Nitrogen, phosphorus and salt transfers at the landscape scale in the Upper Klamath Basin of Oregon and California[1]

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Abstract

The Upper Klamath Basin (UKB) is a high desert region straddling the California-Oregon border east of the Cascade Range. Irrigation and other agricultural practices in the region may result in impaired surface water quality for wildlife and anadramous fish. To investigate the relationships among agricultural practices and surface water quality in the UKB, a multi-year (1995-2000) reconnaissance survey of surface water and agricultural tile drain locations was conducted, focusing on total dissolved solids, N, and P concentrations and mass transfers. Data were collected at 18 surface and 10 tile drain locations every ten days during the irrigation season (March through October) and one or two times a month during the remainder of the year. Water samples were analyzed for N, P, temperature, pH and electrical conductivity (EC_w). Climate and water balance data were available over a multi-decade time interval. These data were used together with concentrations derived from sampling to estimate transfers of salts and nutrients within the UKB. The salt content of surface waters increased nearly threefold as water moved through the watershed. Mean EC_w levels in water entering the region were 250 :S cm^{-1}, while water sampled at the main irrigation drain increased to 600 :S cm^{-1} over the sample period and to 700 :S cm^{-1} by the time water reentered the Klamath River. The EC_w values observed in subsurface tile drains were higher on average than in input and other surface waters in the region (2,500 :S cm^{-1}). Total N increased from 2.3 mg L^{-1} on average for the years reported in input waters to 4.0 mg L^{-1} in outflows at the Klamath Straits Drain. For total P (TP), input waters averaged approximately 0.27 mg L^{-1} to 0.40 mg L^{-1} over the same pathway. Atomic ratios (TN:TP) of surface water samples remain constant at approximately 10:1 throughout the system, suggesting that the amount of small particulate matter in surface waters affects the values observed. In spring or early summer large NO_3-N values (range: 1 to 40 mg L^{-1}) were observed in shallow (1.1m) subsurface tile drains, leading to the inference that some N from fertilizer and soil organic matter is lost in drainage. More N is removed in crop biomass than is applied as N fertilizer in the region, but less P. More efficient fertilizer use can help bring P inputs and outputs into balance in local farming systems. Since surface waters entering the region are already enriched with N and P, it appears unlikely that further reducing N and P losses from farming, if possible, would make surface waters significantly less eutrophic.

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Reusing some drainage water for irrigation would reduce nutrient loads in the Klamath River.

Introduction

The Upper Klamath Basin is a 1.5 million ha watershed on the border of California and Oregon east of the Cascade Mountains. It is the site of two large and several small irrigation districts, including the Klamath Irrigation District (KID) in Oregon and the Tulelake Irrigation District (TID) in California. These districts receive water from the U. S. Bureau of Reclamation (USBR) as part of the Klamath Project (Fig. 1). Farming and ranching are the economic foundation of the region. The climate is semi-arid with average precipitation equal to approximately 25 % of potential evapotranspiration. Irrigation necessary for crop production. Water for the Klamath Project is derived from the Lost River and Upper Klamath Lake. Upper Klamath Lake is part of the Klamath River. Farm fields border on or are located within the Tule Lake National Wildlife Refuge (TLNWR) and the Lower Klamath Lake National Wildlife Refuge (LKNWR). Water flows directly into the refuges' marshes from irrigation drainage channels. The TLNWR is bordered on its north and east by TID, and in the west by Sheepy Ridge and the south by Lava Beds National Monument. About 8,900 ha of the Tule Lake and Lower Klamath National Wildlife Refuges are leased annually to approximately 80 farmers. The wildlife refuge receives water from undiverted Lost River flows and subsurface and surface drainage from the TID and Klamath Irrigation District (KID) to the north in Oregon. Subsequently, water from the Tule Lake Sumps is diverted to LKNWR and from there to the Klamath River below the city of Klamath Falls. This diversion is an artifact of the Klamath Project because the Lost River and Klamath River watersheds are otherwise hydrologically separate. On its way to the river, diverted water is supplemented with additional drainage from the Klamath Drainage District (KDD) added to the Klamath Straits Drain (Fig. 1).

