J. Aquat. Plant Manage. 59s: 107–111

Modeling nitrogen runoff from Sacramento and San Joaquin river basins to Bay Delta Estuary: Current status and ecological implications

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ABSTRACT

The Sacramento and San Joaquin river watersheds, located in the upstream regions of the Delta Estuary in California, have intense agricultural activities, which contribute a significant amount of nitrogen loading to the downstream Delta. Because nitrogen is one of the most important abiotic factors to facilitate the rapid growth of invasive aquatic plants, it is important to quantify the total nitrogen loading entering the Delta, as well as the seasonal patterns, concentration levels, and different contributions from the two upstream watersheds. This study aimed to model nitrogen fate and transport from the Sacramento and San Joaquin river basin to the Delta using the U.S. Department of Agriculture (USDA) Soil and Water Assessment Tool (SWAT) model. Daily continuous NO_3-N exports (loading and contributions) were reconstructed via calibrated SWAT simulation. Frequency analysis was employed to compare the distribution pattern of NO_3-N loading from two upstream watersheds. The Sacramento River basin generates five times more nitrogen load than the San Joaquin River basin does, with loadings of 14.81 and 2.72 thousand tons yr^{-1}, respectively. Nitrogen runoff peaks are found in winter months for both watersheds. These results provide insight into the timing of the peak growth of aquatic weeds in the Delta and scientific evidence for the benefits of more-efficient watershed management practices in controlling excess nutrient export.

Key words: delta estuary, nitrogen runoff, Sacramento river basin, San Joaquin river basin, SWAT.

INTRODUCTION

The Sacramento–San Joaquin Delta and its waterways have been infested by invasive aquatic weeds, including both floating aquatic vegetation (FAV) and submerged aquatic vegetation (SAV), making it one of the most invaded estuaries in the world (Cohen and Carlton 1998). Previous studies using remote-sensing technologies to identify and map invasive vegetation (Underwood et al. 2006, Hestir et al. 2008) have shown an increasing trend of total invaded area in the Delta region (Ta et al. 2017). Boyer and Sutula (2015) reported an increased invaded area of a FAV (waterhyacinth) [*Eichhornia crassipes* (Mart.) Solms] from 200 to 800 ha between 2004 and 2014. For one SAV (Brazilian egeria) (*Egeria densa* Planch.), the invaded area increased from 2,000 to 2,900 ha during the same time span as the FAV. The rapid growth of invasive aquatic weeds in the Delta region has had negative impacts, such as impeding water flow, impairing commercial navigation and recreational activities, degrading water quality, and altering ecosystem community interactions (Hestir 2010).

The growth and distribution of invasive aquatic weeds are regulated by many abiotic constraints, such as solar radiation, water temperature, sediment quality, and nutrient availability (Sprenkle et al. 2004). Nutrient availability is deemed one of the most important factors facilitating the rapid growth of invasive aquatic weeds (Kennedy et al. 2009). Because most coastal water bodies are nitrogen limited (Whitall 2008), nitrogen movement from the land to the Delta has an important role in controlling primary production and the resultant trophic state (Paerl 1997, Yuan et al. 2018). Many studies have indicated that invasive aquatic weeds are very responsive to increased nitrogen levels, and their leaf nitrogen levels are closely related to water nitrogen (Wilson et al. 2000).

The Sacramento and San Joaquin river watersheds, located in the upstream regions of the Delta Estuary in California, have intense agricultural activities, which contribute a significant amount of agrochemical loading, including nitrogen, to the Delta. Because nitrogen is one of the most important abiotic factors to facilitate the rapid growth of invasive aquatic plants, especially vascular floating plants (Cedergreen and Madsen 2002, Henry-Silva et al. 2008), it is critical to quantify the total nitrogen loading entering the Delta, as well as the seasonal patterns, concentration levels, and contribution quantities from the two upstream watersheds.

Ecohydrological modeling is based on physical principles as well as empirical relationships and is often used to reflect and simplify the processes affecting water quantity and the quality of a watershed (Wang and Kalin 2018). Because it is difficult to gather measurements for all possible hydrological, biophysical, and physiochemical processes covering the entire study region for the entire time span, a reliable and calibrated model is very helpful to extend simulations spatially and temporally when observations are limited by cost or certain sites accessibility (Wang et al. 2018). Compared with other estimation methods (paired catch-

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ments approaches, time series analysis), mechanical modeling provides a framework to conceptualize and quantify impacts of various factors (e.g., climate, management practices) separately and jointly, which is helpful toward understanding their relative importance on hydrology and water quality. In addition, the water-quality information from a watershed loading model can be further integrated with hydrodynamic, aquatic weed growth, and bioeconomic models, if the scope of research is beyond quantifying agrochemical loading from upstream basins.

