1-29-96

SANDIA REPORT

SAND95-2187 • UC-902
Unlimited Release
Printed December 1995

Ground Water Flow Velocity in the Bank of the Columbia River, Hanford, Washington

Sanford Ballard

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-94AL85000

SF2900Q(8-81)

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831

Prices available from (615) 576-8401, FTS 626-8401

Available to the public from
National Technical Information Service
US Department of Commerce
5285 Port Royal Rd
Springfield, VA 22161

NTIS price codes
Printed copy: A03
Microfiche copy: A01

SAND95-2187
Unlimited Release
Printed December 1995

Distribution
Category UC-902

GROUND WATER FLOW VELOCITY IN THE BANK OF THE COLUMBIA RIVER, HANFORD, WASHINGTON

Sanford Ballard
Geophysics Department
Sandia National Laboratories
Albuquerque, New Mexico 87185-0750

Abstract

A suite of In Situ Permeable Flow Sensors was deployed in the bank of the Columbia River at the 100H Area on the Hanford Site to characterize the hydrologic regime within the banks of the river. The three dimensional flow velocity was recorded on an hourly basis from mid May to mid July, 1994 and for one week in September. The first data collection interval coincided with the seasonal high water level in the river while the second interval reflected conditions during relatively low seasonal river stage. Two flow sensors located approximately 50 feet from the river recorded flow directions which correlated very well with river stage, both on seasonal and diurnal time scales. During time intervals characterized by falling river stage, the flow sensors recorded flow toward the river while flow away from the river was recorded during times of rising river stage. The flow sensor near the river in the Hanford Formation recorded a component of flow oriented vertically downward, probably reflecting the details of the hydrostratigraphy in close proximity to the probe. The flow sensor near the river in the Ringold Formation recorded an upward component of flow which dominated the horizontal components most of the time. The upward flow in the Ringold probably reflects regional groundwater flow into the river.

The magnitudes of the flow velocities recorded by the flow sensors were lower than expected, probably as a result of drilling induced disturbance of the hydraulic properties of the sediments around the probes. The probes were installed with resonant sonic drilling which may have compacted the sediments immediately surrounding the probes, thereby reducing the hydraulic conductivity adjacent to the probes and diverting the groundwater flow away from the sensors.

olc

Acknowledgments

Thanks to Bob Henckel and Dick Biggerstaff for their support during the conduct of this project. Thanks also to Bob Peterson for many thought provoking discussions about the interpretation of the data. I greatly appreciate the assistance of Doug Vaught for organizing field activities and for his help with the data acquisition system when things went south. The project would not have been possible without invaluable technical support from Glenn Barker. I am also indebted to Marianne Walck and Chris Young for reviewing the manuscript.

Contents

List of Figures

List of Tables

Introduction

To properly characterize the transport of contaminants from the sediments beneath the Hanford Site into the Columbia River, it is important to accurately characterize the hydrologic regime in the banks of the river. Flow in the near shore environment (within a few hundred feet of the river) is complicated by the rise and fall of the river level. While the net flow is from the banks into the river when averaged over time periods longer than a few days or months, there are times when the river stage is high and water flows from the river into the banks. Close to the bank of the river, there are three components of the groundwater flow velocity which are superimposed and interact in a complex manner: relatively steady flow from the interior of the Hanford site to the near shore environment, reasonably steady flow downstream, and flow in and out of the banks of the river in response to changes in river stage.

In Situ Permeable Flow Sensors

To investigate the interaction between groundwater and river water, a technology is required which is capable of measuring groundwater flow on a continuous basis for months at a time. In Situ Permeable Flow Sensors are ideally suited to this task. This technology uses a thermal perturbation technique to directly measure the full three dimensional groundwater flow velocity vector in the subsurface (Ballard, 1992a, 1992b, in press; Ballard et al., 1994, in press). Each probe consists of a slender cylinder 30 inches long by 2 inches in diameter made of very low thermal conductivity polyurethane foam. The cylinder is covered with a thin-film, flex circuit style heater and an array of 30 carefully calibrated temperature sensors. When approximately 80 watts of electric power is applied to the heater, a spatially and temporally uniform heat flux out of the probe is established. This heat flux warms the probe and the soil and water around the probe with the surface of the probe achieving a temperature about 20 to 25°C above ambient. If there is flow past the probe then the heat emanating from the probe is advected around the probe by the moving fluid, perturbing the temperature distribution on and around the probe. The temperature distribution on the surface of the probe, which is recorded by the temperature sensors, reflects the flow velocity past the instrument, with relatively cool temperatures on the upstream side of the probe and relatively warm temperatures on the downstream side. The direction of the flow velocity is revealed by the pattern of the probe surface temperature distribution while the magnitude of the flow velocity is calculated from the magnitude of the temperature variations on the surface of the sensor. The flow sensors can measure flow velocities as low as about 0.01 ft/day.

The manner in which the flow sensors are deployed is critical to obtaining a valid measurement. The probes must be buried in intimate contact with the formation; they cannot be deployed in a borehole. The existence of a borehole, along with the associated casing, screen and gravel pack, can significantly alter the direction and particularly the magnitude of the flow velocity in and around the hole, relative to the undisturbed formation flow velocity. The approach which has been adopted is to fabricate relatively inexpensive probes which can be permanently buried in the ground. While this means the probes cannot be moved or retrieved after deployment, they can provide flow velocity data from one location for extended periods, up to many months or even years.

In this experiment, a resonant sonic drill rig was used to emplace the probe. The rig was used to drive a 4-inch diameter steel casing with a plug in the end down to the desired depth. This technique pushes aside the sediment displaced by the borehole, effectively compacting the sediments around the hole. No cuttings were retrieved during drilling. When the casing had been driven down to the desired depth, the plug at the bottom was removed, the probe was lowered down the interior of the casing to the bottom of the hole and the casing retracted, leaving the probe in the hole. Given the saturated, unconsolidated nature of the sediments involved, the formation readily collapsed around the tool leaving it permanently buried in the subsurface. The instruments were lowered down on 1-inch PVC pipe which had been marked in such a way as to permit the horizontal orientation of the probes to be known after emplacement. This was necessary in order to deduce the direction of the horizontal component of the flow velocity.

Once the probes were installed, Campbell Scientific CR10 data loggers were attached to each probe. The data loggers were connected together into a network which was in turn connected to a personal computer located in a small shed near the center of the site. The computer automatically collected data from the data loggers every few hours. The data were then transferred back to Sandia for processing via modem and cellular telephone.

Site Description

The flow sensors were deployed at the 100H Area, an old reactor site on the southern bank of the Columbia River (Figures 1 and 2). The stratigraphy at the site consists of approximately 50 to 60 feet of Hanford Formation overlying the Ringold Formation. The Hanford Formation is comprised of very poorly sorted, unconsolidated sandy gravel deposited during glacial flooding events. The Ringold Formation consists of somewhat more consolidated silty sands deposited in a river floodplain environment. The hydraulic conductivity of the Hanford Formation is several orders of magnitude higher than that of the Ringold Formation and the vertical hydraulic gradient at the site is upward resulting in upward flow across the Ringold/Hanford contact (Bob Peterson, pers. communication).

The Columbia River borders the site to the northeast. The hydrology of the site is significantly impacted by the river stage (Figure 3), which is controlled by the amount of water released from the Priest Rapids Dam, located approximately 25 miles upstream from the site. Discharge from the dam varies according to the demand for electric power; the higher the demand, the more water is released and the higher the river stage adjacent to the 100H Area. Since demand for power is greatest during the day and decreases at night, the river stage rises and falls with a diurnal frequency. The amplitude of the daily oscillations is about 3 to 5 feet. In addition, demand for power is reduced on the weekends resulting in relatively low river stage on weekends and a significant surge of water being released on Mondays. On longer time scales, there is a seasonal variation in river stage, with relatively high water in mid June and low water in the fall. The amplitude of the seasonal river stage variations is about 6 to 8 feet.

Data

Four flow sensors were deployed at the 100H Area. Their locations are illustrated in Figures 2 and 4 and their depths defined in Table 1.