Both water quantity and water quality limitations affect the region. Water supplies in the Klamath River are needed for urban use, agriculture, and anadramous fisheries management. Especially in years with below average precipitation, supplies are insufficient to satisfy competing interests. In addition to water quantity limitations, there are concerns that agricultural practices may result in impaired surface water quality, possibly reducing its value for wildlife conservation in the TLNWR and LKNWR and particularly by raising nutrient levels in water returned to the Klamath River. The surface water within the basin is judged to be highly eutrophic because of high pH, high levels of un-ionized NH_3, and low dissolved oxygen (DO) during warm months. Farming may enrich surface water with nitrogen and phosphorus from fertilizer applications or from mineralization of the region's organic matter rich soils, contributing to the growth of algae and other aquatic plants. Low levels of dissolved oxygen occur in surface waters throughout the Upper Klamath Basin in the summer, and are related directly to the growth and subsequent death and decomposition of aquatic plants and other organisms (Sorenson and Schwarzbach, 1991). If DO in surface waters is influenced by drainage discharge, it occurs through the leaching of nutrients from soils that subsequently stimulate the growth of aquatic plants where they would otherwise not grow. Apart from work carried out by Kaffka et al. (1995, 2002), tile drainage data from farm fields have not been collected intensively, and no attempt to quantify the possible effects of agriculture on water quality have been made in the region.

Methods

To investigate the relationships among agricultural practices and surface water quality in the UKB, a multi-year (1995-2000) reconnaissance survey of surface water and agricultural tile drain locations was conducted, focusing on total dissolved solids (TDS, expressed as electrical conductivity: EC_w), N, and P concentrations and mass transfers. At collection, water temperature, pH, and electrical conductivity (EC_w : a measure of salinity) were determined. Samples were stabilized with toluene and refrigerated until analysis. Sample aliquots were filtered through 5 micron filters and analyzed for filtratable, reactive P by direct colorimetric analysis (AOCS 973.55; Watanabe and Olsen, 1965) and for soluble N (NO_3-N) using HPLC methods (Thayer and Huffaker, 1980). A second aliquot was digested using a procedure modified from Johnes and Heathwaite, (1992), using persulfate digestion. Digested samples were then analyzed for N and P using HPLC and colorimetric methods as above. Filtered samples were also digested and analyzed for N and P as above. Ammonia was collected separately in acidified sample bottles and refrigerated until analysis. HPLC and spectrophotometry methods are used for determination (Goyal et al., 1988). Methods are discussed in greater detail in Kaffka and Danosky (2002). Data were collected at 18 surface and 10 tile drain locations every ten days during the irrigation season (March through October) and one or two times a month during the remainder of the year. Water samples were analyzed for N, P, temperature, pH and EC_w. Climate and water transfer data (from USBR) were available over a multi-decade time interval. Most surface water transfers are measured or estimated from pump operations. These data were used together with concentrations derived from sampling to estimate transfers of salts and nutrients within the UKB. Emphasis was given to the southern portion of the project, principally the areas included in the the TID, KID, KDD, TLNWR, and LKNWR.

A simplified equation accounting for the water balance in the portion of the Klamath Project studied is:

$$I_i + P_i + C_i = O_i + ET_i$$

where I_i are the sum of all measured or computed inflows into the southern portion of the Klamath Project determined at location i, P_i is precipitation occurring, and C_i is a closure term that includes unaccounted inflows or outflows and measurement errors. O_i includes measured outflows and ET_i is the sum of all estimated evapo-transpiration occurring in the region of interest. More specific equations for water balances for each of the sub-areas analyzed are depicted in Fig . 2 and included in Table 1. Mass transfers are calculated by linking salt, N or P concentrations in water with water volumes calculated over ten day intervals (the period between sample collections).

