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FINAL

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SUBJECT: LOWER PUTAH CREEK REGIONAL GROUNDWATER INFLUENCE STUDY LITERATURE REVIEW AND SUMMARY

Solano County Water Agency (SCWA) commissioned Luhdorff and Scalmanini, Consulting Engineers (LSCE) to evaluate whether groundwater level information can be used to predict streamflows in Lower Putah Creek. In response to SCWA's request, LSCE initiated the investigation with a literature review that was focused on original research and investigations concerning (i) streamflow, (ii) seepage gains and losses, and (iii) stream-aquifer interactions relating to Putah Creek. Over 50 documents were obtained and reviewed for this purpose and the results are documented in this Technical Memorandum. Key observations are summarized below:

1. Field investigations of stream-aquifer interactions and stream seepage rates carried out by various researchers prior to and after the construction of the Solano Project yielded very similar results and are in general agreement regarding the rate of Lower Putah Creek streamflow gains and losses both spatially and temporally.
2. Extensive streamflow measurements conducted by SCWA between 1990 and 2002 document the existence of a perennial groundwater ridge, in direct hydraulic communication with the stream channel, extending from the Putah Diversion Dam to Stevenson Bridge under all but severe drought conditions. Limited data available for the reach between Stevenson Bridge and Interstate 80, and below the Interstate 80 overpass, suggest the same.
3. Estimates of annual net seepage losses exhibit large variability between water years and between research efforts. Systematic differences are probably largely explained by (i) the different stream reaches that were investigated and (ii) different estimates of ungauged inflow and outflow components.
4. At least two separate attempts were made to correlate near-stream groundwater elevations to stream channel seepage rates. The correlations were weak.
5. Using groundwater level data to estimate seepage rates poses several difficulties. One difficulty arises from the challenge of identifying a well that is representative of seepage conditions of a particular stream

reach over a wide range of hydrologic conditions. Another difficulty is the identification of the length of that reach.

6. The Riparian Water Availability Forecasting Model (Model) is used to provide riparian water availability forecasts. By definition, riparian flow is a hypothetical quantity. Therefore, Model predictions of riparian flow cannot be checked and verified by means of streamflow measurements. The Model could be modified to estimate actual streamflow instead of hypothetical riparian water availability. To estimate actual streamflow, the model input of unimpaired streamflow entering Lower Putah Creek at the Diversion Dam would need to be replaced with actual releases from the Putah Diversion Dam into Lower Putah Creek. In addition, other inflows (e.g., tributary inflows, agricultural return flows, University of California at Davis [UCD] wastewater discharges) and outflows (e.g., riparian water users) would need to be included. Such a modification of the Model in conjunction with streamflow measurements would allow for the comparison of simulated flow and observed flow (i.e., performance evaluation).

1. Stream Reaches of Putah Creek Below Monticello Dam

Below Monticello Dam, Putah Creek extends approximately 30 miles to the Yolo Bypass. Its termination point, River Mile 0.0 (RM0), is defined as the point where the South Fork of Putah Creek enters the Yolo Bypass and is typically identified as the point where the flood control levee that parallels the north bank of the South Fork of Putah Creek turns and heads northerly (Sanford, 2005). Lower Putah Creek, as used in this document and consistent with Sanford (2005), refers to the 23-mile segment of the stream in the lower drainage area between the Putah Diversion Dam (RM22.6) and RM0. The 7-mile segment between Monticello Dam and the Putah Diversion Dam is also located within the lower drainage area, but it is not part of Lower Putah Creek and is of tangential interest to the subject of this document.

Several investigators that explored the hydrology of the lower drainage area divided the stream below Monticello Dam into reaches (i.e., stream segments) to facilitate hydrologic analysis. The segmentation varies between authors and has been based on both stream gain/loss characteristics (i.e., which are related to the local geology) and the stream's accessibility for flow measurement purposes. Seepage gains are streamflow gains attributed to groundwater entering the stream channel (gaining stream reach). Seepage losses from the stream channel are losses attributed to infiltration and percolation of surface water into the subsurface (losing stream reach).

Most recently, Sanford (2005) divided Lower Putah Creek into 5 reaches for the development of the Riparian Water Availability Forecasting Model (Model). The Model was developed to provide riparian water availability forecasts pursuant to the Putah Creek Accord of 2000 and is presently in use. Availability forecasts are made several times a year and provided on SCWA's webpage. The Model's conceptual framework is of significance to the question of stream-aquifer interactions and is discussed in greater detail below following the review of earlier investigations. Due to the importance of the Model, stream reaches for which forecasts are made are listed below:

1. DD-505 reach: from Putah Diversion Dam (RM22.6) to the Interstate Highway 505 Bridge (RM18.27)
2. 505-Stv reach: from the Interstate Highway 505 Bridge to Stevenson Bridge (RM12.8)
3. Stv-I80 reach: from the to Stevenson Bridge to the Interstate Highway 80 Bridge (RM8.0)
4. I80-Mace reach: from the Interstate Highway 80 Bridge to Mace Boulevard (RM4.1)
5. Mace-RM0 reach: from Mace Boulevard to River Mile 0.0.

Although early quantitative streamflow and seepage investigations (i.e., prior to the construction and operation of the Solano Project), such as conducted by the U.S. Bureau of Reclamation (USBR), U.S. Geological Survey (USGS), and the California Department of Public Works Division of Water Resources (DWR), were based on slightly different stream segmentation, comparison of the results remains useful.

Mann (1992) conducted a literature review and devised what was probably the most rigorous subdivision of Lower Putah Creek into 6 reaches (named A through F) based on geologic and hydrologic characteristics that exert the most control on stream-aquifer interactions within individual reaches.

2. Historical Streamflow Records

Whipple (1914) investigated Putah Creek as a source of water supply for irrigation purposes and noted that "...usually during the dry season the small summer flow is lost by percolation before reaching Davis, leaving the remainder of the channel dry." Huberty and Johnston (1941) observed that "A minimum streamflow of 4 or 5 cubic feet per second passes from the upper to the lower basin throughout the summer, but it soon disappears in the porous gravels of the lower basin. Normally, no water passes the town of Winters after July 1, percolation into the porous underground strata being at such a rate as to absorb the entire flow."

These historical accounts are supported by streamflow measurements of the USGS:

1905 – 1931 At Winters station; was located just downstream of the present day Putah Creek Bridge at Winters.

1930 – present Near Winters station; located approximately 1 mile downstream of Monticello Dam.

1948 – 1957 Near Davis station; was located at the junction between the old North Fork of Putah Creek and the South Fork (the North Fork was blocked off and abandoned in the late 1800's in an attempt to protect Davis from flooding; the South Fork is a 10-mile artificial channel conveying Putah Creek water to the Yolo Bypass).

