaeta (Lumbriculidae) (Fig. 7).

At TWINSpan level 2, the division of hyporheic sites seemed depth related—generally shallow sites separated from sites deeper under the river bed (Fig. 6). The division between shallow and deep sites was closer to the surface of the river bed during the summer and winter and deeper beneath the bed during spring and fall. In each of the seasons the division was based on the abundance of the diagnostic taxa. For each season, differential taxa of the shallow hyporheic sites included pseudospecies 2 taxa (i.e., high abundance), while deeper hyporheic sites included pseudospecies 1 taxa (low abundance). The division of groundwater sites generally separated riparian groups from those directly beneath the active river channel (Fig. 6). Lumbriculidae were found exclusively outside the active channel, whereas Hyalinellidae were found in greater abundance beneath, but within the lateral limits of, the river.

TWINSpan level-3 divisions failed to produce any discernible patterns. Group membership often was limited to too few sites (one or two samples) to prove meaningful.

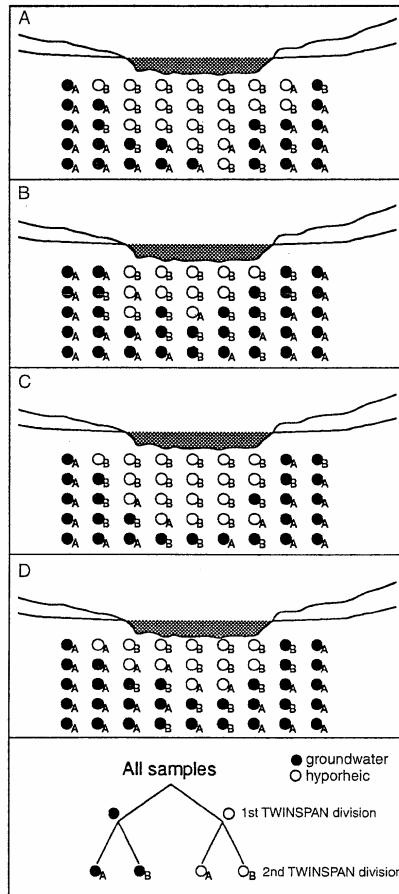


FIG. 6. Classification of the 45 sampling sites as revealed by TWINSpan analysis for (A) spring, (B) summer, (C) fall, and (D) winter. Stream cross section is as described in Fig. 1B.

DISCUSSION

One strategy previously employed to locate the hyporheic/groundwater interface has been to separate the interstitial community into its epigeal, hypogean, and hyporheal (fauna derived from the hyporheic zone) subunits. Williams (1989) used community classification (TWINSpan) to make a distinction between three faunal subunits: bank, river, and one that was unique

TABLE 4. Mean seasonal values (± 1 SE) of environmental variables significantly correlated with CA Axis 1 or CA Axis 2 for the TWINSPAN level-1 site groups and *t* test results (*P* value) for the comparison of TWINSPAN site group means.

Season	Variable	TWINSpan 1 (groundwater)	TWINSpan 2 (hyporheic)	<i>P</i>
Spring	alkalinity (mg CaCO ₃ /L)†	334 (28)	271 (32)	0.002
	conductivity (μ S/cm)†	541 (31)	474 (34)	0.002
	dissolved oxygen (mg/L)	1.4 (2.8)	2.8 (4.3)	0.53
	nitrate (mg/L)	0.32 (0.1)	0.30 (0.2)	0.86
	sodium (mg/L)	4.2 (0.7)	3.9 (1.0)	0.91
Summer	alkalinity (mg CaCO ₃ /L)	294 (18)	260 (11)	0.03
	conductivity (μ S/cm)	491 (21)	451 (27)	0.02
	dissolved oxygen (mg/L)	1.2 (1.8)	4.7 (2.2)	0.03
	nitrate (mg/L)†	0.38 (0.1)	2.5 (0.1)	<0.0001
	sodium (mg/L)	4.0 (0.3)	3.8 (0.5)	0.87
Fall	alkalinity (mg CaCO ₃ /L)	297 (11)	261 (22)	0.03
	conductivity (μ S/cm)†	562 (28)	480 (19)	0.002
	dissolved oxygen (mg/L)	1.6 (3.1)	3.9 (4.2)	0.37
	nitrate (mg/L)†	0.17 (0.18)	1.97 (1.18)	<0.0001
	sodium (mg/L)	4.3 (0.5)	4.4 (0.7)	0.86
Winter	alkalinity (mg CaCO ₃ /L)	295 (14)	258 (21)	0.03
	conductivity (μ S/cm)	496 (28)	441 (9)	0.04
	dissolved oxygen (mg/L)	1.5 (3.4)	4.5 (4.1)	0.26
	nitrate (mg/L)†	0.26 (0.33)	3.76 (1.77)	0.001
	sodium (mg/L)	3.8 (0.2)	4.1 (0.4)	0.64

