CALFED
BAY-DELTA
PROGRAM

CALFED SCIENCE FELLOWS PROGRAM

Sea Grant
California

In cooperation with the

California Sea Grant College Program

FELLOWSHIP APPLICATION COVER PAGE

APPLICANT TYPE ☒ Postdoctoral Researcher ☐ Ph.D. Graduate Student

PROJECT NUMBER

PROJECT TITLE Modeling Nutrient and Organic Carbon Loads and Sources in Central Valley Watersheds: Taking Existing Monitoring Data to the Next Stage

FINANCIAL SUMMARY

First Year CALFED Funds Requested: $89,750
Total CALFED Funds Requested: $269,250
Duration: 3 years
Proposed Start/Completion Dates: September 1, 2005/August 31, 2008

APPROVAL SIGNATURES

FELLOW:

Name: John Harrison
Position/Tit Postdoctoral Associate
Departmen Institute of Marine and Coastal Sciences
Institution: Rutgers University
Address: 71 Dudley Rd.
City, State New Brunswick, NJ 08901
Telephone: (732)932-6555 x234
Fax: (732)932-1792
E-mail: harrison@imcs.rutgers.edu

MENTOR/PRINCIPAL INVESTIGATOR:

Randy Dahlgren

Name: Randy Dahlgren
Position/Title: Professor of Soil Science
Department: Dept. of Land, Air, and Water Resources
Institution: University of California-Davis
Address: Dept. of Land, Air, and Water Resources
City, State & UC, Davis, CA 95616-8627
Telephone: (530)752-2814
Fax:
E-mail: radahlgren@ucdavis.edu

AUTHORIZED INSTITUTIONAL REPRESENTATIVE:

Kathleen P. Babcock

Name: Kathleen P. Babcock
Position/Title: Contracts and Grants Officer
Department:
Institution: Office of Research
Address: Sponsored Programs, 118 Everson Hall
City, State & Zip: University of California
Telephone: One Shields Avenue
Fax: Davis, California 95616-8671
E-mail:

Will animal subjects be used? ☐ Yes ☒ No
APPROVAL DATE: PROTOCOL #: PENDING:

Does this application involve any recombinant DNA technology or resea ☐ Yes ☒ No

Modeling Nutrient and Organic Carbon Loads and Sources in Central Valley Watersheds: Taking Existing Monitoring Data to the Next Stage

1. Introduction/Question/Objectives

1.1. Introduction

Over the past 50 years, world population, food production, and energy consumption have increased approximately 2.5, 3, and 5-fold, respectively (FAO 2001; United Nations 2002; US Census Bureau 2005). These changes have resulted in a massive mobilization of bioactive nutrients such as nitrogen and phosphorus (N and P) on land. Through activities such as fertilizer production, fossil fuel consumption, and the planting of leguminous crops, humans have more than doubled the rate at which biologically available N enters the terrestrial biosphere (Vitousek and Matson 1993). The global phosphorus (P) cycle has also been greatly altered by human activity. P mining and subsequent use as fertilizer has more than doubled P inputs to the environment over natural, background P from weathering (Mackenzie et al. 1998; Bennett et al., 2001; Fixen and West 2002).

Significant fractions of these mobilized nutrients are washed into flowing surface waters where they have been associated with a number of negative environmental impacts including, drinking water degradation, loss of biodiversity, low dissolved oxygen (DO) conditions leading to fish kills and other stresses, and an increase in frequency and severity of harmful and toxic algae blooms, among other effects (Howarth et al. 1996; Galloway and Cowling 2002; Anderson et al. 2002; Townsend et al., 2004; Carpenter et al., 1998). N and P inputs to surface waters are projected to continue to increase over the next several decades, both globally and regionally (Kroeze and Seitzinger 1998; Harrison et al. 2005).

Over the past century California has paralleled global trends, experiencing large increases in population, food production, energy consumption, and hence nutrient mobilization (USDA-NASS 2004; http://www.nass.usda.gov/ca/indexhist.htm; State of California Department of Finance 2005a and 2005b; EIA 2005). In the San Joaquin River (SJR), this increase in nutrient mobilization (along with increases in the prevalence of subsurface drainage) has been associated with a pronounced (~10-fold) increase in nitrate (NO_3^-) concentrations (Figure 1; Kratzer and Shelton 1998; Dahlgren Pers. Comm.). Over this same time period, P inputs to Central Valley (CV) watersheds have also increased greatly, and a recent study in the Sacramento Basin reported that total phosphorus (TP) concentrations were equal to or greater than national guidelines in almost all tributary streams draining urban and agricultural lands (Domagalski et al. 2000).