On September 25, 1953, ground breaking ceremonies were held at the site of Monticello Dam and construction lasted through much of 1957 (USBR, 1959). Historical streamflow records indicate that portions of Lower Putah Creek frequently went dry in the summer months prior to the Solano Project (**Table 1**).

Table 1: Putah Creek median monthly flow rates (cfs) prior to the construction of Monticello Dam and 1970 fixed release schedule at Putah Diversion Dam (DD)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Near Winters (1930 - 1953)	6	20	234	664	751	679	263	96	33	7	5	4
At Winters (1905 - 1931)	0	16	207	885	1,440	636	333	97	24	5	0	0
Near Davis (1948 - 1953)	0	0	1,776	1,321	772	663	223	123	1	0	0	0
DD "fixed" (1970 - 1993)	20	25	25	41	51	34	46	43	43	43	34	20

Data compiled from Sanford (1998), Tables 1 and 4.

The data summarized in **Table 1** show the dual effect of the 1970 fixed release schedule on streamflow below the Putah Diversion Dam. Median streamflows in historical high-flow months (December-May) were drastically reduced and median streamflows in historical low-flow months (June-November) were substantially increased. The 1970 fixed release schedule provides year-round releases from Putah Diversion Dam, which essentially ensure that the DD-505 reach perennially carries water. This includes months during which Putah Creek typically became dry before construction of the Solano Project such as August through October (see **Table 1** At Winters station). The minimum releases recorded between 1970 and 1993 occurred in September and October (15 cfs) and February (16 cfs) (not shown in **Table 1**). Prior to the implementation of the 1970 fixed release schedule, the Solano Project was operated under the live stream release schedule, which more closely mimicked historical unregulated flow conditions.

3. Pertinent Investigations of Lower Putah Creek

To investigate Putah Creek streamflow losses via seepage into the subsurface and, conversely, streamflow gains via groundwater seepage into the stream channel, the USGS obtained 22 sets of low-flow discharge measurements during the spring and summer of 1949, 1950, and 1951 (Thomasson et al., 1960). Measurements were obtained from 14 sites along the stream between the low water bridge (RM24.0; 4 miles southwest of Winters) and the bridge at the Yolo-Solano County line at RM3.8 (3 miles southeast of Davis). To supplement the analysis, 6 sets of measurements from 4 sites made in July, August, and September 1941 were obtained from the USBR.

Measurements were made during periods of practically constant stage elevation, and individual sets were made in downstream order to minimize the effect of changes in flow when measurements occurred. The authors note that the magnitude of seepage gain or loss was so small between adjacent measuring sites that when streamflows exceeded about 200 cfs, errors inherent in the current-meter measurements became large enough to compromise or "mask completely" the small differential streamflow quantities measured. Therefore, measurements were obtained when stream discharge ranged from 2 to 200 cfs. Agricultural diversions or tributary inflows were estimated when observed, and seepage gains/losses adjusted accordingly. Evaporative losses from the creek's surface were considered negligible and not individually quantified.

The results of this investigation showed that during the measurement periods (spring and summer 1949, 1959, and 1951) (i) the reach between the gauging station near Winters (RM27.8) and at Winters (RM19.6) was a losing reach with the greatest rates of seepage losses typically estimated between the gauging station at Winters and observation stations approximately 2 miles upstream, (ii) Putah Creek downstream of the gauging station at Winters remained a losing reach for about 2 miles, then gradually changed to a stream with near-zero losses, and eventually to a predominantly gaining stream, (iii) the reach between the Stevenson Bridge (RM12.8) and observation stations approximately 2 miles upstream from the Stevenson Bridge was consistently a gaining reach (between 0.1 and 2.0 cfs per mile) with the exception of April 25, 1951 when the net gain/loss was zero, and (iv) Putah Creek below Stevenson Bridge was consistently a losing stream with only very small seepage losses in the reach downstream of the gauging station near Davis (RM9.0).

The interaction between surface water in the stream channel and underlying groundwater was further investigated by compiling water level records from existing wells near Putah Creek (dating back to 1912) and preparing water level hydrographs, maps depicting contours of equal groundwater level elevations, and water level profiles along the Creek. The historical data were supplemented with data collected from 12 newly installed in-channel test holes. The analysis of the combined groundwater level data set in conjunction with Creek stage measurements qualitatively supported the quantitative results obtained by the differential discharge measurements.

The net seepage loss between the low water bridge (RM 24.0) and the county line bridge (RM3.8) was estimated to range between 20 and 30 cfs; and it was typically less than 25 cfs. This net loss was found to be relatively constant when flow in the stream channel occurred at up to 200 cfs. The groundwater level data collected for this investigation also showed the build-up of a groundwater ridge under the creek channel, which extended from west of Winters to near Davis. Thomasson et al. (1960) explained the lack of correlation between surface flow and rate of seepage loss as follows:

> "…,as soon as the ground-water level was built up to stream level, the controlling factor in the rate of exchange between the stream and the adjacent ground-water body was not the wetted area covered by surface pools or the infiltration capacity of the stream-bed materials immediately in contact with the water in the surface stream. The rate shown by the measurements appears to have been governed largely by the capacity of the sediments to transmit the sediments laterally down the slopes of the water-table ridge, away from the channel." (p. 247)

The volume of the groundwater ridge in 1949-51 was estimated to range from 1,000 to 2,000 acre-feet (af). Based on the low flow measurements (i.e., a stable seepage loss rate of 25 cfs) and information regarding flow

duration in the stream channel, net seepage losses (in water years 1948 to 1952) were calculated to range from 10,000 to 13,700 af (**Table 2**). The mean annual net seepage loss for this period was estimated to be 13,000 to 14,000 af.

DWR (1955) includes a Putah Creek Percolation Study that estimates annual percolation from the reach between the Near Winters station (RM27.8) and Near Davis (RM9.0) as the difference between supply and disposal. Supply was quantified as Putah Creek inflow (as measured at the Near Winters station), tributary inflow, and estimates of rising groundwater (seepage into the creek channel). Disposal was quantified as Putah Creek outflow (as measured at the Near Davis station), estimates of riparian consumptive water use, and agricultural diversions. The sum of evaporative losses from the surface of the Creek and sewage inflow (from the City of Winters and the Yolo County Farm Labor Camp downstream of Winters) were found to constitute less than 0.5 percent of the Putah Creek inflow; therefore, these were not included due to their small overall contribution to the water budget. The estimated annual gross seepage for 5 water years investigated between 1949 and 1954 ranged from 6,200 to 51,600 af (see **Table 2**).