† *P* < 0.0025.

to the margin between the two. The position of this margin faunal group was coincident with breaklines in several water chemistry parameters, and it was proposed that this faunal component of the interstitial community was an indicator of the hyporheic/groundwater interface. In a similar fashion, Ward and Voelz (1994) used frequency of occurrence data to characterize the hyporheic and hypogean elements of the invertebrate community at the South Platte River, Colorado. Whereas both studies identified taxa that were particularly diagnostic, it is not clear whether the distinction between the biotic subunits is truly representative of a spatial distinction between the hyporheic and groundwater habitats. The same concern can be raised with regard to the invertebrate data collected in this study. Although some taxa were found exclusively in either the groundwater or hyporheic habitat, it is difficult to make a clear distinction between what the TWINSPAN analysis divided into the two interstitial faunal subunits. This is perhaps not surprising when we consider that the concentration range of individual water chemistry parameters measured was likely well within the tolerance range of the interstitial taxa collected. It is possible that various abiotic (e.g., sediment features, interstitial flow patterns) or, alternatively, biotic factors (e.g., competition, predation, reproduction, food resources) that were not measured may more adequately explain the distribution of, and distinction between, hyporheic and hypogean taxa. These factors are likely of varying importance, but to date few definitive data are available to assess their importance, especially in field situations (Ward and Palmer 1994). Further, acquiring these data may still be some time away as the

required background information regarding the physiological status and ecological requirements of the vast majority of interstitial organisms is presently lacking. Therefore, while the invertebrate data may provide a useful measure of probable habitat location, it likely provides poor spatial resolution in terms of pinpointing the location of the hyporheic/groundwater interface.

In contrast to faunal distribution, the water chemistry data proved more definitive in distinguishing between the hyporheic and groundwater habitats. Concentration discontinuities in a number of the chemical parameters measured, with breaklines typically occurring from a meter or two landwards of the river margins down under the channel, were recorded. Concentration discontinuities of this sort were first reported by Williams (1989) at both the Rouge River and Duffin Creek, in southern Ontario. Since the latter study, others also have reported chemical discontinuities or steep concentration gradients over small spatial scales extending vertically beneath and laterally outside the wetted channel (e.g., Triska et al. 1989, 1993a, Holmes et al. 1994, McClain et al. 1994). We suggest that these discontinuities represent the nonphysical boundary between the hyporheic and groundwater environments. Groundwater was characterized by higher levels of alkalinity, conductivity, and ammonium, and lower levels of nitrate. Differences in alkalinity and conductivity between the two water masses probably can be attributed to site-specific local and, to a lesser extent, regional geomorphological features. However the nitrate-ammonium relationship is one that has been observed in several other systems. For example, Valett et al. (1990) found high levels of NO₃-N in the hyporheic zone of