High nutrient concentrations in the lower SJR have been associated with an increase in algal standing crop, which in turn has been blamed for low dissolved oxygen (DO) episodes in the lower SJR (R. Dahlgren Unpub. Data). Low DO conditions may act as a barrier to upstream migration of spawning Chinook salmon, and other anadromous fish species (California Regional Water Quality Control Board, 2004). As a result, a major water quality objective of the State's basin plan for the region is to maintain DO levels above 6 mg/L in the SJR between Stockton and Turner Cut during the fall fish runs (September-November) and above 5 mg/L at all other times (California Regional Water Quality Control Board, 2004). Recent investigations suggest that reducing nutrient loads from agriculture and municipalities is one strategy for achieving the DO TMDL in the SJR (Lee and Jones-Lee, 2003).

In addition to the issues associated with increased mobilization of N and P, dissolved organic carbon (DOC) is also of great concern. This is due in part to DOC's role in the formation of potentially carcinogenic and mutagenic compounds (trihalomethanes and haloacetic acids) during drinking water disinfection (U.S. EPA 2000). Concern over the role of DOC in the formation of these compounds has led CALFED to propose an average target concentration of total organic carbon (TOC) of 3 mg/L at drinking water intakes (CalFed 2000). The Sacramento and San Joaquin Rivers, hereafter collectively referred to as the SSJ system, constitute an important source of carbon (270 Mg DOC day^{-1}) to the Bay-Delta region (Jassby et al., 2000; Saleh et al., 2003; Sobczack et al., 2005), the source of drinking water for over 20 million Californians. On average, 75% of the DOC exported to the State Water Project is from upstream watersheds (Sonnerup and Bergamaschi 20002). With nearly 85% of the water exported in the State Water Project coming from the Sacramento River, understanding DOC sources supplying the CV rivers and the factors affecting DOC cycling in the CV is important for planning the use of surface water resources in California's future.

In addition to the health concerns associated with DOC, DOC is also important from ecosystem and biogeochemical perspectives. In the Bay-Delta region, dissolved organic matter (DOM), of which DOC is a constituent, makes up the majority of organic matter inputs (as opposed to particulate organic matter (POM)), and river inputs constitute the largest input of DOM to SF Bay (Sobczak et al. 2005).

Furthermore, DOC has been shown by mass balance to support over 75% of the San Francisco Estuary's net energy demands (Sobczak et al. 2005). In addition to feeding the Bay Delta ecosystem, DOC can control the availability of dissolved nutrients and metals, and affect the optical properties of aquatic systems (Findlay and Sinsibaugh 2001).

There is currently an enormous amount of water quality and discharge information available for the SSJ system (e.g. Kratzer and Shelton 1998; Domagalski and Dileanis 2000). However, these data have not yet been synthesized into models that can predict nutrient export from watersheds as a function of land use and nutrient inputs. Nor have they been used to quantify the relative importance of different land-based nutrient and DOC sources within CV watersheds. With the work outlined in this proposal, we will develop the first spatially explicit, models for predicting DOC, DIN and DIP export, concentrations, and sources for major CV river systems. We will focus on DOC, DIN, and DIP initially because these compounds are the most abundant forms of C, N, and P, respectively (and an even greater proportion of the bioavailable C, N, and P) in much of the SSJ system (Kratzer and Shelton 1998; Alexander et al. 1996).

1.2. Objective and Research Questions:

The objective of the proposed research is to use existing data, in combination with models, to gain a quantitative understanding of current and likely future fluxes, sources and controls of DOC, DIN, and DIP transported through the SSJ system. Specifically, we will address the following research questions:

1. **What are the relative contributions of various land-based sources of DIN, DIP, and DOC to the Sacramento and San Joaquin River systems?**
2. **How can we improve our ability to predict river DOC, DIN, and DIP concentrations, export, and sources?**
3. **How are river DOC, DIN, and DIP concentrations, loads, and sources likely to change as a function of climate, population growth, water demand, and land-use change in the next few decades?**

2. Approach

In the following section we describe the study system, the datasets and models we will use to address our research questions, and how we will use these datasets and models to address each of the questions we have posed. We also outline schedule by which we will accomplish the research we have described.