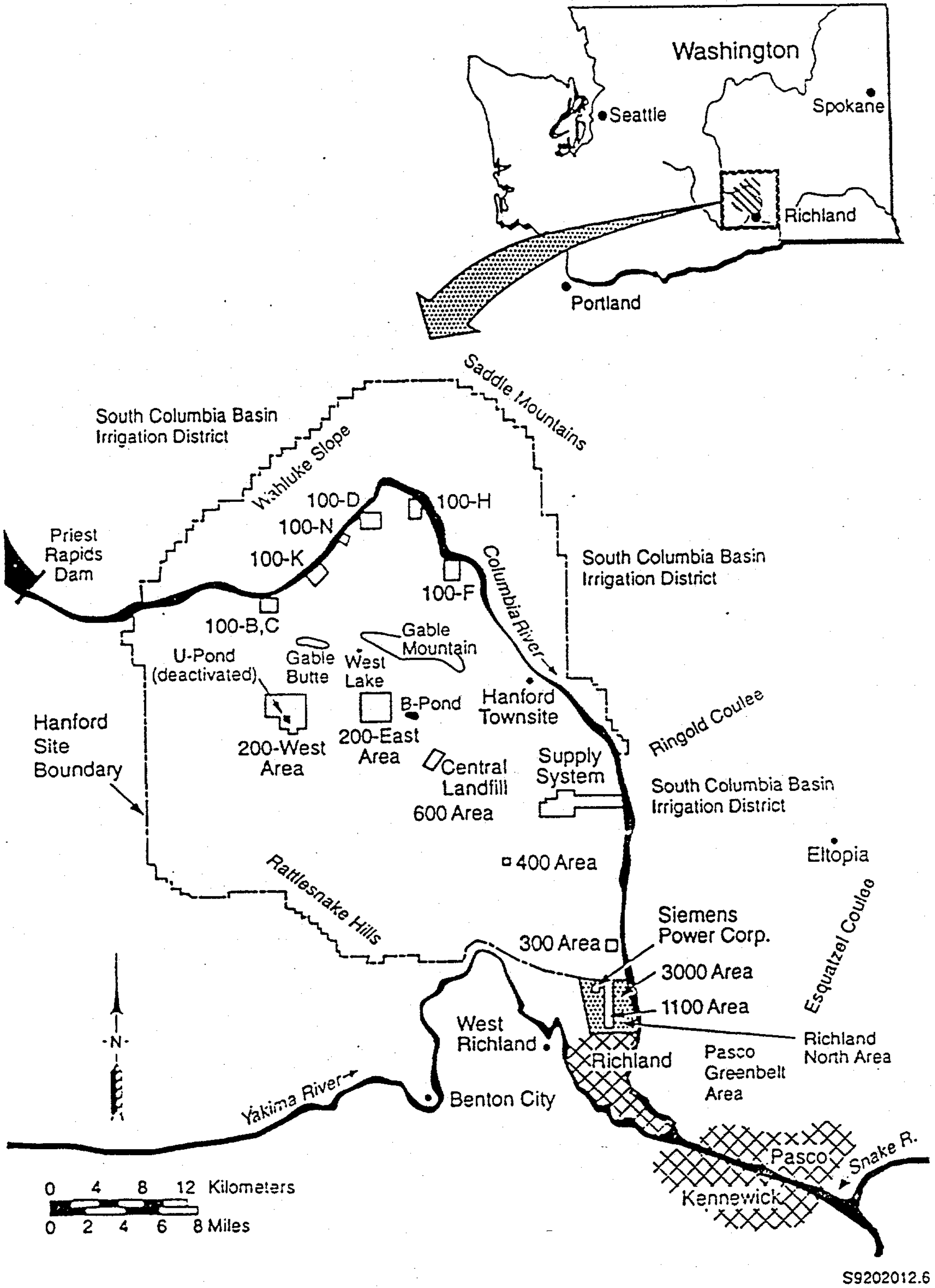

Figure 1 - Map of the Hanford Site showing the location of the 100H Area.

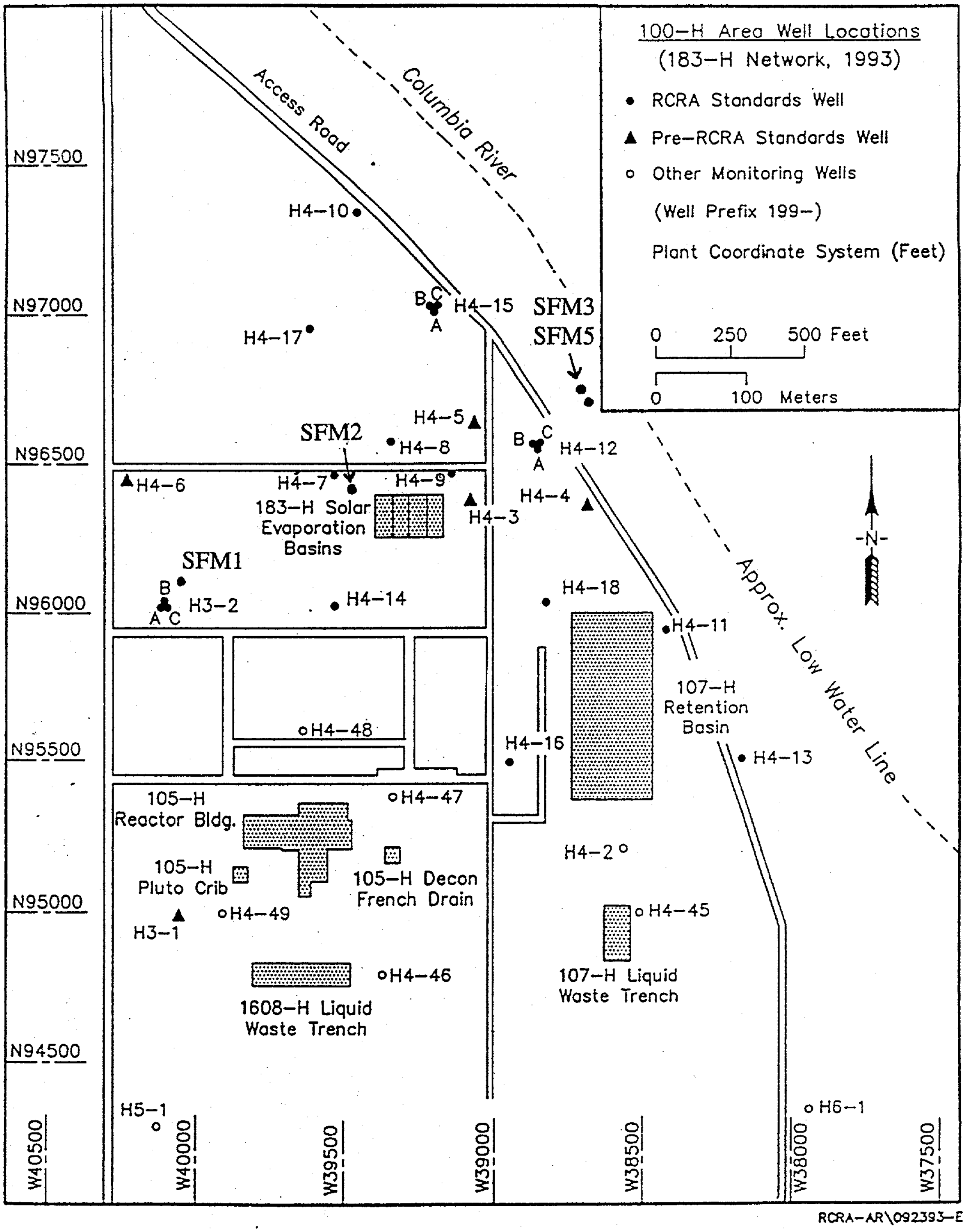

Figure 2 - Map of 100H Area showing the locations of flow sensors SFM1, SFM2, SFM3 and SFM5, in relation to the river.