Fundamentally, DWR's percolation loss estimates differ from those provided by the Thomasson et al. (1960), as they incorporate an estimate (not a measured quantity) of streamflow gains (i.e., seepage directed into the stream channel). Therefore, the calculated seepage loss is a gross value. In comparison, the USGS calculated net seepage losses via streamflow measurements used to quantify both seepage gains and losses. Annual seepage estimates from the two agencies were as follows:

Table 2: Estimates of annual Putah Creek seepage losses

Water Year	USGS (Net) [af][1]	DWR (Gross) [af][2]
1948	13,400	---
1949	11,700	6,200
1950	10,000	19,700
1951	12,500	42,100
1952	13,700	51,600
1953	---	28,700
1954	---	32,600

1. Calculated between the low water bridge (RM24.0) and Yolo-Solano County line at RM3.8, Thomasson et al. (1960)
2. Calculated between Near Winters station (RM27.8) and Near Davis station (RM9.0), DWR (1955)

The above tabulation of seepage estimates shows that the calculated net seepage losses were substantially smaller than gross seepage losses except in 1949. This trend is expected and DWR (1955) clearly states that their seepage loss calculations are not comparable to the estimates made by the USGS. However, the discrepancies between the two agency's estimates are too large to be solely explained by DWR's explicit incorporation of 3,000-5,000 af of seepage inflow. DWR estimated the seepage inflow based on a correlation between groundwater levels at Well 8N/1E-17K1 and the difference in streamflow measurements. However, the presented correlation suggests the potential for over- and underestimation of seepage inflow by several hundred percent over the range of water levels encountered in the well.

DWR seepage estimates exhibit large variability (order of magnitude) between years. The variability is somewhat related to the magnitude of the tributary inflow estimates. For example, the largest difference between seepage estimates occurred in water year 1952 when the tributary inflow was estimated to be 27,400 afy. Potential error in large unmetered tributary flow estimates (3,600 to 27,400 afy) may also have contributed to an overestimation of gross seepage losses.

For comparison, the annual seepage estimates by Thomasson et al. (1960) were largely extrapolated from measurements obtained during summer months when streamflow was relatively small. This approach may have introduced error to the USGS estimates leading to possible underestimation of the annual net seepage losses.

USBR (1950) estimated the annual groundwater recharge from Putah Creek to be 7,200 af and cited the low permeability of materials underlying the stream channel and small streamflows in the summer and fall as reasons for the relatively small amount of seepage. The authors do not explain how the seepage was estimated. Later, USBR (1952) cites (non-specific) preliminary studies when suggesting an annual seepage loss from Lower Putah Creek of 15,000 af.

Net seepage losses to groundwater between Monticello Dam (RM29.3) and RM7.2 calculated by USBR as part of the annual progress reporting for the Solano Project (USBR, 1965 and 1970) are shown in Tables 3 and 4. USBR's estimates are based on an inventory of inflows (gauged inflows, estimates of tributary inflows and agricultural return flows, University of California at Davis (UCD) drain flow, and sewage inflow) and outflows (diversions to Putah South Canal, water uptake by riparian vegetation, evaporation from Lake Solano, and agricultural diversions). A priori estimates of seepage into the creek channel were not included in the water budget. Therefore, the overall seepage estimates are net values comparable to the estimates provided by Thomasson et al. (1960).

Table 3: Estimates of net annual Putah Creek seepage losses (USBR, 1965) in af

Water Year	Upper Reach[1]	Lower Reach[2]	Total
1958	7,670	7,440	15,110
1959	15,520	960	16,480
1960	16,660	10,790	27,450
1961	19,330	8,660	27,990
1962	15,450	11,500	26,950
1963	17,300	5,690	22,990

1. Between RM29.3 and RM 17.0
2. Between RM17.0 and RM7.2

Table 4: Estimates of net annual Putah Creek seepage losses (USBR, 1970) in af

Water Year	Upper Reach[1]	Lower Reach[2]	Total
1964	18,610	10,810	29,420
1965	22,230	13,050	35,280
1966	25,200	4,680	29,880
1967 (3)	43,010	-810	42,200
1968 (3)	17,810	-3,270	14,540
1969 (3)	39,807	-4,862	34,945

1. Between RM29.3 and RM 17.0
2. Between RM17.0 and RM7.2; a negative number denotes streamflow gains.
3. Modified method: a constant loss rate of 10 cfs was applied to the reach between Monticello Dam (RM29.3) and Putah Diversion Dam (RM 22.6) to avoid "unaccountable variations in flow measurements" (USBR, 1970).

USBR conducted a test to estimate stream channel seepage between the USGS gauge below Monticello Dam (RM29.3) and the Putah Diversion Dam (RM22.6). The test was conducted between October 6 and November 18, 1958 and documented in the Solano Project's Second Progress Report (USBR, 1960). During the first 9 days of the test, Lake Solano was rapidly filled from a stage height of approximately 117 to 130.8 feet (to its maximum depth of 15 feet); this stage was maintained until the test was terminated. Lake water levels and groundwater levels in 15 wells were closely monitored. Based on streamflow measurements at the USGS gauge below Monticello Dam and the Putah Diversion Dam, calculated seepage losses for the period prior to the test (i.e., eight sets of measurements between September 4 and 29) ranged from 8.1 to 12.6 cfs in this reach with an average seepage loss of 9.83 cfs (=19.5 afd). During the period of filling, seepage losses increased to up to 88.46 afd on October 14, but the losses quickly decreased and were considered stabilized from October 23 through the end of the test, averaging 10.74 cfs (=21.3 afd) for a 27-day period.

It was concluded that seepage losses in this reach do not appreciably increase in response to an increase of hydraulic head within the channel, with the exception of a temporary increase during a brief period of hydraulic adjustment of groundwater levels in response to the filling of the lake. This phenomenon was explained by flattening groundwater gradients and the limited capacity of the sediments to transmit water laterally down the slopes of the water-table ridge. The USBR's observation is similar to downstream observations and interpretations made by Thomasson et al. (1960), and indicates the lack of correlation between surface flow and rate of seepage loss.

The USBR conducted a second test to estimate stream channel seepage between the USGS gauge below Monticello Dam and the Putah Diversion Dam in October and November 1962 (USBR, 1965). The pool elevation was initially held constant at 129.6 feet (for 9 days) and then increased and held constant at 130.8 feet for 11 days. The average seepage losses were 7.6 and 9.5 cfs, respectively. The occurrence of tributary inflow during the earlier part of the test was noted as a possible source of error (tributary inflow was estimated between 0.2 to 1.6 afd). Consequently, the estimated seepage loss of 7.6 cfs during the earlier part of the test was regarded as less accurate than the seepage loss of 9.5 cfs during the latter portion of the test.