2.1. The Study System

The Sacramento and San Joaquin rivers basins are the two largest river systems draining California's Central Valley region, and encompass approximately 70,000 and 28,000 km^2, respectively (Figure 2a). The Sacramento River is the largest river in California, and together with the SJR, contributes ~97% of the river freshwater, as well as the majority of organic matter, and river nutrient input to the Bay-Delta system (Jassby and Cloern 2000; Sobczak et al., 2005).

The land use, land cover, climate, and topography are all extremely spatially diverse in both basins (Figure 2b; Gronburg et al., 1998; Saleh et al., 2003). In both basins, there are sub-basins that range from almost entirely un-altered systems, to systems that have been completely altered by human activity and water engineering projects. Land uses in both basins include forestry, rangeland, irrigated agriculture, wildlife refuges, dairies, municipalities, and industry (Figure 2b). Major water uses in the SSJ system include irrigation, municipal and domestic water supply, power, fresh water habitat for wildlife and fish (migration and spawning), recreation and industrial processing (California Regional Water Quality Control Board, 2004). The SJR and Sacramento basins support 4120 and 8090 km^2 of irrigated crops, respectively, including corn, alfalfa, pasture, orchards, vineyards and various other commodities (Kratzer et al., 2004). The hydrology of both systems has been extensively altered by irrigation impoundments and diversions (Ingram 1996; Kratzer and Sheldon 1998). During the irrigation season, up to 50% of the flow in the San Joaquin can originate from irrigation return flows.

We intend to exploit the high degree of landscape, climatic, and land-use diversity within the SSJ system, along with the large amount of existing water quality and discharge data to determine sources and controls on DIN, DIP, and DOC fluxes through these river systems.

2.2. River Nutrient and Discharge Data

Over the past 30 years, at least 6 agencies and organizations (USGS, US-EPA, the Bureau of Reclamation, NWIS, UC-Davis, and the California Department of Water Resources) have carried out extensive and intensive long-term water quality monitoring programs in both the Sacramento and SJR basins. These efforts have resulted in a tremendous amount of publicly available, high-quality nutrient, DOC, and water discharge data for the SSJ system. In the San Joaquin Basin alone between the years of

1972 and 1990, over 13,000 nutrient samples have been analyzed and reported (Kratzer and Shenton 1998). Counting only sites with over 15 samples, there are approximately 10,000 quality assured and quality controlled nitrate measurements available from 41 sites in the SSJ system (C. Kratzer Pers. Comm.). Similar data coverage exists for DIN, DIP, and DOC, and at least 20 (probably more) of these sites are gauged (Saleh et al., 2003), facilitating accurate river nutrient flux estimates at several points throughout the SSJ system. These data are almost entirely available via the web through EPA-STORET (http://www.epa.gov/storet/dw_home.html), USGS-NWIS (http://waterdata.usgs.gov/nwis/qw), and the CDEC (http://cdec.water.ca.gov/) websites.

In addition to these data sources, we will also make extensive use of a dataset collected by Dr. Dahlgren, which contains biweekly data on 28 biogeochemical parameters at 25 sites in the Central Valley since October 1999 and an additional 9 sites in the upper Sacramento River watershed as of October 2002. These sites were chosen specifically to aid in more precisely determining sources of nutrients in the basin ("CALFED Directed Action Proposal For Monitoring and Investigation of the San Joaquin River and Tributaries Related to Dissolved Oxygen." CALFED Ecosystem Restoration Program, Sacramento, CA (Will Stringfellow et al., proposal)). These samples have all been collected using appropriate methods and subject to rigorous quality assurance and quality control procedures, including chain of custody, spikes, blind samples, field blanks, replicates, reference materials, setting of control limits, criteria for rejection, and data validation methods (Kratzer et al., 2004). These data are also being used extensively by many CALFED and state/federal agency programs (e.g. DO TMDL in the San Joaquin Basin and USGS), as they represent the best-available data set for this period of time on water quality for Central Valley Rivers. In addition to the above sources of data, we will also search existing peer-reviewed and gray literature and query water quality monitoring agencies and individuals for additional data.