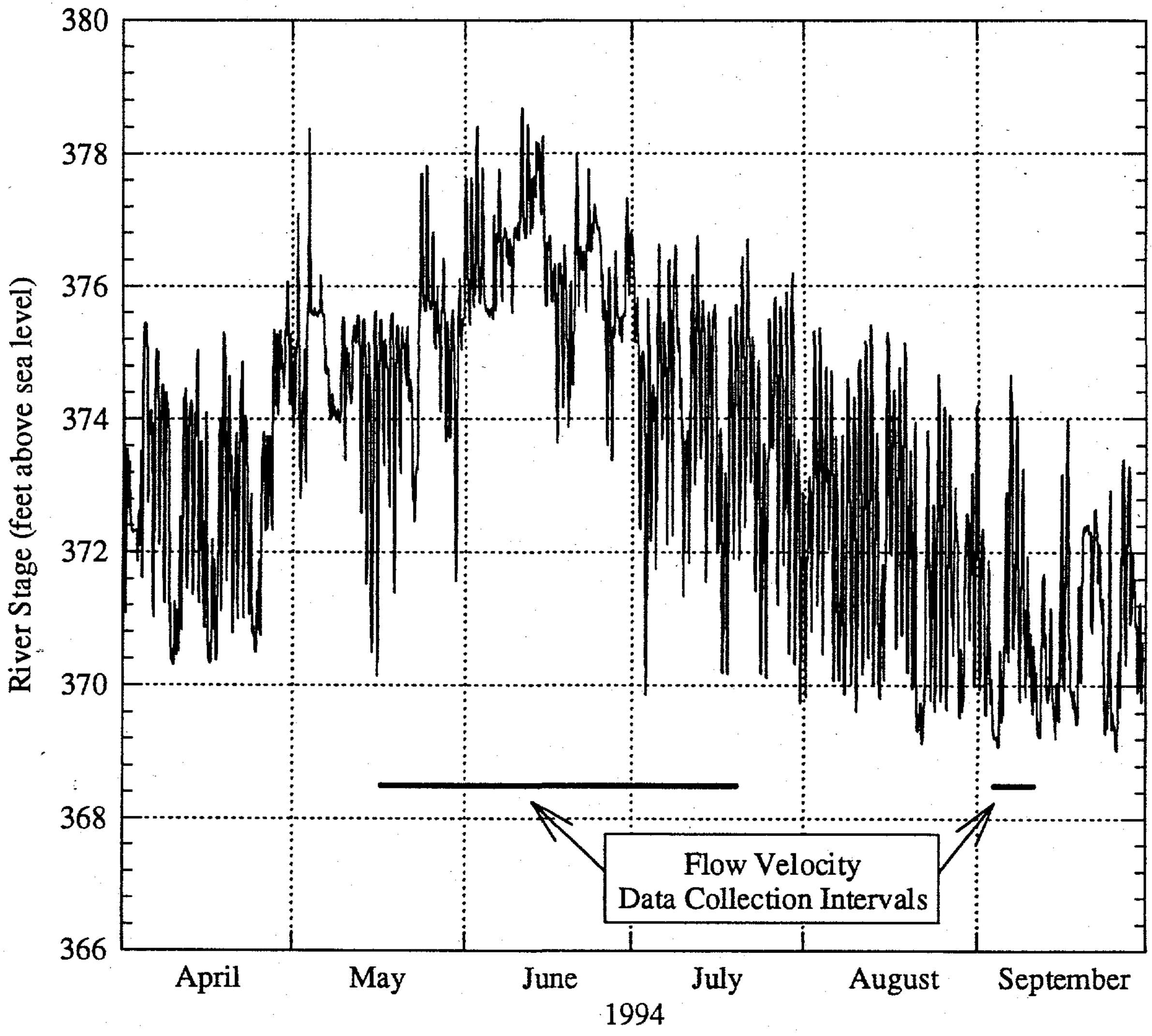

Figure 3 - Columbia River stage. The horizontal bars indicate the time intervals during which flow velocity measurements were made.

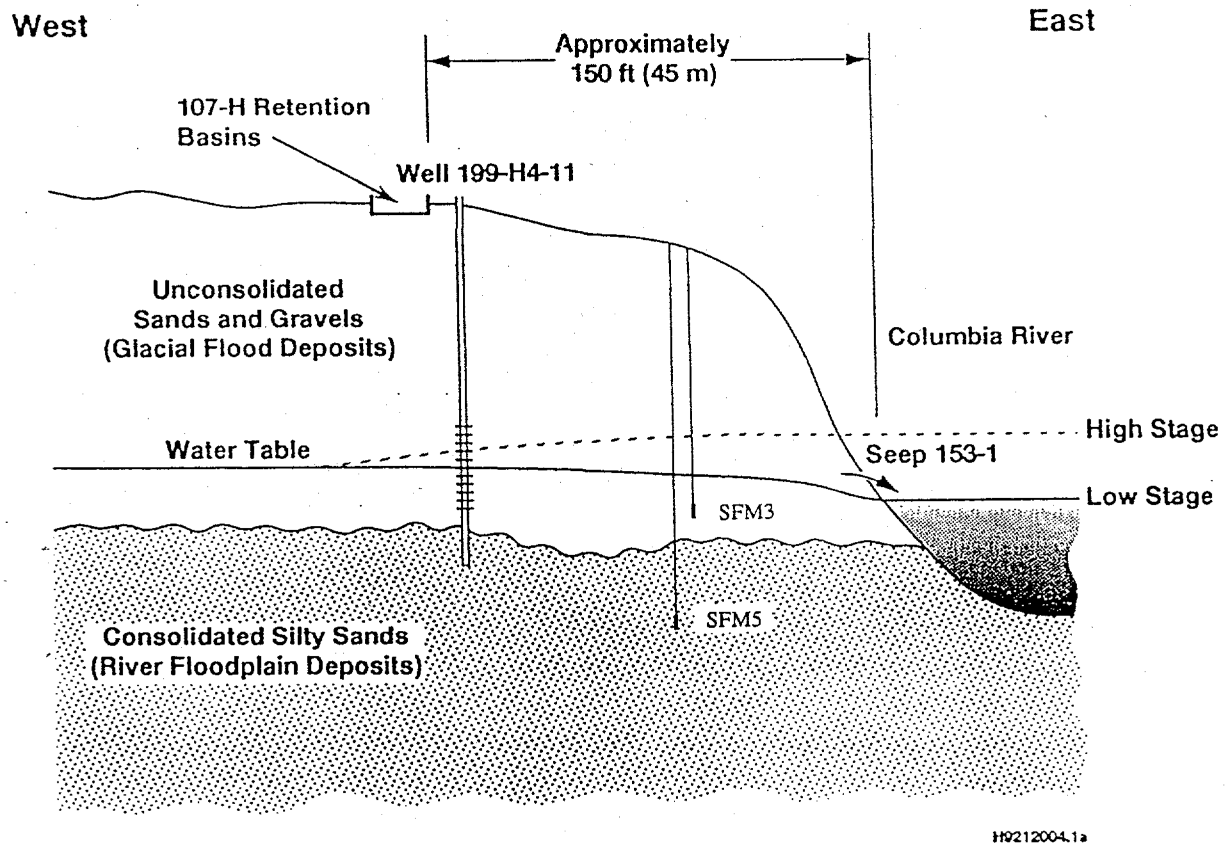

Figure 4 - Cross section through the southern bank of the river in the 100H Area.

Table 1 - Locations of flow sensors

Flow Sensor Name (Closest Borehole)	Approx. Distance from River (feet)	Formation	Probe Depth (feet)	Approx. Depth to Water Table (feet)	Depth of Hanford/Ringold Contact (feet)
SFM1 (H3-2)	1500	Hanford	48	40	60
SFM2 (H4-7)	800	Hanford	52	46	54
SFM3 (H4-12)	50	Hanford	46	38	53
SFM5 (H4-12)	50	Ringold	74	38	53

Flow velocity data were obtained from the flow sensors during two time intervals (Figure 3). The first lasted 64 days from May 17 to July 20, 1994 while the second lasted for one week from September 4 to 11, 1994. The first data collection interval coincided with the time of highest river stage while the second measured the flow velocity after the summer high water had subsided.