Results

The salt and nutrient content of surface waters increased nearly threefold as water moves through the watershed from the Lost River and J canal diversion to the Klamath Straits Drain. Mean EC_w levels in input waters at the J canal diversion were approximately 250 :S cm^{-1}, while water sampled at the D pump increased to 600 :S cm^{-1} on average over the sample period. By the time water reentered the Klamath River, salt concentrations increased to approximately 700 :S cm^{-1}. The EC_w values observed in subsurface tile drains were higher on average than in input waters and surface waters elsewhere in the region, especially in the Lease Lands area of the Tulelake Irrigation District (TID). EC_w values averaged approximately 2,500 :S cm^{-1}. Recycling irrigation water through soils in the TID increases the salinity of the water, especially by the time it reaches and is reused in the Lease Lands area of the Tulelake National Wildlife Refuge (TLNWR). Soils in this part of the Klamath Project area were initially naturally high in salt (Wilson et al, 1961).

Water temperatures in agricultural subsurface tile drains were significantly lower than surface water temperatures during the growing season when tile drains were active. pH values in tile drains were lower than surface water values. The temperature and pH of tile drains does not influence surface water values.

For total phosphorus (TP), input waters at the J canal irrigation diversion for the TID averaged approximately 0.27 mg L^{-1} (Fig. 3). Water leaving the Tulelake Sumps at the D pump increases to 0.33 mg L^{-1}. Water leaving the Lower Klamath National Wildlife Refuge (LKNWR) sampled at the start of the Klamath Straits Drain, averaged 0.33 mg L^{-1}, similar to those at the D pump. TP increased further to 0.40 mg L^{-1} at the end of the Klamath Straits Drain. The overall increase in P concentration in surface waters was much less than for salt, suggesting that processes other than simple enrichment are occurring, particularly those associated with the exchange of sedimentary P and aquatic plant species. TN increases from 2.3 mg L^{-1} to 4.0 mg L^{-1} over the same pathway. Atom ratios (TN:TP) of surface water samples remain constant at approximately 10:1 throughout the system, suggesting that the amount of sediment and other small particulate matter in surface waters affects the values observed. The amount of sediment is influenced in part by the agitation of surface water as it passes through pumps, over weirs, or moves rapidly through irrigation and drainage canals.

Direct comparisons over the growing season between water collected from shallow (1.1 m), subsurface tile drainage lines and water in the field end-ditches into which they empty could be made at two locations. Other tile drain sample locations had drainage for only part of the season. In both cases, larger amounts of TP were found in the samples from the ditches than in the tile drain water, and a larger proportion of the P measured was observed in the particulate P fraction in the ditches- approximately 35 % compared to 20 % in tiles. This was not true for salts, which were higher in the tile drain samples than in the ditches. TN concentrations, however, were greater in the tile drains than in the ditches into which they emptied. TN in tile drains occurred primarily as NO_3-N and soluble organic N. Like TP, approximately

30 % of TN was particulate N in end-ditches compared to less than 10% in tile samples. The average seasonal TP value in tile drains beneath farm fields is 0.34 mg L^{-1}. The amounts of N and P in the ditches occurred in the approximate N:P ratios found in most surface water samples in the basin (10:1), while in the tile drain samples they were higher: approximately 50 :1 and 250:1 in the two locations discussed.

While average total P values in subsurface tile drains were not different from those found at the outlet from the TLNWR and TID (the D pumping station) and the LKNWR outlet, the range in values was large (0.1 to 0.8 mg L^{-1}). Similarly, high NO_3 -N values were observed at times in tile drains (up to 40 mg L^{-1}). In shallow subsurface tiles, a large amount of N was observed in the soluble organic N (SON) fraction, defined as the difference between soluble N in undigested and digested samples (Kaffka and Danosky, 2002). This SON was not largely ammonia, but rather soluble organic N or colloidal N compounds derived from the region's organic matter rich soils (Snyder and Morace, 1997). Very high values in tile drains lead to the inference that some fertilizer N and P, combined with nutrients from decaying organic matter, is lost in drainage water. There are few tile drained fields, however, in the TID. Most fields are drained via end "interceptor"ditches which are emptied via pumps into larger drainage canals linking fields to the TLNWR. The subsurface transfer of nutrients from fields to drainage ditches via water movement from fields to ditches has not been studied. Tile drainage samples provide an indication of soil water quality in the root zone but may not reflect actual losses to surface waters. This issue requires further analysis.