The Sacramento and San Joaquin river basins are different in drainage area, crop types, and climate, which would be expected to exhibit discrepancies in hydrology and water-quality runoff patterns. Therefore, we aimed to model nitrogen runoff from the Sacramento and San Joaquin river basins to the Delta using the U.S. Department of Agriculture (USDA) Soil and Water Assessment Tool (SWAT) model (Arnold et al. 1998).

SWAT is one of the most commonly applied watershed models for evaluating agricultural management practices and land disturbances on hydrology and water quality (Krysanova and White 2015). SWAT is the precipitation-driven model, which contains several hydrological modules simulating infiltration, evapotranspiration, soil moisture, surface and subsurface runoff, and channel processes (Wang et al. 2017, Yen et al. 2018). The movement and transformation of soil nitrogen is also simulated by SWAT by accounting for fertilization, volatilization, mineralization, plant uptake, nitrification, and denitrification processes (Niraula et al. 2011, Liu et al. 2019). Soil nitrogen can be introduced to the rivers via surface and subsurface runoff and is eventually transported to downstream water bodies via channel processes (Gassman et al. 2007).The detailed water and nitrogen simulation mechanisms make SWAT a suitable tool for evaluating the impacts of agricultural activities on water quality. In this study, we used SWAT modeling to understand the current nitrogen runoff (represented as NO_3-N by SWAT) exporting status from both upstream watersheds. In addition, we discuss their ecological implications on the growth of invasive aquatic weeds in downstream Delta waterways.

MATERIALS AND METHODS

ArcSWAT 2012 (Winchell et al. 2013) was used to prepare spatial input data for the SWAT model in both watersheds. The Sacramento River basin (23,300 km^2) was partitioned into 34 subbasins and 724 hydrologic response units (HRUs), with the HRU being defined as the basic simulation unit with identical overlapped land use, soil, and slope. Similarly, the San Joaquin River basin (15,000 km^2) was partitioned into 27 subbasins with 647 HRUs. The main land use in the Sacramento River basin is rangeland (~62%), followed by agricultural land (33%), with rice as the dominant crop. The San Joaquin River basin has more-diverse land use types. Forest and rangeland are the most abundant (57%), followed by almonds (13%), vineyards (7%), alfalfa (6%), and other agricultural crops, including oats, corn, cotton, and tomatoes (CA-DWR 2009).

The simulation period was set from 1 January 2003 to 31 December 2016, with 2 yr (2001 and 2002) as the model-initialization period, which allowed the SWAT model to fully adjust to the hydrological cycle for the watersheds. First, default algorithms of SWAT were modified to better-represent complex regional hydrological and water-quality conditions in both watersheds. Then, models were calibrated and validated to ensure simulation performance with the help of observed data (daily streamflow discharge and monthly NO_3-N loadings) at multiple stations (Ficklin et al. 2013, Chen et al. 2017, Wang et al. 2019a).

The Sacramento River watershed contains transbasin flood diversions via bypass or canals between the main stream channel and its tributaries. There are six main flood weirs in the Sacramento River basin to control water depth in the main channel, which alleviates the potential winter flood risk for the major rivers by diverting flow to wetlands or other receiving bodies (Ficklin et al. 2013). Therefore, a flood conveyance routine representing weir management is included in the original code. If the main river discharge is above a certain threshold, then excess water is removed from the river and routed to the diversion destination but not transported through the main stream (Ficklin et al. 2013). This modification is helpful for capturing the peak flow discharge during the winter months and the nitrogen loading transported with that flow as well.