The flow velocity from the two probes near the river, SFM3 and SFM5, were resolved into Cartesian coordinates with the positive x-component directed into the bank (S50W), the positive y-component directed downstream (S40E) and the positive z-component directed vertically upward. In Figure 5, the into-bank component of the flow velocity measured by probe SFM3 during the first data collection period is compared with river stage. The correlation between the velocity data and river stage is excellent. During times of high river stage, water flowed from the river into the bank while during times of low river stage, groundwater flowed toward the river. There appears to be about a 5 hour phase lag between times of maximum river stage and maximum into-bank flow velocity. In Figure 6, the into-bank component of flow observed by flow sensor SFM3 is compared to the displacement into the bank. The latter quantity was calculated by integrating the into-bank flow velocity over time. The initial value at the beginning of the data collection period was arbitrarily set to be zero. During late May/early June, the displacement into the bank was increasing indicating net groundwater flow from the river into the bank. The displacement reached a maximum in mid-June at the same time that the river achieved its maximum seasonal stage, and then decreased precipitously for the remainder of the data collection interval. The decreasing displacement indicates that the net groundwater flow is toward the river.

In Figure 7, the into-bank component of the flow velocity measured by probe SFM5, which was located down in the Ringold Formation, is compared to river stage. Again, the correlation between flow velocity and river stage is excellent. The magnitude of the velocity oscillations is much reduced compared to the oscillations observed by probe SFM3 located in the much more hydraulically conductive Hanford Formation.

The downstream components of the flow velocities recorded by probes SFM3 and SFM5 are compared to each other and to river stage in Figure 8. Both probes recorded steady downstream flow velocities with the velocity in the Hanford Formation being higher than that in the Ringold

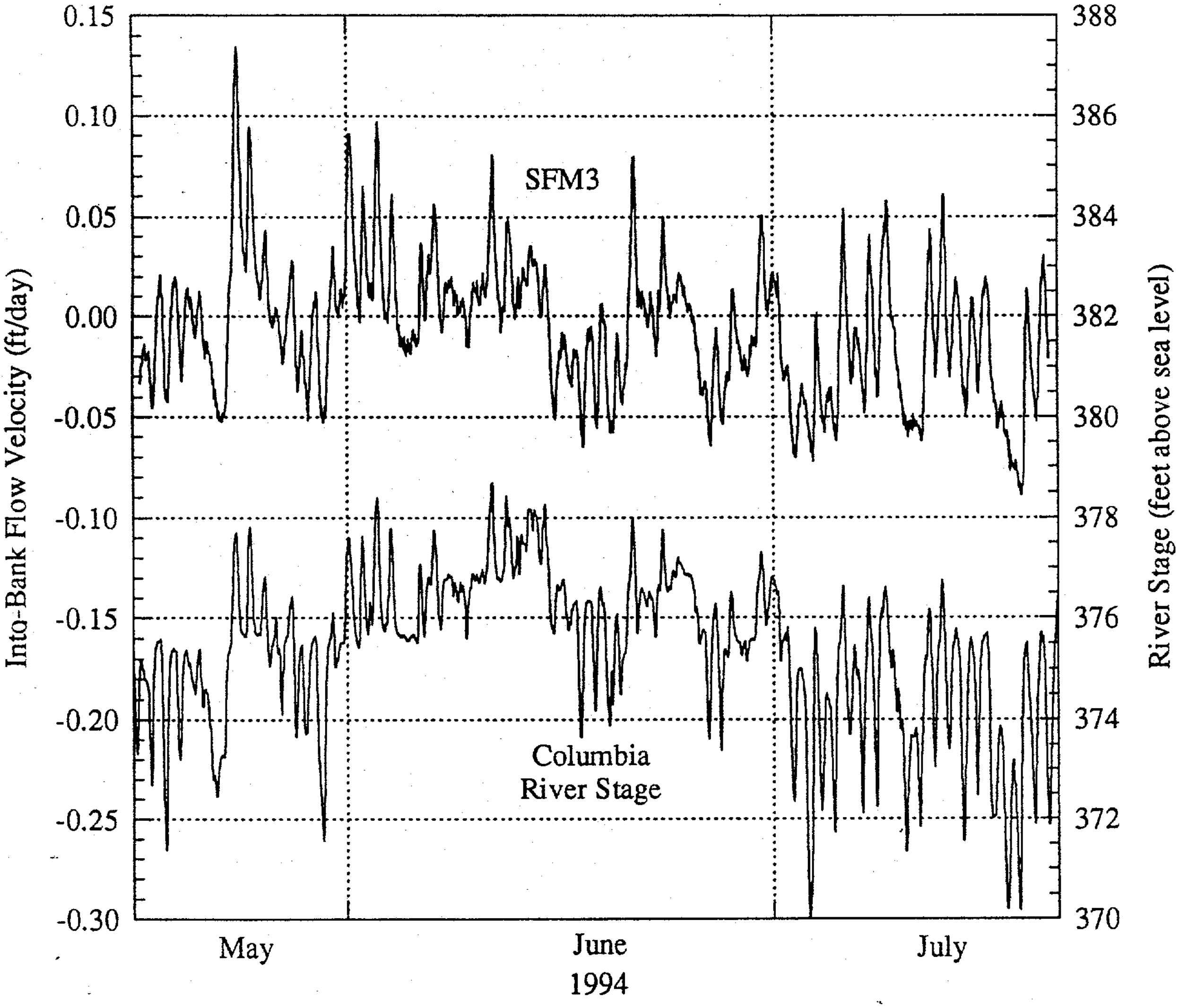

Figure 5 - Into-bank component of flow velocity measured by flow sensor SFM3 located in the Hanford Formation approximately 50 ft from the river.

Formation. There is only a very weak correlation between the downstream component of the flow velocity and river stage.

The vertical component of flow recorded by the two flow sensors is compared to river stage in Figure 9. The flow observed in the Hanford Formation is negative, indicating downwardly directed flow, suggesting that the flow sensor was located at a vertical position where the hydraulic conductivity of the sediments was changing from relatively low conductivity above the tool to higher conductivity material below the tool. The vertical component of flow at SFM3 appears to be uncorrelated with river stage, at least on daily time scales. It does appear that the magnitude of the downward flow increased somewhat over the two month data collection interval. The vertical flow observed by probe SFM5 in the Ringold Formation was positive, indicating upward flow. In fact, the vertical component of the flow velocity observed by SFM5