Mullen and Nady (1985) provide water budgets for 20 major streams in the Central Valley prepared for water years 1961-1977. The water budgets for Putah Creek were prepared for the reach between the Near Winters station (RM25.1)[1] and the South Fork Putah Creek station (RM4.3) as the difference between supply and disposal. Supply was quantified as Putah Creek inflow (as measured at the Near Winters station) and tributary inflow. Disposal was quantified as Putah Creek outflow (as measured at the South Fork Putah Creek station) and estimates of agricultural diversions. As in the DWR (1955) study, evaporative losses from the surface of the Creek and sewage inflow were not included in the water budget. A priori estimates of seepage into the creek channel were also not included in the water budget. Therefore, the overall seepage estimates are net values comparable to the estimates provided by Thomasson et al. (1960) and USBR estimates.

Table 5: Estimates of annual Putah Creek inflow and seepage losses by Mullen and Nady (1985) in af

Water Year	RM25.1 Inflow	Seepage RM25.1 to 14.2	Seepage[1] RM14.2 to 9.9	Seepage[1] RM9.9 to 4.3	Total Seepage RM25.1 to 4.3
1961	128,300	15,800	1,900	4,300	**22,100**
1962	135,300	4,800	3,300	5,800	**14,000**
1963	154,900	8,400	-1,000	5,000	**12,400**
1964	177,500	18,300	1,600	7,700	**27,600**
1965	406,800	20,300	10,500	600	**31,400**
1966	255,200	19.200	2,100	300	**21,600**
1967	548,500	10,600	-9,900	7,500	**8,200**
1968	285,100	13,500	1,600	-5,900	**9,100**
1969	594,100	-	-	-	**6,800**
1970	691,200	-	-	-	**26,800**
1971	310,800	-	-	-	**17,200**
1972	264,700	-	-	-	**26,300**
1973	283,000	-	-	-	**1,700**
1974	616,200	-	-	-	**41,900**
1975	336,700	-	-	-	**4,900**
1976	296,000	-	-	-	-
1977	228,400	-	-	-	-

1. A negative number denotes streamflow gains.

[1] It is unclear how this gauging station relates to the Near Winters station (RM27.8) discussed by Thomasson et al. (1960), DWR (1955), and various USBR progress reports on the Solano Project.

Net seepage estimates in Table 5 exhibit order of magnitude differences between water years. The smallest seepage loss was calculated for water year 1973 (1,700 af) and the largest seepage loss was calculated for water year 1974 (41,900 af). The median seepage loss is 17,200 af. This is higher than the median seepage loss calculated by Thomasson et al. (1960) for the 1948-1952 water years (12,500 af). Mullen and Nady (1985) incorporate 1.1 river miles upstream of RM24.0 (i.e., 1.1. miles of stream not included in the estimates provided by Thomasson et al. [1960]), which have relatively high seepage losses compared to the far downstream reaches of Lower Putah Creek. This may partially explain the higher seepage losses. Further, streamflow sustained during the summer months by the Solano Project may also have contributed to increased annual seepage losses.

Inspection of seepage estimates and Putah Creek inflow reveals no correlation between these quantities, which suggests a more complex relationship between annual runoff and seepage losses. Also, seepage estimates show no correlation to tributary inflow.

It is important to recognize that annual net seepage loss estimates vary widely despite similar approaches used in the estimations by USBR (1965 and 1970) and Mullen and Nady (1985). For 9 water years (1961 – 1969) where a direct comparison is possible, USBR's seepage estimates are consistently larger (on average 1.7 times larger) **(Table 6)**. The systematic differences are probably largely explained by (i) the different choice of overall stream reaches that were investigated and (ii) different estimates of ungauged inflow and outflow components. It is beyond the scope of this report to reconcile these discrepancies.

Table 6: Comparison of Estimates of annual Putah Creek seepage losses in af

Water Year	Thomasson et al. (1960)[1]	USBR (1965, 1970)[2]	Mullen and Nady (1985)[3]
1948	13,400	-	-
1949	11,700	-	-
1950	10,000	-	-
1951	12,500	-	-
1952	13,700	-	-
- - -	- - -	- - -	- - -
1958	-	15,110	-
1959	-	16,480	-
1960	-	27,450	-
1961	-	27,990	22,100
1962	-	26,950	14,000
1963	-	22,990	12,400
1964	-	29,420	27,600
1965	-	35,280	31,400
1966	-	29,880	21,600
1967	-	42,200	8,200
1968	-	14,540	9,100
1969	-	34,945	6,800
1970	-	-	26,800
1971	-	-	17,200
1972	-	-	26,300
1973	-	-	1,700
1974	-	-	41,900
1975	-	-	4,900
1976	-	-	-
1977	-	-	-

1. Calculated between the low water bridge (RM24.0) and Yolo-Solano County line at RM3.8.
2. Calculated between RM29.3 and RM7.2.
3. Calculated between RM25.1 and RM4.3.

Mann (1992) provides 6 conceptual geologic cross sections through the aforementioned reaches A – F of Putah Creek below Monticello Dam and summarizes the hydrogeologic conditions that influence surface/ groundwater interactions within individual reaches. Interpretations are largely based on review of work done by Thomasson et al. (1960) and DWR (1955). The author observes that the lowering of the water table due to groundwater pumping in the immediate vicinity of Putah Creek would only affect seepage losses when there is a "fully developed groundwater ridge". However, as soon as an unsaturated zone develops under the streambed, additional pumping would cease to affect streamflow losses. He concludes that groundwater pumping appears unlikely to have a significant effect on surface streamflows in Lower Putah Creek during periods of drought. This is explained by the absence of a fully developed groundwater ridge beneath most of the stream during drought years. This condition likely occurred more frequently prior to implementation of the 1970 "fixed" release schedule, when Putah Creek was operated under the live stream release schedule.

Benjamin (1994) investigated stream-aquifer interactions in a stream segment extending approximately 2 miles upstream of the Stevenson Bridge in 1993 and 1994. For purposes of this study, several piezometers were installed near Putah Creek and below the creek bed to various depths, instrumentation for in-stream seepage measurements was installed, and streamflow measurements were conducted at three locations. Results of the investigation documented that this stream segment was predominantly gaining at net rates between 0.84 and 1.1 cfs per mile. Further, it was determined that streamflow gains increased corresponding to the start of the irrigation season in April as documented by increased hydraulic gradients toward the creek.