2.3 Models

Though much nutrient flux data has been collected in the SSJ system, there has not yet been a successful effort to use these data to develop any nutrient or DOC export models for these systems. In other systems, several studies have modeled the dynamics of river DOC, DIN and DIP transport at local to regional scales with mixed success (e.g. Boyer et al., 1996; Weller et al. 2003; HSPF (Bicknell et al., 1997); QUAL2E (Chapra and Pelletier 2003); SWAT (Neitsch et al., 2002); and WASP (Wool et al., 2004); SPARROW (Alexander et al., 2002)). However, these models have generally been developed and highly tuned for specific systems, and are therefore not easily applied to other system types. It is also difficult to use these models to predict system response to hypothetical future conditions because they have been narrowly calibrated to the conditions that exist within a specific watershed or region. Therefore, when run with new input parameters that fall outside of the range to which the models were originally calibrated, these models may act erratically.

Recently, several global models have been developed to predict river export of bioactive elements (N, P, and C) and their respective forms (inorganic/organic, dissolved/particulate; e.g. Dumont et al., In Press; Harrison et al. In Press a and b). Because these models were created as part of a work group called **G**lobal **N**utrient **E**xport from **W**ater**s**heds (Global NEWS), they are referred to as NEWS models, and models for predicting DIN, DIP and DOC export are called NEWS-DIN, NEWS-DIP, and NEWS-DOC, respectively. These models were calibrated and validated using globally distributed rivers, so they are robust over a much broader suite of conditions than models that have been calibrated to a particular system, and they may therefore be more appropriate for making predictions about how a system will respond to novel conditions.

We propose to scale down NEWS-DIN, NEWS-DIP, and NEWS-DOC models, using higher spatial and temporal resolution datasets than were available for the global application of these models, and apply them to both the entire SJR and Sacramento systems and to sub-basins of those systems. Such an effort will constitute the first time a global nutrient export model has been applied at a sub-basin scale, and will therefore be a significant step forward for the global nutrient export modeling community. This effort will also improve understanding of factors controlling nutrient export from CV basins as it will constitute the first effort to ascribe DIN, DIP, and DOC to land-based sources within CV basins. It will show where knowledge is lacking regarding our understanding of nutrient sources in CV watersheds, and therefore where future research efforts should be directed. It will also lay the groundwork for the scenario analyses we describe below in section 2.7., and provide a basis for comparison with other nutrient export models that are eventually developed for CV basins.

2.3.1 NEWS-DOC

To model DOC fluxes, concentrations, and sources, we will initially rely on a regional application of the NEWS-DOC model (Figure 3a; Harrison et al., In Press a; For more detailed information on NEWS-DOC than is included here, please find a preprint at the following URL: http://marine.rutgers.edu/globalnews/data/NEWS_Papers_Submitted_2005/Harrison_gbc_DOM.pdf ; username: globalnews, password: gl0balnews). NEWS-DOC predicts DOC yield (*DOC*; kg C km^{-2} yr^{-1}) as a function of runoff, wetland area, and consumptive water use. The model's central equation is as follows: $DOC = Q_{act} / Q_{nat} \cdot (R^a \cdot (C_{wet} \cdot W + C_{dry} \cdot (1 - W)))$, where Q_{act}/Q_{nat} is the ratio of present-day discharge (Q_{act}) to pre-dam discharge (Q_{nat}), R is annual runoff (m), W is the fraction of a watershed that is wetland by area, a is a unit-less coefficient describing the shape of the relationship between runoff and DOC yield, and C_{wet} and C_{dry} represent the export coefficients (kg C km^{-2} yr^{-1}) for wetlands and non-wetlands, respectively, calibrated using global datasets. Total DOC export per basin (kg C basin^{-1} y^{-1}) to coastal systems is simply the product of DOC yield and basin area, and DOC concentration can be calculated by dividing DOC load by water discharge. (N.B. The same transformations can be performed for the NEWS-DIN and NEWS-DIP predicted DIN and DIP yields described below.) For the initial applications of NEWS-DOC, we will use area-weighted basin average values as model inputs. However, this may be modified in future, regionally focused, versions of NEWS-DOC (Section 2.5).

NEWS-DOC's formulation is consistent with published regional analyses showing strong relationships between runoff and DOC export (Ludwig et al., 1996) and between basin percent wetland area and DOC export (Dillon and Molot 1997; Gorham et al. 1998; Mulholland 2003; Raymond and Hopkinson 2003; Stepanauskas et al. 2003). In addition to estimating total DOC load and concentration, NEWS-DOC can also be used to calculate the magnitudes of wetland and non-wetland DOC.