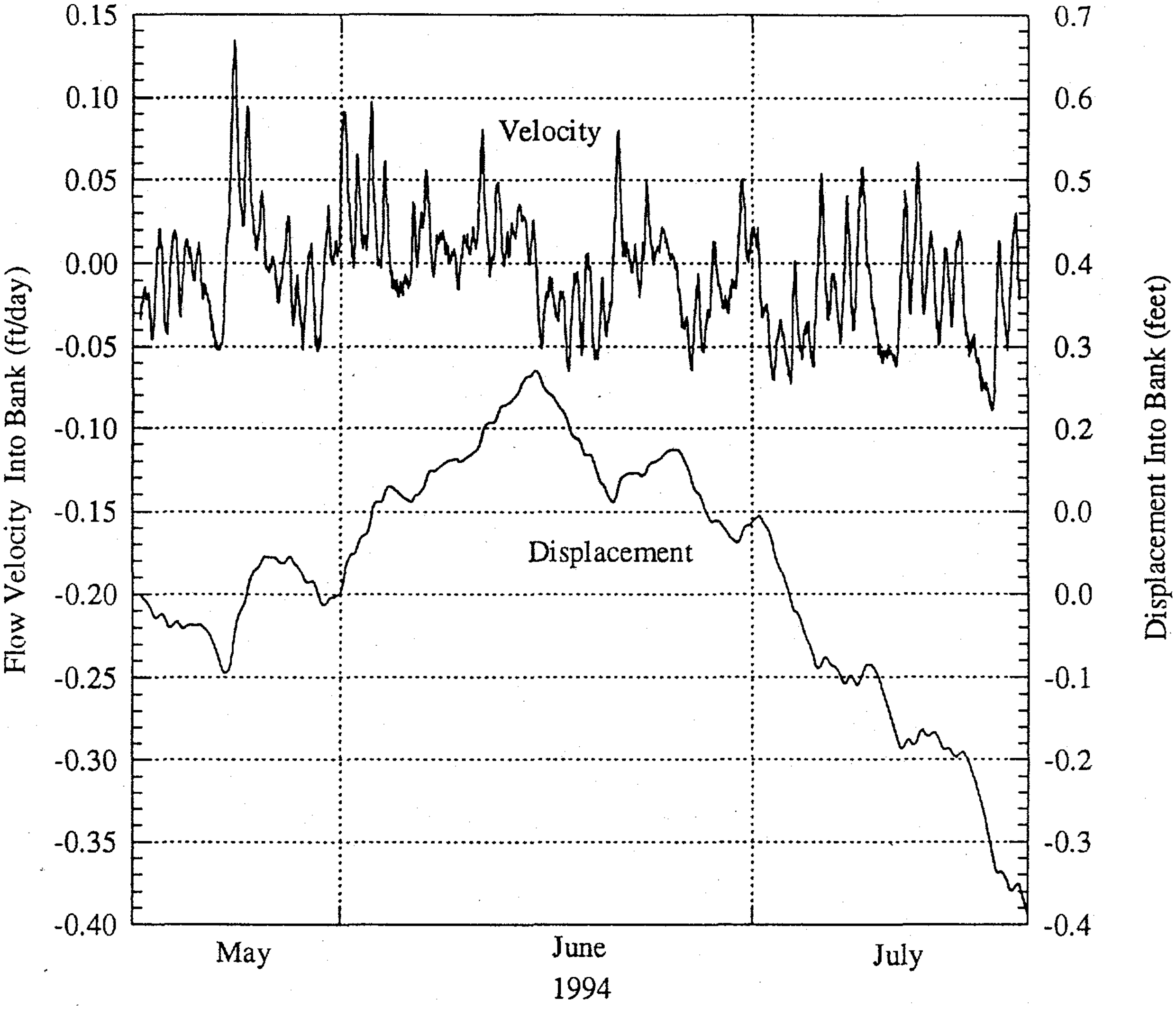

Figure 6 - Into-bank component of flow velocity measured by flow sensor SFM3 compared to ground water displacement which was calculated by integrating the into-bank velocity over time.

dominated the horizontal components most of the time. This observation is consistent with the fact that the site is a regional ground water discharge area.

In Figure 10, the into-bank components of flow measured in the Hanford and Ringold Formations near the river are compared to river stage in two different time intervals. On the left, the data during a one week time interval in June, when the river was at its highest level, is displayed. On the right are illustrated the flow and river stage data during a one week period in September, when the river stage was about 7 feet lower than it was at its peak in June. It should be noted that September 5th, 1994 was Labor Day and relatively little water was released from the dam upriver over the long holiday weekend. There is a marked difference in the flow velocities recorded by the flow sensors in September as compared to June. In June, the nominal flow velocity observed by the two probes was essentially zero, with positive or negative excursions

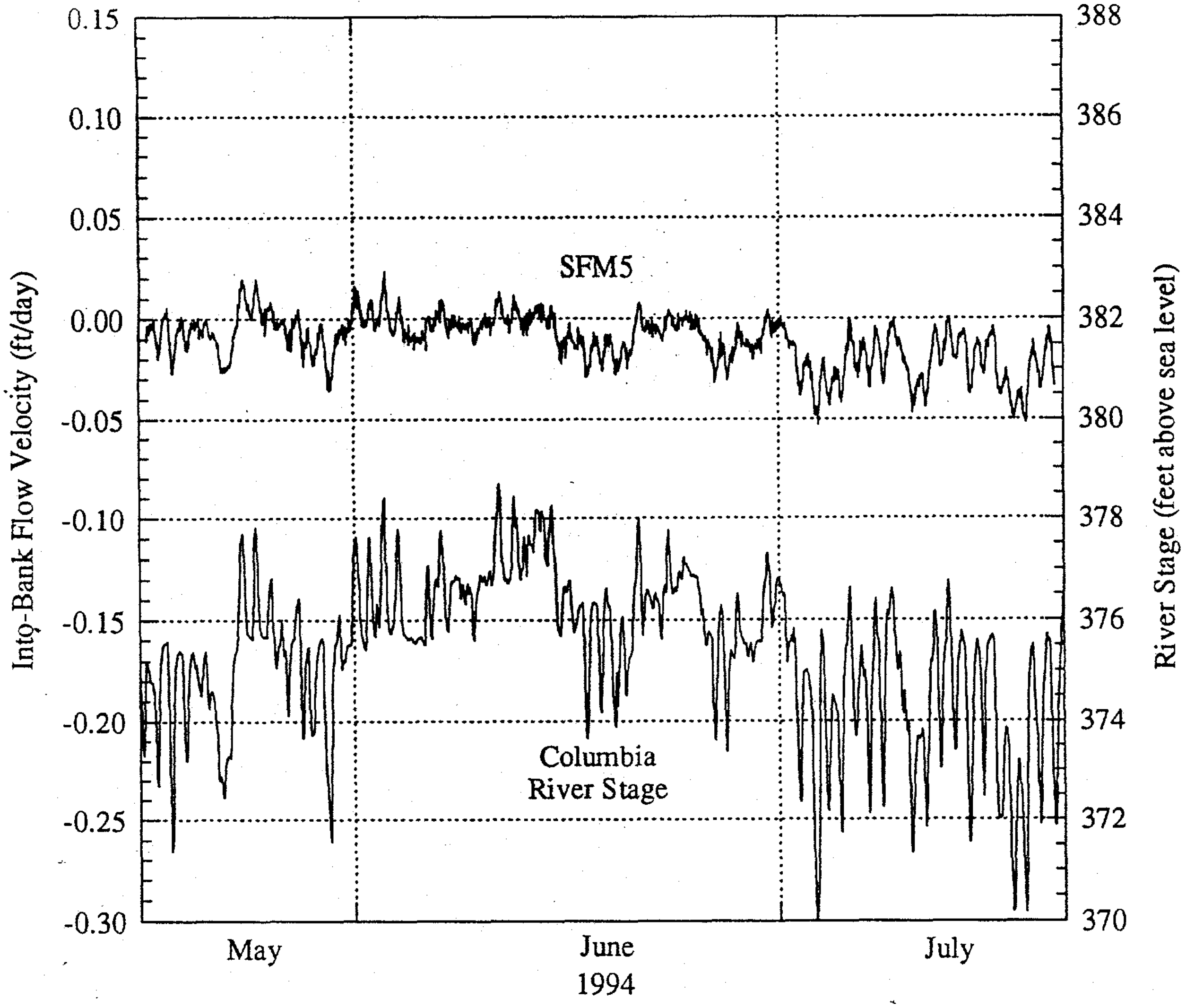

Figure 7 - Into-bank component of flow velocity measured by flow sensor SFM5 located in the Ringold Formation approximately 50 ft from the river.

during times of high and low river stage, respectively. In September, when the river stage was low, the flow was predominantly from the bank toward the river, with into-bank flow observed only briefly during times of the very highest river stage.