Between March 1993 and December 1994 (March, June, and October 1993 and monthly from March to December 1994 [2 sampling events in July] for a total of 13 sampling events), SCWA conducted systematic measurements of Putah Creek streamflow at 9 observation locations (Sanford, 1995). The farthest upstream location was at the Interstate 505 bridge (RM18.27) and the farthest downstream location was at Stevenson Bridge (RM12.8). The total length of this reach of Putah Creek is 5.47 miles; this reach was further subdivided into stream segments ranging in length from 0.14 to 1.20 miles. Using USGS methodology, stream seepage rates were estimated by measuring streamflow at the observation locations and computing the incremental increase/decrease in streamflow with increasing distance from the Interstate 505 bridge. The cumulative net groundwater seepage gains along the entire 5.47 mile reach were estimated to range from 0.5 to 12 cfs (i.e., 0.1 to 2.2 cfs per mile) with a median of 3 cfs (0.5 cfs per mile).

Seepage gain rates, calculated based on streamflow measurements, were correlated to groundwater levels at Well 8N/1E-17F1 (located northwest of Stevenson Bridge). However, data were sparse and the correlation was weak.

Altogether, SCWA conducted over 160 canoe surveys along Lower Putah Creek between 1990 and 2002. These surveys spanned the length of the creek between the Putah Diversion Dam and RM0 to measure streamflow gains and losses, mostly during the months of April and October. These surveys were augmented by over 1,000 streamflow measurements at 5 stream crossings (Interstate Highway 505, Stevenson, Pedrick Road, Interstate Highway 80, and Mace Boulevard Bridges).

The results of SCWA's extensive monitoring efforts agree with earlier observations made by the USGS, USBR, and Benjamin (1994). Moreover, the comprehensive data set compiled by SCWA provides essential insight regarding the seasonal variability of stream seepage and long-term trends over a wide range of hydrologic conditions (wet years and dry years).

The seasonal variability of stream seepage provides strong evidence for the existence of a perennial groundwater ridge in direct hydraulic communication with the stream channel. The variability is predominantly caused by changing hydraulic gradients between the stream channel and underlying groundwater. In contrast, under unsaturated conditions beneath the stream channel, seepage losses would be expected to be nearly constant.

For example, for the DD-505 reach[2], measurements for 115 months are available. This reach was identified as a losing reach in 107 months, as a gaining reach in 5 months (either in April or May), and as neither a gaining nor a losing reach in 3 months (**Figure 1**).

1. During the drier part of the year (June – November), the median seepage rate ranged from -10 to -13 cfs[3] (i.e., indicating seepage losses). During the wetter part of the year (December – May), the median seepage rate ranged from -6 to -8 cfs[4].
2. Seepage rates display consistent seasonal variability from lowest seepage rates typically observed between February and April to greatest seepage rates typically observed between August and October. The lowest seepage rates occur when seasonally high groundwater levels are typically observed. The greatest seepage rates occur when seasonally low groundwater levels are typically observed.
3. The greatest seepage losses occurred in 1991 and 1992, i.e., in the midst of the 1987-1992 drought. However, due to the short duration of these large seepage losses, they provided no indication whether saturated or unsaturated conditions existed at that time.

These observations provide strong evidence for a perennially existing groundwater mound under the DD-505 reach, i.e., fully saturated conditions and direct hydraulic communication between the creek and groundwater.

For the 505-Stv reach[5], measurements for 106 months are available. This reach was identified as a losing reach in 23 months and as a gaining reach in 83 months (**Figure 2**).

1. Using only seepage loss rates: During the drier part of the year (June – November), the median seepage rate ranged from -8 to -9 cfs. During the wetter part of the year (December – May), the median seepage rate ranged from -4 to -7 cfs.
2. Using only seepage gain rates: During the drier part of the year (June – November), the median seepage rate ranged from 5 to 9 cfs. During the wetter part of the year (December – May), the median seepage rate ranged from 7 to 13 cfs.
3. Seepage rates display consistent seasonal variability from greatest streamflow gains observed toward the end of the wetter season (March to May) to smallest streamflow gains observed between August and October. The greatest streamflow gains occur when seasonally high groundwater levels are typically observed. The smallest streamflow gains occur when seasonally low groundwater levels are typically observed.
4. Seepage losses only occurred in 1991 and 1992, i.e., in the midst of the 1987-1992 drought. The greatest seepage loss rate (-9 cfs) was observed during 3 consecutive months (August to October 1992). The magnitude, persistence, and constant nature of this condition may indicate that an unsaturated zone had developed under the stream bed.

These observations provide strong evidence for a perennially existing groundwater mound under the 505-Stv reach, i.e., fully saturated conditions and direct hydraulic communication between the creek and groundwater during all but severe drought conditions.

For the Stv-I80 reach[6], measurements for 52 months are available. This reach was identified as a losing reach in 38 months, as a gaining reach in 10 months, and as neither a gaining nor a losing reach in 4 months (**Figure**

[2] These observations are based on data provided in Table 2-1 (Sanford, 2005).
[3] In this discussion, medians were calculated using both positive fluxes (indicating seepage gains) and negative fluxes (indicating seepage losses) unless otherwise specified. As such, the term 'seepage rate' does not imply either a seepage gain or a seepage loss. The sign of the seepage rate (i.e., positive or negative) identifies the direction of the seepage.
[4] Due to the danger associated with canoe surveys conducted during months of high streamflow, these surveys could often not be carried out in January, February, and March. Consequently, the data set is somewhat skewed toward times of less streamflow, and the difference between the median values calculated for 'dry' and 'wet' seasons is very likely less distinct than a more complete data set would yield.
[5] These observations are based on data provided in Table 2-2 (Sanford, 2005).

3). Data are not available for calendar years 1995, '98, and '99; only one to two measurements are available for calendar years 1994, '96, and 2000; and only four measurements in 1998. However, even the limited data exhibit seasonal seepage variability similar to the upstream reaches and, as such provide evidence for the existence of a groundwater ridge. The greatest seepage loss rates (-11 to -12 cfs) were observed during 4 consecutive months (June to September 1991). A constant seepage loss rate of -11 cfs was observed for 6 consecutive months (July to December 1992) during the 1987-1992 drought. The extended occurrence of a constant seepage loss rate in 1992 and a near-constant seepage loss rate of similar magnitude in 1991, suggests the absence of a groundwater ridge during these times. This concept is supported by the observation of the absence of continuous stream flow through this reach for both a period of several consecutive weeks in 1991 and for a period of several consecutive days in 1992, when isolated pools of water were reported (Sanford, 11-22-2009 email correspondence).