The differences in water quality between tiles and drainage ditches suggest as well that the ditches and the overall water management infrastructure of the TID and other irrigation districts in the region play a role in regulating nutrient transfers and can contribute nutrients (especially TP) to the system from internal hydrologic cycles present in the ditches and canals, from agitation of sediments, from the death and decay of aquatic plants, from N fixation by blue green algae, and from agitation of sediments due to pumping and transfer of water. These ditches may also serve to buffer nutrient transfers, and result in losses of nutrients, especially TN. The cycling of nutrients in surface drainage structures built in the organic soils of the UKB region has not been studied.

Un-ionized ammonia can be a critical water quality component. Ammonia N was at or below the limit of detection in subsurface agricultural tile lines and one to two orders of magnitude below the values observed in surface waters. Un-ionized ammonia increases with temperature. Values above 0.25 mg L^{-1} were observed in late summer at several surface water locations (Kaffka and Danosky, 2002).

Some leaching of soluble salts and nutrients is unavoidable when crops are irrigated. P fertilizer is applied at rates higher than crop removal, while fertilizer N is applied at rates less than crop removal (Table 2). Reduced fertilizer use can help bring P inputs and outputs into balance and may reduce further any avoidable losses of P. This objective should be the subject of an agronomic research program.

Discussion and Conclusions

Surface waters entering the TID, the TLNWR, and the LKNWR are already enriched with N and P. It seems unlikely that reducing N and P losses from farming in the TID, if possible, would influence surface water quality sufficiently to make them significantly less eutrophic. For P, the hypothesized threshold concentration limiting algae growth in fresh waters is 5 to 25 times smaller than the values observed in waters entering the TID for irrigation use. Wetland sediments, large amounts of organic matter in soils, and water introduced for irrigation contain essentially unlimited amounts of nutrients for aquatic plant growth. It is not apparent how this circumstance could be changed in any reasonable time frame, if ever. Nor is it clear what limits aquatic plant growth in surface waters in the UKB. In freshwater systems, P is often the nutrient considered most limiting (Correll, 1998; Grobbelar and House, 1995; Hecky and Killam, 1988). Low TN:TP ratios and the presence of abundant blue-green algae to supply atmospheric N suggest that if N were transiently or spatially limiting within the surface water ecosystems, it will be derived readily from atmospheric sources (Kaffka et al., 2002, 1995). Yet there may be complex biogeochemical relations between N and P in nutrient rich waters that confound simple judgments about limitations to aquatic plant productivity in nutrient rich waters (Foy et al., 2004). At different times and places, N lost from farm fields may stimulate additional aquatic productivity. Overall, however, it seems reasonable to infer that the addition of nutrients from agriculture in the TID largely does not significantly influence the quality of already eutrophic surface waters entering the TID.

More efficient fertilizer use can help bring P inputs and outputs into balance in local farming systems. N appears to be managed with deficit fertilization in the region due to high organic matter soils (Kaffka et all, 1995; Snyder and Morace, 1997). Since surface waters entering the region are already enriched with N and P, it appears unlikely that further reducing N and P losses from farming, if possible, would make surface waters significantly less eutrophic. Wetland sediments, local soils high in organic matter, and nutrients contained in water introduced for irrigation create effectively non-limiting amounts of nutrients for aquatic plant growth. Calculations suggest that wetland management and farming practices in the southern portion of the UKB result in the net removal of nutrients from the waters diverted for irrigation on a yearly basis, compared to allowing the same amount of water to simply flow down the river unused (Fig. 4). Large errors of estimation for the amounts of water transferred and large year to year climate variation occur. Together with smaller errors associated with sampling and sample estimation, these uncertainties suggest that nutrient regulation using a short term monitoring approach based on quantitative limits for nutrients like N and P (Parry, 1998) may not be an effective or efficient policy for reducing nutrients in return flows to the Klamath River. Seasonal recycling of some drainage water for irrigation would reduce the amount of nutrients returned to the river on a yearly basis more effectively. Some recycling of drainage water for irrigation already occurs within the TID and other drainage districts in the region.

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Table 1. Water balance equations and symbols.