The horizontal flow velocity recorded by flow sensor SFM2, located approximately 800 ft from the river, is reported in Figure 11 in cylindrical coordinates. Figure 11a illustrates the azimuth of the horizontal component of the flow velocity, relative to geographic north, while the magnitude of the horizontal component of the flow velocity is provided in Figure 11b. The data suggest that the groundwater at this location is flowing in a direction N60W which is more or less parallel to the upstream direction (N40W). There is no readily identifiable explanation for this flow direction; flow toward the river was expected (N50E). It is possible that the flow is perturbed by buried structures near the site. The location of SFM2 is not far from a large

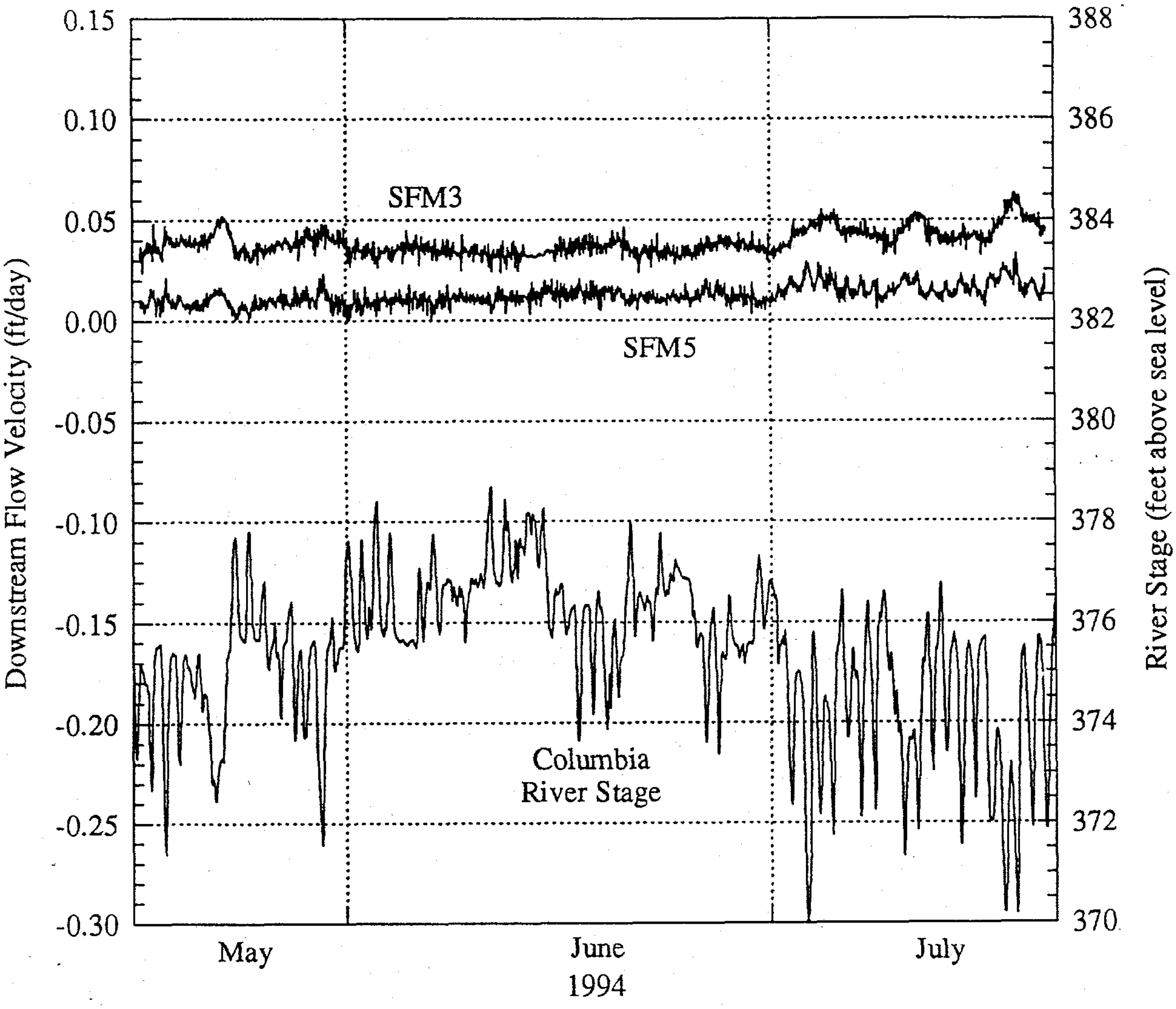

Figure 8 - Downstream component of flow velocity measured by flow sensors SFM3 and SFM5, compared to river stage.

concrete-lined evaporation basin (Figure 2). It should be noted that other flow velocity measurements at this location also yielded anomalous results. Kearl and Gardner (1994) used the Colloidal Borescope to measure flow in a direction N8W in borehole H4-7 which is located only about 30 feet from the position of SFM2.

The magnitude of the horizontal component of the flow velocity recorded by flow sensor SFM2 during the first data collection period is plotted in Figure 11b. The flow appears to vary between about 0.05 and 0.075 ft/day with the highest velocities recorded in June when the river stage was highest. By September the measured flow velocity was in essentially the same direction but was reduced in magnitude down to about 0.03 ft/day. These observations support the azimuth measurements which indicate that the flow is more or less away from the river. When the river level went up, the flow away from the river increased; when the river stage fell, the flow

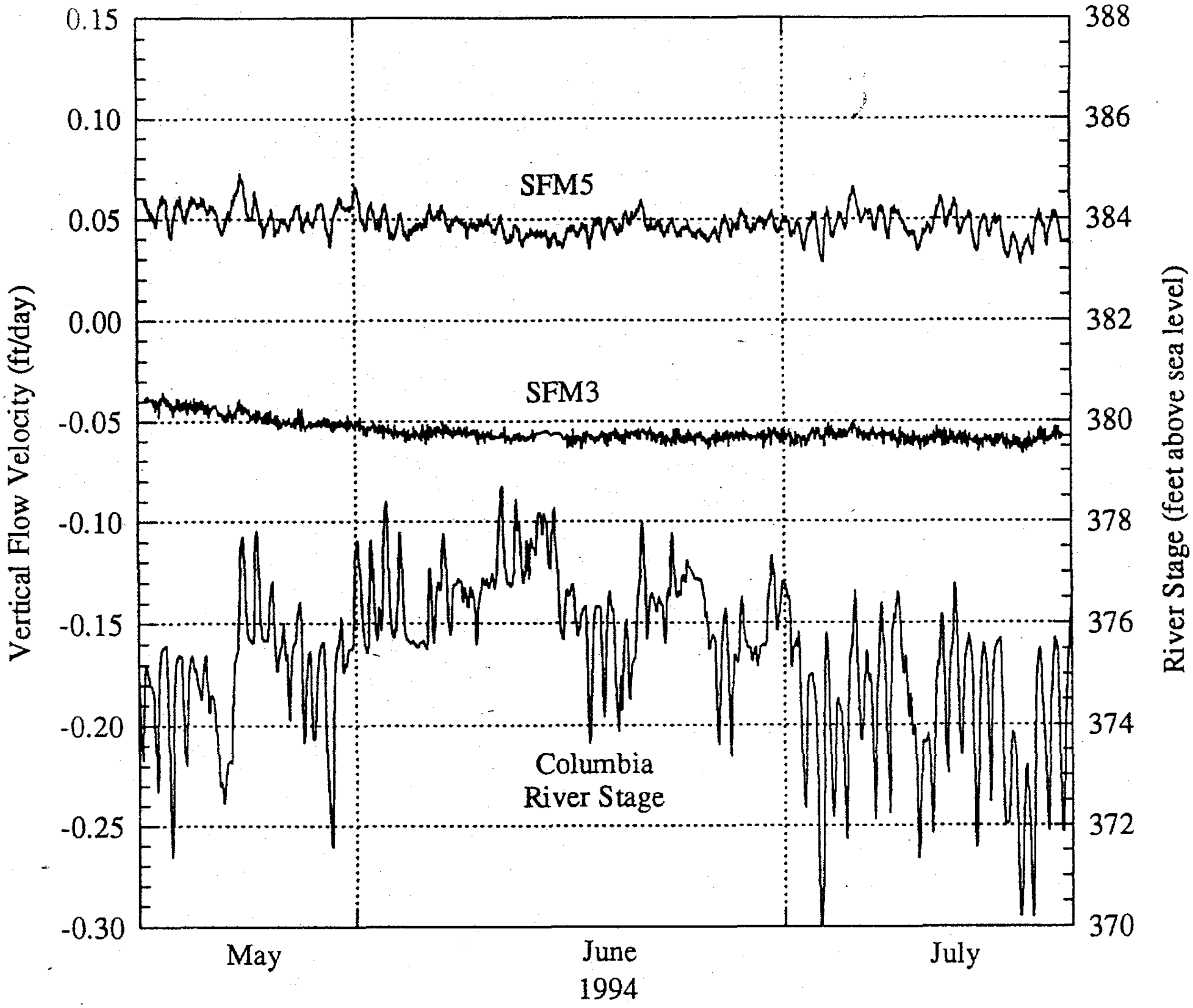

Figure 9 - Vertical component of flow velocity measured by flow sensors SFM3 and SFM5 compared to river stage.

away from the river decreased. Also plotted in Figure 11b for comparison is the integrated flow velocity measured by flow sensor SFM3. There appears to be a good correlation between these two measurements which again suggests that SFM2 observed flow away from the river. The increase in flux observed by flow sensor SFM3 in late May/early June reflects a rise in the water table near the river. This would lead to a dam effect near the river and an increase in flow away from the river at the position of SFM2. There is some suggestion of a daily variation in flow velocity, but the amplitude of the oscillations is too small to be reliably measured by the flow sensors.