In the San Joaquin River watershed, there are many tile drains installed in the western agricultural region of the watershed (Saleh and Domagalski 2015). The tile drainage system is a commonly used agricultural practice to control a perched water table in a poorly drained region, avoiding excess water stresses at the root zone. Tile drainage changes the original flow pathway, conveying infiltrated water to surface water, making the receiving water bodies vulnerable to nitrate pollution. The SWAT default tile-drain algorithm is empirically based and mainly controlled by three empirical parameters: DDRAIN, TDRAIN, and GDRAIN, which represent "depth to subsurface drain," "time to drain soil to field capacity," and "drain tile lag time." TDRAIN and GDRAIN are usually estimated by modelers, which introduces more simulation uncertainties. The alternate (nondefault) tile-drainage routine, in contrast, employs more physical-based Hooghoudt and Kirkham equations (Moriasi et al. 2012). Hooghoudt and Kirkham equations rely on explicit physical parameters, such as drain spaces, lateral hydraulic conductivity, and drain-tube radius to mimic the subsurface drainage process. Applying the physical-based tile drainage routine substantially improved model performance by changing the shape of the nitrate-runoff hydrograph, altering the original abrupt peak to a smoother curve, which was more consistent with *in situ* measurements (Wang et al. 2019a).

After applying physical-based algorithms in both watersheds, we calibrated and validated the SWAT model at multiple sites and followed the flow-sediment-nutrient sequence to reduce uncertainties associated with shared transport processes. Nutrients are transported by surface and subsurface flow and soil erosion. Mineral nitrogen is usually transported by flow, whereas organic nitrogen is usually associated with soil particles and transported by soil