In summary, the extensive streamflow measurements conducted by SCWA between 1990 and 2002 document the existence of a perennial groundwater ridge, in direct hydraulic communication with the stream channel, extending from the Putah Diversion Dam to Stevenson Bridge under all but severe drought conditions. The data available for the reach between Stevenson Bridge and Interstate 80 are less abundant. However, for the available period of record, streamflow measurements also document the existence of a perennial groundwater ridge, in direct hydraulic communication with the stream channel except periods during the last two years of the 1987-1992 drought. Similar conditions are reported for the stream reach below the Interstate 80 overpass reported (Sanford, 11-22-2009 email correspondence).

4. Lower Putah Creek Riparian Water Forecasting Model

As noted in *Section 1*, SCWA presently uses the Riparian Water Availability Forecasting Model (Model) developed for Lower Putah Creek to provide riparian water availability forecasts pursuant to the Putah Creek Accord of 2000. The purpose of the Model is to inform the (mostly agricultural) riparian water users along Lower Putah Creek about how much, and for how long, riparian water is anticipated to be present during April through October of each year. The Putah Creek Accord of 2000 defines riparian water as streamflow present in Lower Putah Creek as a result of rainfall-runoff processes and/or streamflow gains due to groundwater that seeps into the stream channel prior to the Solano Project (Sanford, 2005). By the above definition, riparian flow is a hypothetical quantity. Therefore, Model predictions of riparian flow cannot be checked and verified by means of creek flow measurements (personal communication, April 15, 2009). However, this does not mean that the model performance cannot be tested. As discussed later in this section, a slight modification to the model in conjunction with coordinated streamflow measurements, would allow for the comparison of simulated flow and observed flow (i.e., performance evaluation).

The Model consists of three components to make water availability forecasts. These components are briefly summarized below.

Estimation of Unimpaired Surface Streamflows

Estimates of unimpaired streamflows entering Lower Putah Creek at the Putah Diversion Dam are made based on pre-Solano Project streamflow records from the Near Winters gauging station. Since this station is located about 6 miles upstream of the Putah Diversion Dam, using these records is thought to somewhat overestimate unimpaired flows entering the upstream end of Lower Putah Creek because this approach does not account for historical riparian water diversions nor does it account for percolation losses in this reach. As discussed earlier, streamflow losses in the reach now inundated by Lake Solano are significant. Tributary inflows, notably from Pleasants Creek, are assumed to be lost in their entirety to percolation in that reach. This is particularly so by June and the later summer and early fall months, when the availability of riparian water is most critical. Errors due to the overestimation of unimpaired streamflows are to the benefit of riparian water users and are, therefore, considered acceptable.

[6] These observations are based on data provided in Table 2-3 (Sanford, 2005).

Estimation of seepage gains and losses

Seepage gains and losses are predicted by multivariate regression analysis specific to 5 stream reaches (see *Section 1* of this TM). In this analysis, seepage data collected by SCWA between 1990 and 2002 were correlated to total Putah Creek runoff (as measured at Monticello Dam) in three prior water years[7]. The correlation was found to be significantly improved for the DD-I550 reach by including a term for the releases from the Putah Diversion Dam to Lower Putah Creek in the current water year.

Predictions are made on January 1, March 1, and May 1. Since the January and March predictions are made before the current "rainy" season is over, these Model predictions are based on both actual and projected streamflow conditions. Therefore, the January 1 and March 1 forecasts provide scenarios for a "normal" hydrologic year (50 percent exceedance), a "wet" hydrologic year (25 percent exceedance), and a "dry" hydrologic year (75 percent exceedance). The May 1 forecast is based on actual runoff measured to date.

Streamflow routing

Streamflows at the downstream end of the five reaches are computed by routing the estimated upstream unimpaired streamflows sequentially through each reach by adding and subtracting seepage gains and losses predicted for each reach.

The Model could be used to estimate actual streamflow instead of hypothetical riparian water availability. To estimate actual streamflow, the model input of unimpaired streamflow entering Lower Putah Creek at the Putah Diversion Dam needs to be replaced with actual releases from the Putah Diversion Dam into Lower Putah Creek. The estimation of seepage gains/losses and streamflow routing would remain unchanged. Such a modification of the Model in conjunction with streamflow measurements at the downstream ends of the aforementioned five reaches would allow for the comparison of simulated flow and observed flow (i.e., performance evaluation).

5. Summary and Discussion

1. Field investigations of stream-aquifer interactions and stream seepage rates carried out by various researchers between 1941 and 1954 (prior to the construction of the Solano Project) and between 1990 and 2002 (after the construction of the Solano Project) yielded very similar results and are in general agreement regarding the rate of Lower Putah Creek streamflow gains and losses both spatially and temporally.
2. Extensive streamflow measurements conducted by SCWA between 1990 and 2002 document the existence of a perennial groundwater ridge, in direct hydraulic communication with the stream channel, extending from the Putah Diversion Dam to Stevenson Bridge under all but severe drought conditions. Limited data available for the reach between Stevenson Bridge and Interstate 80, and below the Interstate 80 overpass, suggest the same.
3. Estimates of annual net seepage losses provided by the USGS (for water years 1948-52; Thomasson et al. [1960]), USBR (for water years 1958-69, USBR [1965 and 1970]), and USGS (for water years 1961-75; Mullen and Nady [1985]) exhibit large variability between water years and between researchers. Systematic differences are probably largely explained by (i) the different stream reaches that were investigated and (ii) different estimates of ungauged inflow and outflow components.
4. Estimates of annual gross seepage losses provided by the DWR (1955) (for water years 1949-54) are not directly comparable to estimates of net seepage losses.

[7] Sanford (2005) recognizes the importance of surface-groundwater interactions and the potential for groundwater level information to be used to estimate seepage rates, but concludes: "Unfortunately, based on the analyses performed to date, it appears that the available groundwater elevation data are insufficient to characterize prevailing groundwater elevations in the vicinity of Lower Putah Creek, to the degree necessary for timely and reliable streamflow gain/loss predictions." In the search for a suitable surrogate, the use of rainfall data was also assessed but found not to produce sufficiently strong correlations with seepage measurements.