The vertical component recorded by flow sensor SFM2 was not resolved. The temperatures recorded near the top of the probe were substantially warmer than the temperatures recorded at the bottom of the probe, suggesting very large, upwardly directed flow. However, the data was

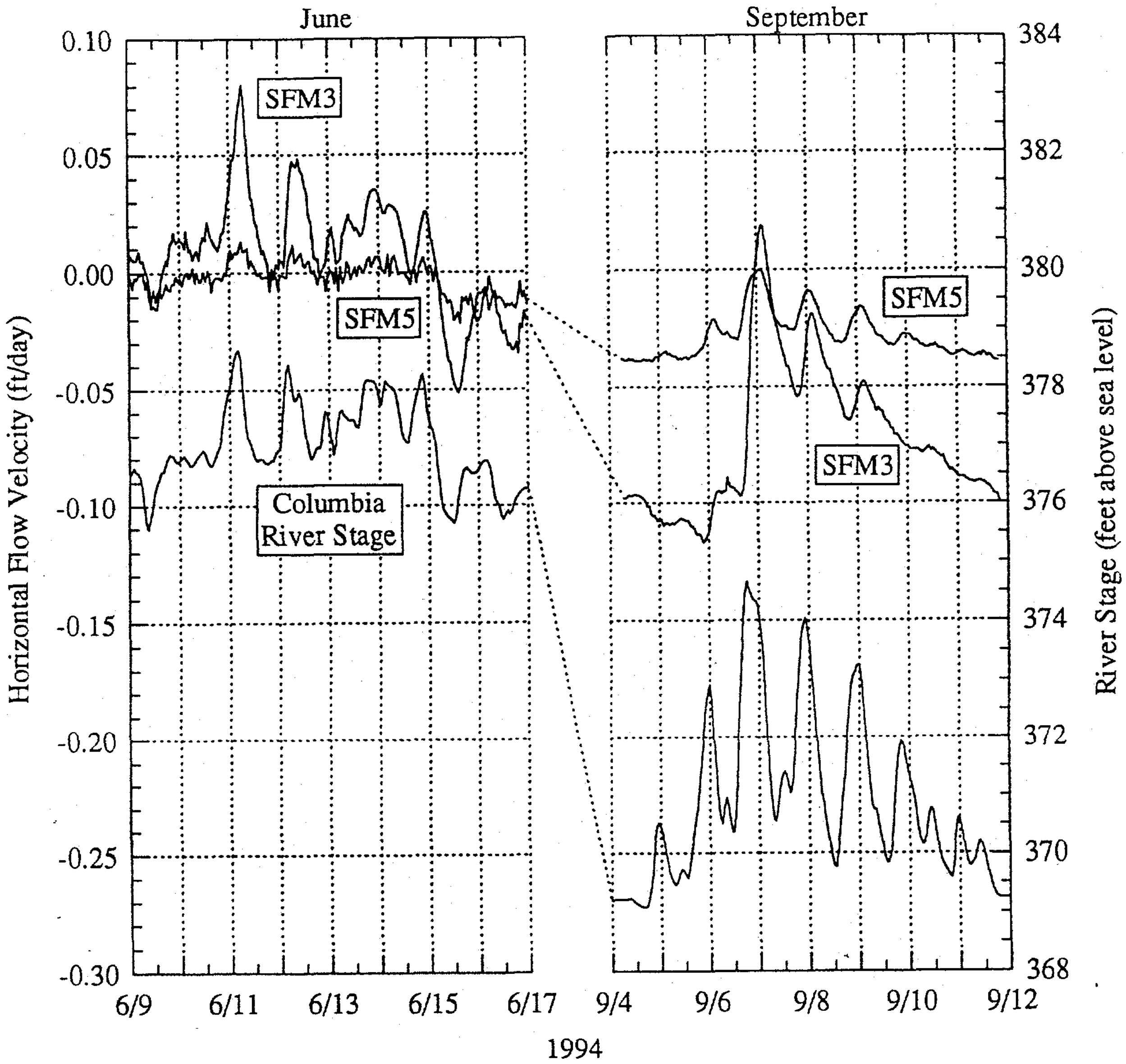

Figure 10 - Into-bank component of flow velocity measured by flow sensors SFM3 and SFM5 compared to river stage during two one-week periods. The June data was collected when the river was at the seasonal high water level while the September data was collected after the river level had fallen substantially.

likely corrupted by heterogeneity of the thermal properties of the medium in which it was emplaced. Because the thickness of the saturated Hanford Formation at the location of SFM2 is only about 8 feet, flow sensor SFM2 was emplaced only a foot or two above the Hanford/Ringold contact. If the thermal conductivity of the Ringold Formation sediments is substantially higher than that of the Hanford Formation then the observed temperature distribution could have been obtained, regardless of the actual vertical flow velocity. Because of this uncertainty, the vertical