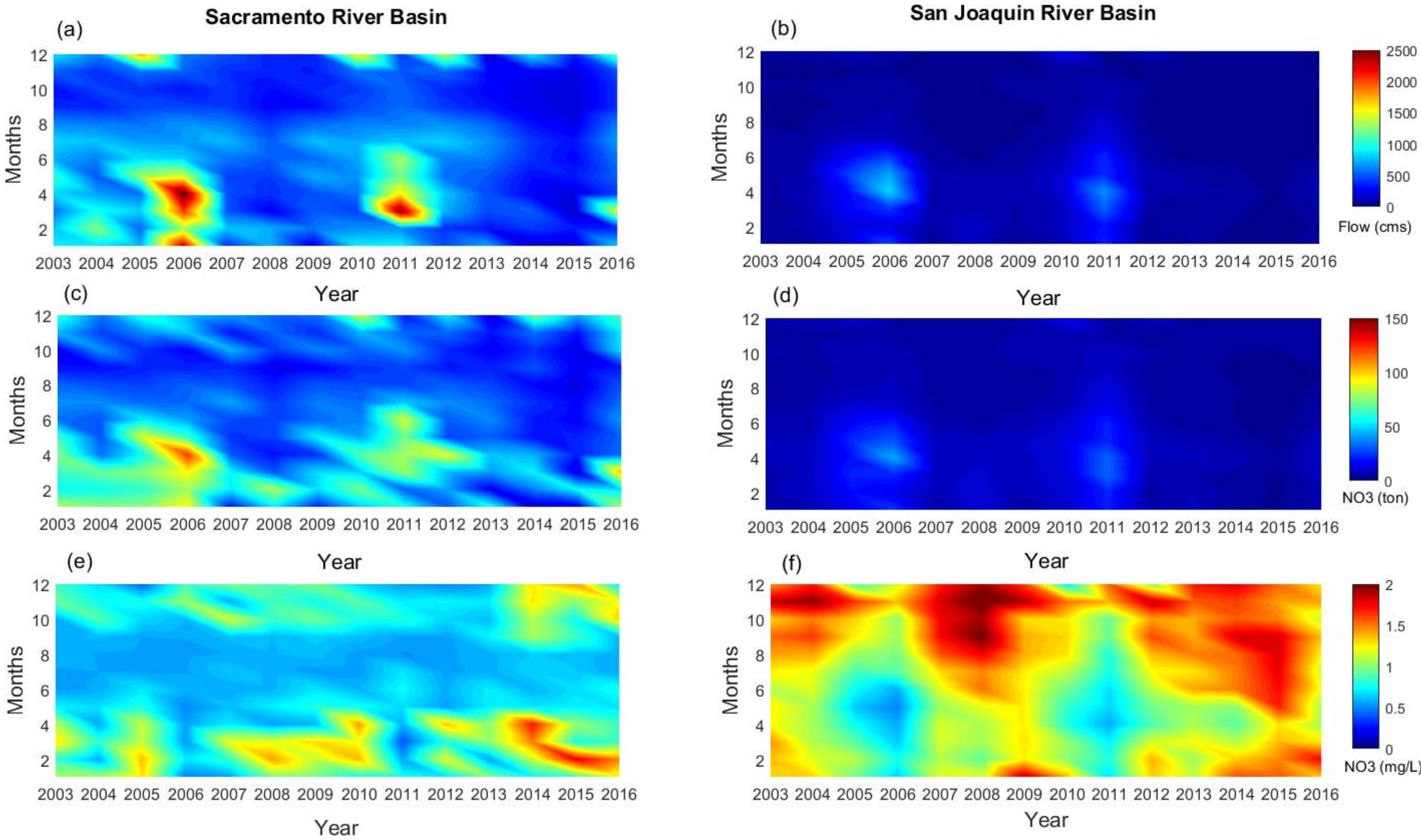

Figure 1. Comparison between Sacramento and San Joaquin river watersheds with respect to (a and b) variations of monthly flow rate (units in $m^3\ s^{-1}$); (c and d) NO_3-N monthly loadings (units in tons); and (e and f) monthly NO_3-N concentrations (units in mg L^{-1}).

erosion (sediment). Soil erosion itself is mainly driven by surface runoff. Therefore, errors in flow estimation will accumulate in further sediment and nutrient simulation. For accurate NO_3-N simulation, calibration is required for the flow first, to guarantee decent model performance, and then, for the sediment. Model performance in flow and nitrogen runoff was reasonable for both watersheds when compared with observed data. Detailed statistics reflecting model performance are available in our previously published modeling studies (Ficklin et al. 2013, Chen et al. 2017, Wang et al. 2019a). Monthly and daily continuous NO_3-N exports (loading and contributions) were then reconstructed via SWAT for the entire simulation period. Frequency analysis was employed to compare the distribution pattern of NO_3-N loading from the two upstream watersheds. The frequency analysis used to compare NO_3-N concentrations was the concentration duration curves (CDCs), which are a commonly used probabilistic approach for studying the statistical distribution of exposure data. Daily concentrations are first ranked in descending order. Then, the probability of exceedance for a certain concentration is computed based on the rank and total amount of data (Wang et al. 2018). The CDC was used to examine the probability of exceedance associated with NO_3-N concentration, indicating how often a specific level of exposure (concentration) is likely to happen (Dick et al. 1983).

RESULTS AND DISCUSSION

An initial analysis was conducted to compare the monthly flow and nitrogen runoff (represented as NO_3-N) pattern in both watersheds (Figure 1). The seasonal pattern of flow generally reflects the climate information in the study region, especially precipitation. California's Central Valley has a Mediterranean-like climate, which is characterized by hot, dry summers and cool, wet winters. Precipitation is usually concentrated in winter and spring months, which cause large amounts of runoff or even floods during extremely wet years (Ficklin et al. 2013, Wang et al. 2019b). For both watersheds, monthly peak flow for each year is usually detected between December and April. Two extremely wet years, 2006 and 2011, had the highest and second highest monthly flows in the entire simulation period (2,595 and 2,472 $m^3\ s^{-1}$, respectively, for the Sacramento River basin; 832 and 651 $m^3\ s^{-1}$, respectively, for San Joaquin River basin). The monthly distribution of NO_3-N loading from both watersheds exhibited quite similar seasonal patterns, with annual peaks found in winter and spring months. Because NO_3-N is highly soluble and easily transported with water, it is not surprising to find similar monthly patterns of flow and NO_3-N loading. Compared with the San Joaquin River basin, the Sacramento River basin generates greater flows and NO_3-N loading. For the entire simulation period, the Sacramento River basin contributed 629 $m^3\ s^{-1}$ in flow and 14.81 tons yr^{-1}

NO_3-N to the Delta, which is five times higher than San Joaquin River basin (95 m^3 s^{-1} in flow and 2.72 tons yr^{-1} for NO_3-N)

The seasonal patterns of NO_3-N concentration are different for the Sacramento and San Joaquin basins. For the San Joaquin River watershed, higher NO_3-N concentration months were usually accompanied by lower stream flows and lower NO_3-N loading. For the wet years 2006 and 2011, the lowest NO_3-N concentrations were found in April. For other years, higher NO_3-N concentrations were usually found after May. For the Sacramento River basin, modeling results indicated that higher NO_3-N concentration was often detected in winter and spring but not in summer months.