5. At least two separate attempts were made to correlate near-stream groundwater elevations to stream channel seepage rates (DWR [1955] and Sanford [1995]). The correlations were weak.
6. Using groundwater level data to estimate seepage rates poses several difficulties. One difficulty arises from the challenge of identifying a well that is representative of seepage conditions of a particular stream reach over a wide range of hydrologic conditions. Another difficulty is the identification of the length of that reach.
7. The Riparian Water Availability Forecasting Model could be used to estimate actual streamflow instead of hypothetical riparian water availability. To estimate actual streamflow, the model input of unimpaired streamflow entering Lower Putah Creek at the Putah Diversion Dam would to be replaced with actual releases from the Putah Diversion Dam into Lower Putah Creek. In addition, other inflows (e.g., tributary inflows, agricultural return flows, University of California at Davis [UCD] wastewater discharges) and outflows (e.g., riparian water users) would need to be included. The estimation method of seepage gains/losses and streamflow routing would remain unchanged. Such a modification of the Model in conjunction with streamflow measurements would allow for the comparison of simulated flow and observed flow (i.e., performance evaluation).

Figures

Figure 1 Putah Creek Seepage Gains and Losses, Putah Diversion Dam to Interstate 505 - Evidence for Perennial Groundwater Ridge

Figure 2 Putah Creek Seepage Gains and Losses, Interstate 505 to Stevenson Bridge - Evidence for Perennial Groundwater Ridge

Figure 3 Putah Creek Seepage Gains and Losses, Stevenson Bridge to Interstate 80

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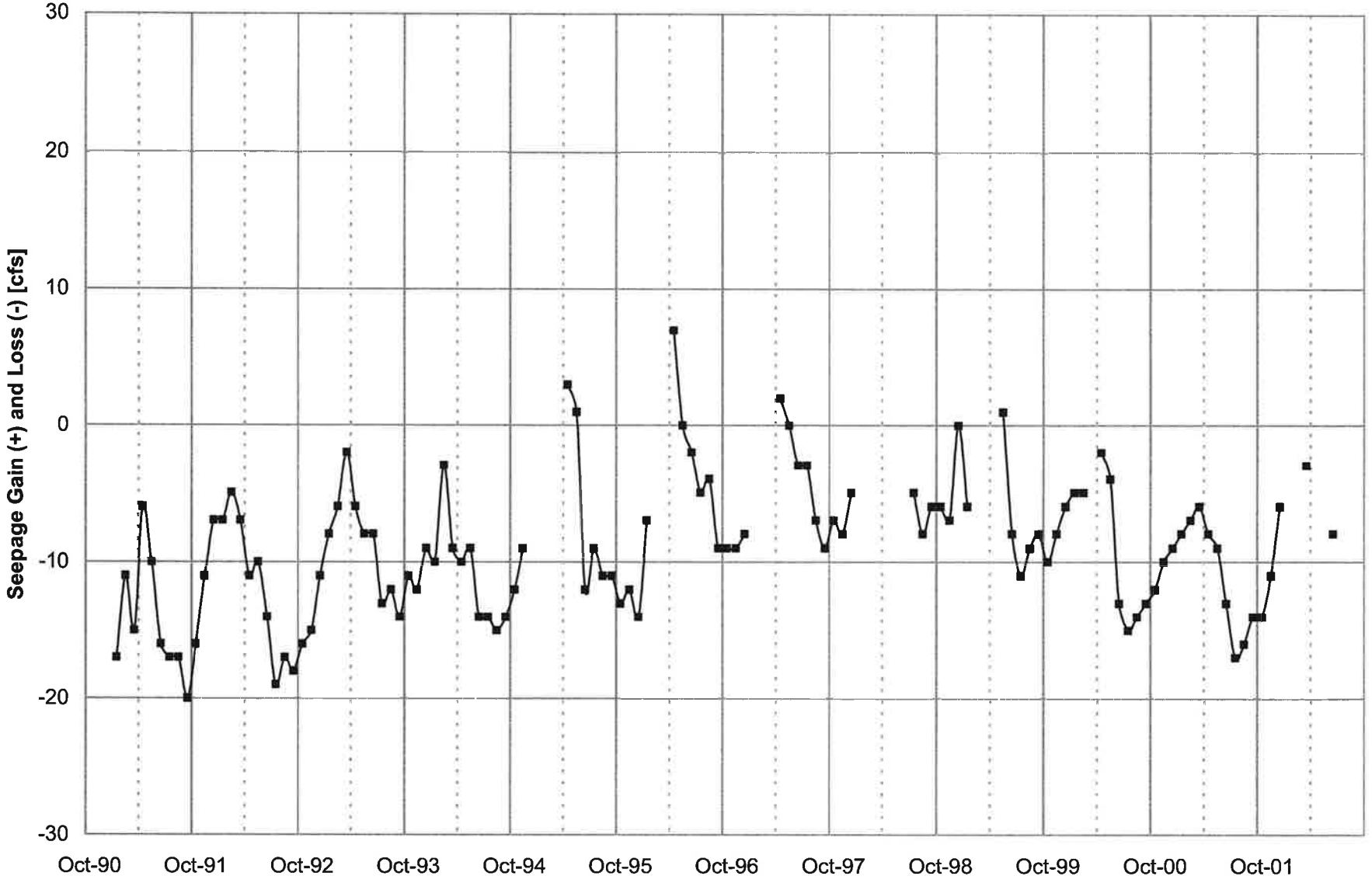

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Figure 1
Putah Creek Seepage Gains and Losses
Putah Diversion Dam to Interstate 505 - Evidence for Perennial Groundwater Ridge