Description	Equation
(1) Watershed 1 (W1)	$I_{LR} + I_J + I_{KID} + P_{W1} + C_{W1} = ET_{c\text{-}TID} + ET_S + ET_{d\text{-}TID} + O_D$
(4) Tulelake Sumps	$I_{LR} + I_S + P_S + C_S = ET_S + O_S + O_D$
TID crop land	$I_J + I_{KID} + O_S + P_{TID} = ET_{c\text{-}TID} + ET_{d\text{-}TID} + I_S + C_{TID}$
Water Use Efficiency in the TID	$WUE = (ET_{c\text{-}TID} / (I_J + I_{KID} + O_S + P_{TID}))*100$
(6) Watershed 2 (W2)	$O_D + I_{ADY} + I_N + P_{W2} + C_{W2} = ET_{W2} + O_{KSD}$
(7) W1 + W2	$I_{LR} + I_J + I_{KID} + I_{ADY} + I_N + P_{W1} + P_{W2} + C_{W1} + C_{W2} =$ $ET_{c\text{-}TID} + ET_S + ET_{d\text{-}TID} + ET_{W2} + O_{KSD}$

Inflow terms: I_{LR} : Lost River flow, I_J : J canal diversion, I_{KID} : Drainage from Klamath Irrigation District, I_S : inputs to the Sumps from TID, I_{ADY} , Inputs to W2 from the ADY canal, I_N : inputs to KDD from the North Canal. Outflow terms: O_S : Outflows from the sumps to TID, O_D : Outflows for the D pump to LKNWR, O_{KSD} : outflow from the Klamath Straits Drain. Precipitation terms: P_{W1} : precipitation in W1, P_S : precipitation for the Tulelake Sumps, P_{TID} : precipitation for TID, P_{W2} : Precipitation occurring in W2. Evapotranspiration terms: $ET_{c\text{-}TID}$: evapotranspiration for TID, ET_S : ET for Tulelake Sumps, $ET_{d\text{-}TID}$: ET from drains in TID, ET_{W2} : ET for W2. Closure terms: C_{W1} : closure term for W1, C_{TID} , Closure term for TID, C_{W2}.: Closure term for W2. (From Kaffka and Danosky, 2002).

Table 2. Crop uptake and fertilizer applications in a typical year (1994 to 2000) in the TID. (Mg or kg ha^{-1}).

Land area (ha)	Fert. N applied	Crop N removal	Diff.	Fert.P applied	Crop P removal	Diff.
TID: 24, 400	2,660 Mg	2710 Mg	- 47.4Mg	910 Mg	750 Mg	160 Mg
(kg ha^{-1})			-2.0			10

Principal crops are wheat, barley, alfalfa hay, potatoes, onions, sugarbeets and grass hay. No N is applied to alfalfa. N Removal by alfalfa is not included. P removal is included. (From Kaffka and Danosky, 2002).

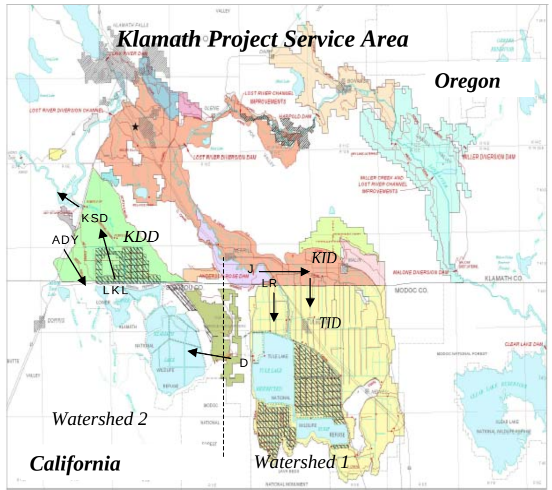

Fig. 1. Important surface water sample locations

Figure 1. The Klamath Project and important surface water sampling locations. J: principle irrigation diversion for the TID, LR: Lost River emptying into the Tulelake Sumps, D: D pump, transferring water from the Tulelake Sumps to LKNWR (transfer from watershed 1 to 2), LKL: outlet rom the LKNWR, KSD: transfer point for water from the Klamath Project to the Klamath River, ADY: Inflows to the LKNWR and KDD from the Klamath River. KID, TID, and KDD are irrigation districts with commercial farming. (Modified from a United States Bureau of Reclamation map. Used with permission)