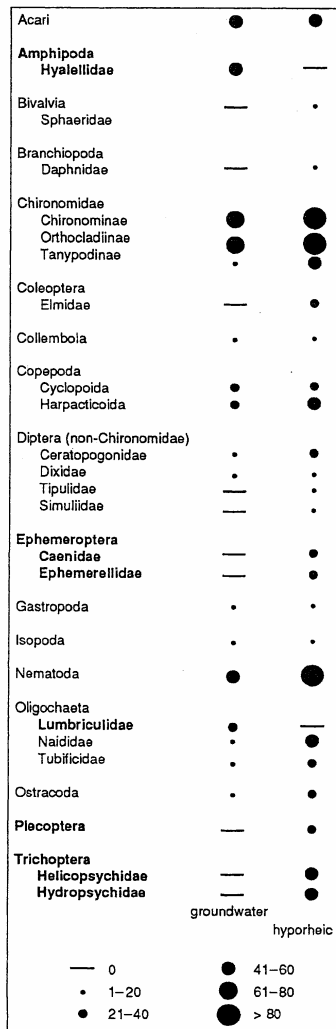


FIG. 7. Percentage frequency occurrence of taxa in TWINSpan level-1 site groups (groundwater and hyporheic) for combined seasonal data. Boldface type indicates fauna defined by TWINSpan as differential taxa for at least three of the four seasons. Nonchironomid dipterans include only the most commonly collected families.

a Sonoran Desert stream, and Triska and his group have repeatedly recorded high levels of hyporheic nitrate alongside low levels of ammonium in the groundwater at Little Lost Man Creek in northwestern California (e.g., Triska et al. 1993). This phenomenon was reported also by McClain et al. (1994) at the Barro Branco Stream in the Central Amazon Basin.

Water chemistry data also provided a more reliable spatial measure of hyporheic/groundwater interface seasonal fluctuation. Faunal data indicated that changes in macroinvertebrate distribution were taxon rather than community based as taxa turnover between the two faunal subunits was not complete. In this sense, therefore, it may be somewhat erroneous to describe boundary fluctuation as indicated by the distribution of the hyporhean and hypogean faunal subunits when it appears that only a number of individual taxa seem to be affected. The occurrence of these indicator taxa may be of use in identifying general spatial trends but would not be appropriate markers of the interface itself. Conversely, differences between the hyporheic and groundwater masses persisted throughout the year, yet the location of the concentration discontinuity varied. Williams (1993) suggested that boundary fluctuation of the hyporheic/groundwater interface was probably the direct result of variation in the upward force of baseflow and the downward force of advecting channel water. Our hydrogeological data support this hypothesis. During the spring and fall sampling periods, the interface was deeper beneath the active channel and farther out laterally under the banks. These same sampling periods coincided with the times at which the hydraulic gradient between the surface and interstitial environments was the least and surface discharge was the greatest. This, along with the fact that our sample transect was located at the head of a riffle (a convex stream bed surface), could account for a high degree of convective flow of river water into the stream bed (Vaux 1968, Boulton 1993). With this reasoning it is plausible that the relative forces of downwelling river water and upwelling groundwater regulate the location and fluctuation of the hyporheic/groundwater interface. In actuality, therefore, it is likely that we have recorded boundary fluctuation as a result of variable channel discharge patterns rather than the effects of seasonality. This implies that in ecosystems where isolated discharge events rather than seasonal discharge patterns regulate surface–subsurface hydraulic exchange the hyporheic zone, or more precisely the hyporheic habitat volume, would fluctuate according to the timing of these events. This suggestion is supported by a recent study (Stanley and Boulton 1995) that reported fluctuations in the boundaries of hyporheic subsystems in response to flooding and drying of a Sonoran Desert stream.

Recent studies have quantified the inorganic nitrogen storage and retention capacity of hyporheic sediments (e.g., Triska et al. 1990, 1994, Kim et al. 1992, Holmes

et al. 1994), along with the implications of the potential availability of the hyporheic inorganic nitrogen pool to lotic environments (e.g., Hendricks and White 1988, Ward 1989). Our study adds a further dimension. A central premise of a model depicting nitrogen cycling between contiguous groundwater and stream water, presented by Triska et al. (1993), was the transient storage of ammonium in hyporheic sediments. We have shown that the hyporheic volume, and therefore the quantity of hyporheic sediments available for ammonium adsorption, varies according to surface discharge patterns. Although the effect this may have on the hyporheic inorganic nitrogen pool has yet to be quantified it warrants inclusion in models that predict solute flow between groundwaters and surface ecosystems. Further studies also will have to: (1) quantify the broader significance of hyporheic volume variation in many biological and geochemical processes, including, for example, nitrification, denitrification, phosphorus cycling, and metabolism; and (2) determine the impact(s) of hyporheic habitat size fluctuation on resident interstitial biota.

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