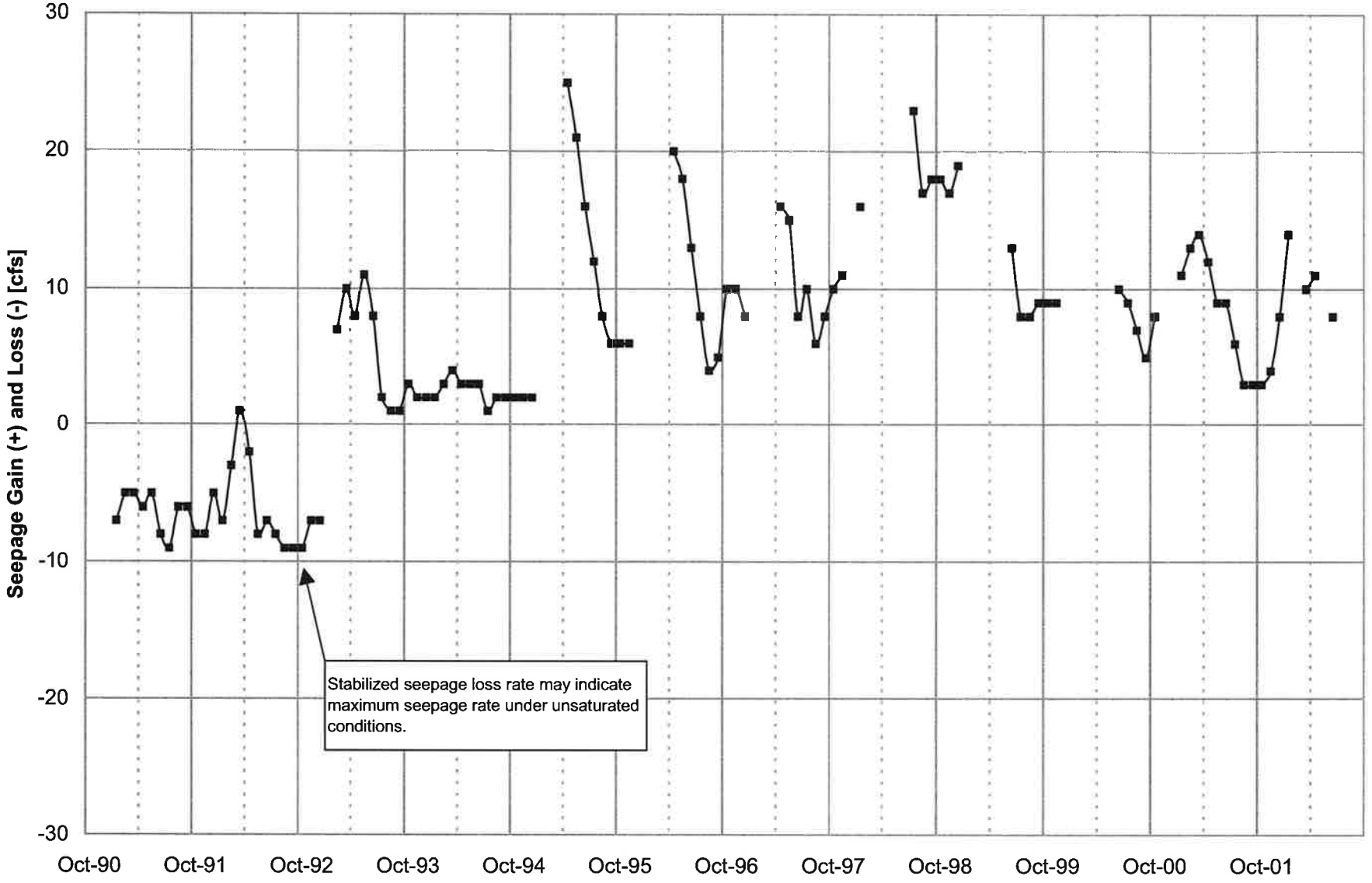

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Figure 2
Putah Creek Seepage Gains and Losses
Interstate 505 to Stevenson Bridge - Evidence for Perennial Groundwater Ridge

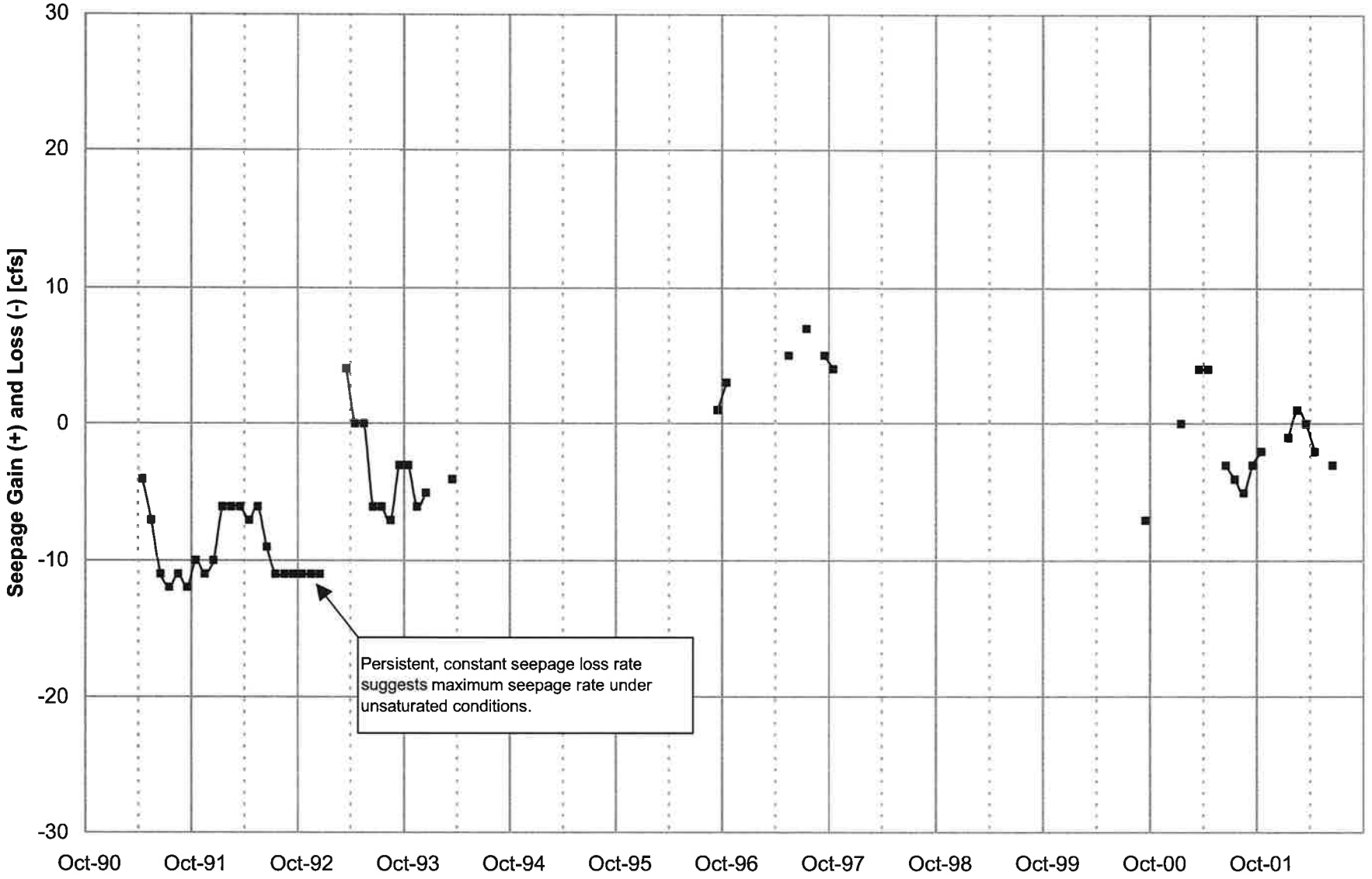

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Figure 3
Putah Creek Seepage Gains and Losses
Stevenson Bridge to Interstate 80