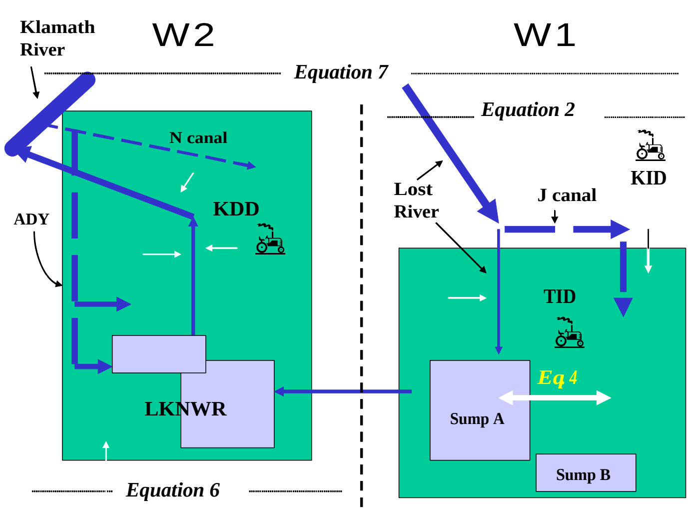

Fig. 2 diagram of water transfers in the study area. Equations refer Table 1. Abbreviations are in the text. Arrows are approximately proportional to the amount of water transferred.