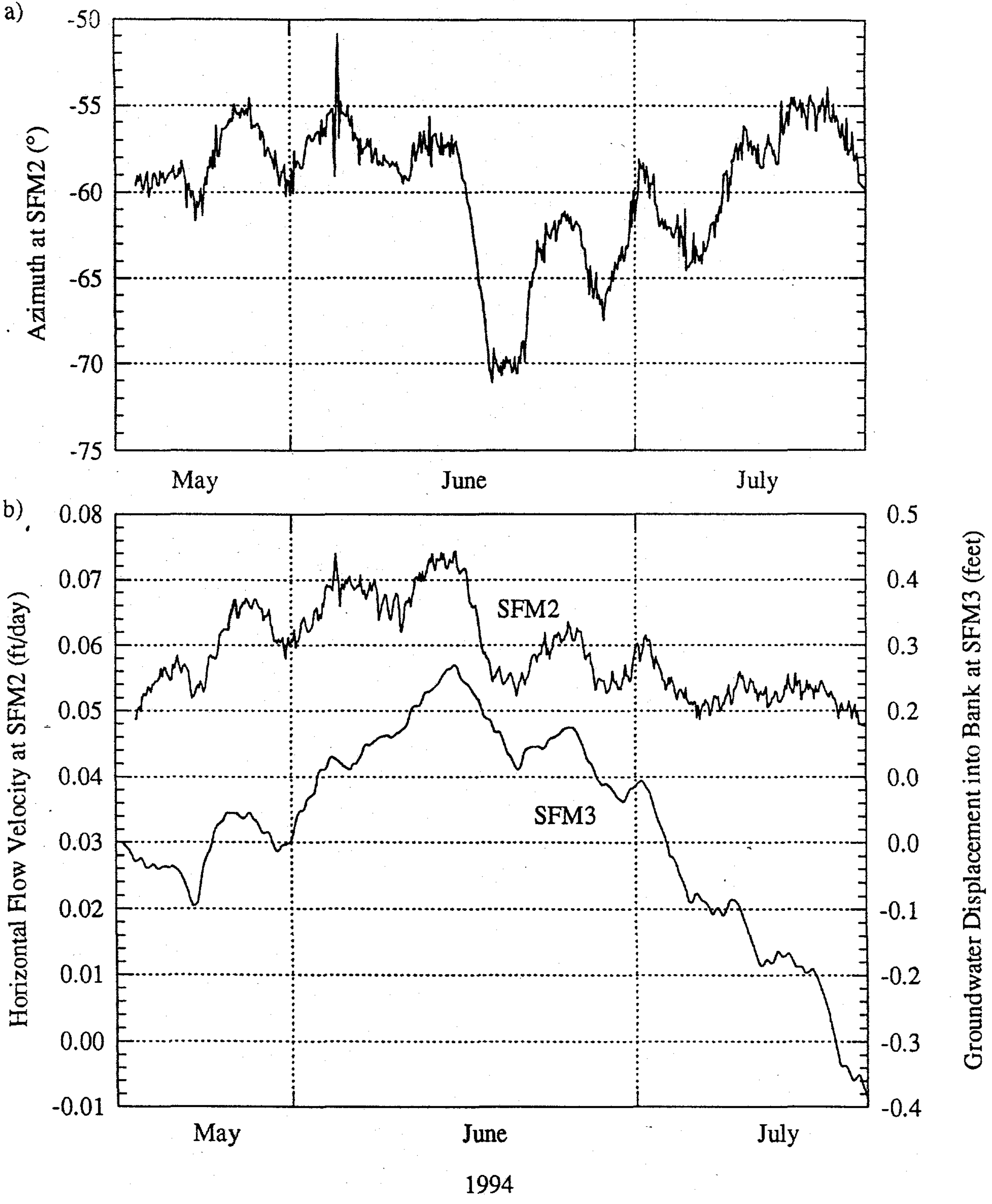

Figure 11 - Flow velocity recorded by flow sensor SFM2, located 800 ft from the river. a) azimuth of the horizontal component of the flow velocity, and b) magnitude of the horizontal component of the flow velocity. Also plotted in b) is the groundwater displacement observed by flow sensor SFM3, close to the river.

component of the flow velocity was ignored and the probe surface temperature distribution corrected so as to preserve the horizontal component of the flow velocity.

Flow sensor SFM1 never provided reliable data. The temperatures recorded by the instrument were highly erratic throughout the data collection period despite repeated attempts to improve the readings by lowering the heat output of the tool. It is likely that this resulted from incomplete collapse of the coarse Hanford Formation gravels around the tool with the result that there existed around the tool water filled voids of substantial size (several inches). Heating the water in such voids would result in significant thermal convection of the water in the voids which could explain the highly erratic temperature signals observed.

Discussion

While the flow velocity directions recorded by the flow sensors near the river correlate well with river stage, the magnitudes seem quite low. This impression is difficult to quantify, given the wide range of values for hydraulic conductivity which have been reported for the Hanford and Ringold Formations both at the 100H Area and at the Hanford Site as a whole (Bob Peterson, pers. communication).

The only other direct velocity measurements available from the site were reported by Kearl and Gardner (1994). They used a colloidal borescope to obtain velocity magnitudes of about 14 ft/day in borehole H4-7, which is very close to flow sensor SFM2. That is more than two orders of magnitude higher than the velocities obtained with the In Situ Permeable Flow Sensors. KV flow meters were also tested and reported by Kearl and Gardner (1994). These meters measured flow velocities of about 2 ft/day, or about 1 order of magnitude higher than was observed with the In Situ Permeable Flow Sensors. The colloidal borescope and the KV meter were not used near the river because of the difficulty they would have measuring flow velocities which change so dramatically on daily time scales. In addition, it was not practical to leave these instruments deployed in the field for long time periods.

If the magnitudes of the velocities measured with the In Situ Permeable Flow Sensors were indeed too low, it may have resulted from the method of emplacement. Resonant sonic drilling was used to install the flow sensors because the technology can drill holes very quickly and cost effectively through the Hanford Formation, which is very difficult to drill using other drilling techniques. Sonic drilling tends to disturb the hydraulic properties of the sediments in the immediate vicinity of the borehole, however. Vibrating the sediments tends to reorient the sediment particles and pushing aside the sediments while driving in the plugged casing significantly compacts the sediments. The effect is to significantly reduce the hydraulic conductivity of the sediments immediately surrounding the flow sensors, thereby diverting the flow slightly away from the probes and reducing the groundwater flow immediately adjacent to the probe surface. These problems have not been encountered when flow sensors are emplaced with hollow stem augers. It is probable that these effects could be minimized by driving in the casing without the plug at the bottom and then cleaning out the casing before installing the flow sensor. This would have prevented most of the compaction caused by driving in the plugged casing. Alternatively, sonic could be used to drill down to a depth a few feet above the target depth of the measurement and then another technique used to drill the last few feet.

Another explanation which might account for the lower than expected flow velocity magnitudes would be the response time of the flow meters. The flow meters can be somewhat slow to respond to rapid changes in flow velocity (Ballard et al, 1994, and in press). The flow sensors are thermal devices and sense temperature variations on their surfaces. When the flow velocity changes abruptly, there is a delay before the heat around the probe is redistributed and the surface temperature distribution once again accurately reflects the flow velocity past the tool. The higher the magnitude of the flow velocity, the more quickly the tool will return to thermal equilibrium after a step change in flow, or the more closely it will track a constantly changing flow velocity. It is not clear that this effect is particularly important in this case because there were days when the river stage changed very little over the course of 24 hours and the flow velocity appeared to achieve equilibrium within only a few hours. This also cannot explain the relatively low velocity magnitude observed by flow sensor SFM2 since it was located sufficiently far from the river that the flow velocity was relatively steady and did not oscillate back and forth the way the probes near the river did.

Conclusion

The two flow sensors deployed near the river, SFM3 and SFM5, measured flow velocity directions which seem plausible given the hydrologic environment. Both flow sensors recorded flow velocities which had steady downstream components, and components perpendicular to the bank of the river which varied according to river stage. During times of high river stage the probes recorded flow velocity which was into the bank while flows from the bank into the river were observed when the river stage dropped. This was true for both the daily and seasonal river stage oscillations. SFM3, the flow sensor in the Hanford Formation, measured vertical flow which was downwardly directed, suggesting that the flow sensor was located at a vertical position where the hydraulic conductivity of the sediments was changing from relatively low conductivity above the tool to higher conductivity material below the tool. Flow sensor SFM5, which was located in the Ringold Formation where the hydraulic conductivity is much lower than in the overlying Hanford Formation, recorded upwardly directed flow, consistent with the fact that on a regional scale, the river is in a discharge area.

Flow sensor SFM2, located about 800 ft from the river, recorded flow which seemed to be away from the river in that the magnitude of the flow was positively correlated with river stage. The measured direction of the flow velocity was N60W, which is essentially upstream. The flow direction may have been influenced by the existence of buried structures nearby.

The magnitudes of the flow velocities are lower than expected, probably due to drilling-induced disruption of the hydraulic properties of the sediments immediately surrounding the probes. These problems have not been encountered when drilling techniques other than resonant sonic drilling have been used and it is likely that they could be avoided by modification of the emplacement technique.

Overall, the excellent correlation between river stage and the measured flow directions near the river indicates that the flow sensors are capable of providing very useful information about the complex hydrologic regimes found in stream banks.

References

Ballard, S., in press, 1996, The In Situ Permeable Flow Sensor: A groundwater flow velocity meter, Ground Water.

Ballard, S., G. T. Barker and R. L. Nichols, 1994, The In Situ Permeable Flow Sensor: A device for measuring groundwater flow velocity, Sandia report SAND93-2765.

Ballard, S., G. T. Barker and R. L. Nichols, in press, 1996, A test of the In Situ Permeable Flow Sensor at Savannah River, SC, Ground Water.

Kearl, P. M. and F. G. Gardner, Field comparisons of the colloidal borescope with other direct velocity measurement methods, Oak Ridge National Laboratory unofficial report, November, 1994.

Distribution

5 Dick Biggerstaff
MS H4-91
Bechtel Hanford, Inc.
450 Hills St., Door 5
Richland, WA 99352

1 Pete Kearl
Environmental Sciences Division
Oak Ridge National Laboratory
P. O. Box 2567
Grand Junction, CO 81502

1	0701	Dick Lynch, 6100
10	0750	Sandy Ballard, 6116
1	0750	Glenn Barker, 6116
1	0750	Marianne Walck, 6116
1	0750	Chris Young, 6116
1	1110	Louis Romero, 1422
1	9018	Central Technical Files, 8523-2
5	0899	Technical Library, 13414
1	0619	Print Media, 12615
2	0100	Document Processing, 7613-2 For DOE/OSTI

Org.	Bldg.	Name	Rec'd by	Org.	Bldg.	Name	Rec'd by

Sandia National Laboratories