Because SWAT also provided daily simulation results, we generated CDCs to better understand the distribution of NO_3-N concentrations for the entire simulation period for the two watersheds. NO_3-N concentration from the San Joaquin River watershed was higher than that of the Sacramento River watershed for most of the simulation period (Figure 2). As shown in Figure 2, for a given threshold concentration of NO_3-N (1.5 mg L^{-1}), the probability of exceedance for San Joaquin River watershed was 25.2%. This indicates that the probability of NO_3-N concentration above the threshold (1.5 mg L^{-1}) was 25.2% for the entire 14-yr period. For the same exposure threshold (1.5 mg L^{-1}), the Sacramento River basin had a much lower probability of exceedance, at 8.2%.

The seasonal pattern of NO_3-N loading and concentration and the CDCs from the two upstream watersheds could have strong ecological implications on the growth of FAVs and SAVs (e.g., waterhyacinth) in downstream Delta waterways because nitrogen sources are important in facilitating their growth, especially for FAVs, for which the uptake of nutrients is primarily from the water column (Sooknah and Wilkie 2004, Moran 2006). Many laboratory experiments have indicated that waterhyacinth is very responsive to nitrogen levels, with increasing nitrogen levels resulting in rapid growth and greater biomass or density (You et al. 2014, Dahm et al. 2016). For example, Wilson et al. (2005) found that greater density and rapid growth rate (10 kg m^{-2} in 50 d) were expected for waterhyacinth under warm conditions (30 C), when dissolved nitrogen was more than 1 mg L^{-1}.

Comparing the NO_3-N CDCs (Figure 2), the probability of exceedance (>1 mg L^{-1}) for the Sacramento River watershed is much lower than that of the San Joaquin River watershed (20 vs. 80%). Therefore, although the Sacramento River watershed generated almost five times more NO_3-N loading than the San Joaquin River watershed did, the higher NO_3-N concentration from the San Joaquin River watershed had more impact on the rapid growth of FAVs in the Delta waterways, especially during warmer water temperatures. Furthermore, compared with the Sacramento River watershed, the months of higher NO_3-N concentration (after May) for the San Joaquin River watershed overlapped with the growing season of water hyacinth (April to late fall) (Hestir et al. 2008), which likely provided the needed nutrients in the appropriate time window to facilitate the rapid growth of water hyacinth and other

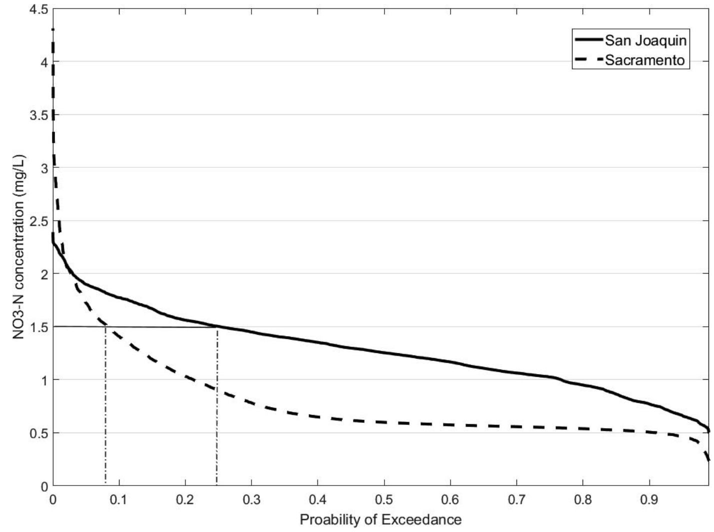

Figure 2. Concentration duration curve (CDC) of daily NO_3-N exposure at two outlets in the Sacramento and San Joaquin river basins.

floating aquatic weeds, such as waterprimrose (*Ludwigia* L. spp.).

Our work modeled the probable nitrogen runoff status from the upstream Sacramento and San Joaquin river watersheds to the Delta Estuary. We analyzed the seasonal loading patterns, concentration levels, and relative contributions of NO_3-N from both watersheds. Although the San Joaquin River watershed provided less NO_3-N loading to the Delta, the NO_3-N concentrations at the San Joaquin River outlet were substantially higher than of the Sacramento River for almost the entire concentration range. The output of NO_3-N from the San Joaquin River watershed to the Delta Estuary would have a greater impact on the rapid growth of invasive aquatic weeds. Future studies should integrate land-surface loading model results with aquatic weed-growth models to evaluate the impact of agricultural nitrogen loading on the phenology of aquatic vegetation, leading to proactive management strategies for aquatic weed control.

ACKNOWLEDGEMENT

Funding was provided by the USDA ARS Delta Region Areawide Aquatic Weed Project (DRAAWP) (58-2030-6-042).

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