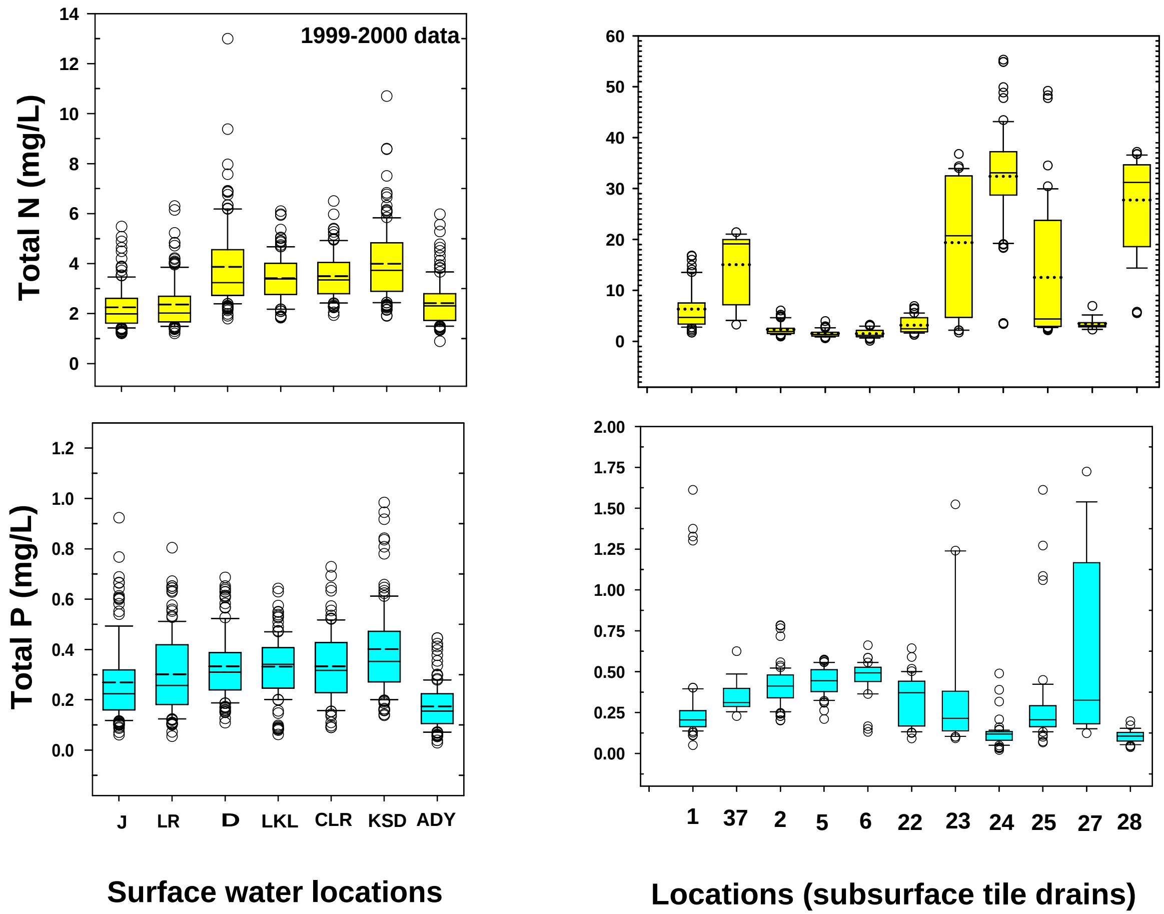

Figure 3a-d.. Box plots for total N in surface water locations, 1999 and 2000 data combined. Locations are arranged sequentially, with water entering the study area on the left and leaving on the right. ADY is an input to the LKNWR and KDD. The top and bottom of the box represent the 75 % and 25 % quartiles, the solid line in the box is the median, the dotted line the mean, and the confidence limits include 95 % of the data. a. Box plots for TN in surface water locations, b. Box plots for TP in surface waters c. Box plots for TN in sub-surface agricultural tile drains, 1999 and 2000 data combined, d. Box plots for TP in sub-surface agricultural tile drains. 1999 and 2000 data combined in all figures.

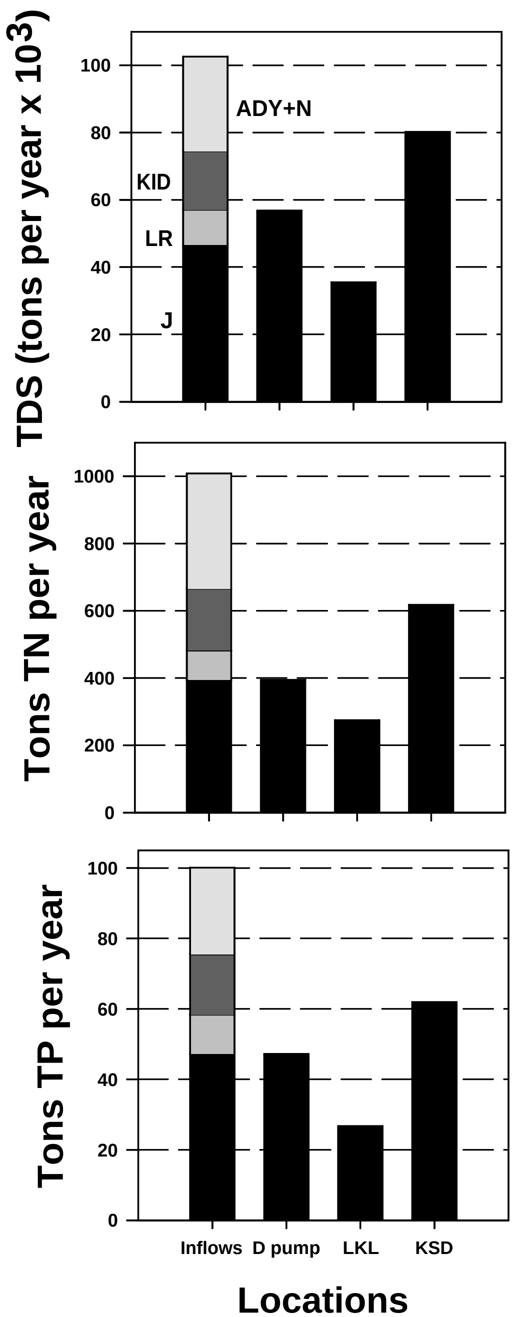

Figure 3 a-c. TDS, TN, and TP transfers in surface waters at the most important surface water sample locations assuming average water transfers and the average concentrations measured at each of these sites during the survey. ADY + N : Inputs to watershed 2 (ADY canal and North canal derived from the Klamath River), KID: drainage from KID into TID, LR: Lost River, J: J canal irrigation diversion. (Units are English tons).