When applied at the global level, NEWS-DOC explained 88% of the variability in DOC yield (kg C km^{-2} yr^{-1}) and 93% of the variability in DOC load (Ton C basin^{-1} yr^{-1}) in validation basins (basins not used to calibrate the model), and was free from bias (Harrison et al., In Press a). When preliminarily applied to the SSJ system using low resolution, global datasets, NEWS-DOC did fairly well, with predictions of DOC load falling within the reported values of annual average DOC export from each basin (Saleh et al., 2004; Alexander et al., 1996).

2.3.2 NEWS-DIN

To model fluxes and sources of DIN, we will refine and apply NEWS-DIN (Figure 3b; Dumont et al., In Press) to CV river systems. NEWS-DIN builds on past work by Seitzinger and Kroeze (1998), Kroeze and Seitzinger (1998), Caraco and Cole (1999), and Seitzinger et al. (2002a and 2002b). The NEWS-DIN model includes several N inputs missing from the original N-model (described in Seitzinger and Kroeze, 1998) such as manure N and biological N_2 fixation. NEWS-DIN also includes N retention and loss terms that were absent from the original N-model such as N retention in river networks, N retention in dammed reservoirs, N loss via consumptive water use, and N removed from a watershed via harvesting and grazing (Figure 3). NEWS-DIN also includes a more sophisticated treatment of sewage point sources than was included in the original N-model, incorporating estimates of sewage treatment, sewage connectivity, and variable N-excretion rates.

NEWS-DIN's core equation is: $DINy_{mod} = FE_{riv} \cdot [PS + (FE_{ws} \cdot DS)]$, where $DINy_{mod}$ is modeled DIN yield per river basin (kg N km^{-2} y^{-1}), PS is DIN from sewage point sources (kg N km^{-2} y^{-1}) and DS is N from diffuse sources that is mobilized from the watershed soils and sediments (kg N km^{-2} y^{-1}). FE_{riv} is a river export fraction representing the fraction (0-1) of total point and diffuse DIN inputs to the river that is exported as DIN. FE_{ws} is a watershed export fraction representing the fraction (0-1) of N from diffuse sources in the watershed that leaches to rivers as DIN. Several of the model components (non-point sources, N fixation) and N sinks are modeled, in part, as a function of system hydrology. Because of NEWS-DIN's structure, it is possible to estimate both the total rate of DIN export to coastal regions (Figure 4A) and the relative contribution of DIN to the coastal zone coming from point and non-point sources (Figure 4B). A full description of the model is available on our website: (http://marine.rutgers.edu/globalnews/data/NEWS_Papers_Submitted_2005/NEWS-DIN_mss_17_2_05-1.pdf ; username: globalnews, password: gl0balnews).

NEWS-DIN explains 72-83% of DIN export (kg N basin^{-1} yr^{-1}) in validation basins (basins not used to calibrate NEWS-DIN), depending on the validation dataset used (Dumont et al., In Press). When compared with other DIN export models (Seitzinger and Kroeze, 1998; Smith et al., 2003; Green et al., 2004), NEWS-DIN demonstrated the highest R^2 between measured and modeled DIN export.

2.3.3 NEWS-DIP

We will use our recently developed, global model (NEWS-DIP; Figure 3c) to predict DIP export from Central Valley watersheds (NEWS-DIP; Harrison et al., In Press). This model predicts DIP yield (*P*) as a function of point source and non-point source P inputs, weathered P, reservoir retention, and consumptive use. The model's central equation is:

$$P = (Q_{act} / Q_{nat}) \cdot (1 - D) \cdot (H \cdot E_{cap} + (1/(1+(R/a)^{-b})) \cdot (W_{max} + L_{max} \cdot (P_{fert} + P_{am})))$$

where *P* is the area-weighted mean DIP yield (kg P km^{-2} yr^{-1}) for an entire river basin (as opposed to DIP-load (kg P basin^{-1} yr^{-1}) or DIP concentration (mg P-L^{-1})). *P* is calculated as a function of within-basin P sources and sinks. Source terms include point sources and diffuse sources. Point sources are calculated as a function of population density (*H*) (individuals km^{-2}) and per-capita DIP yield (E_{cap}) (kg P person^{-1} yr^{-1}). Diffuse sources are calculated as a function of runoff (*R*) (m yr^{-1}), fertilizer P inputs (P_{fert}) (kg P km^{-2} yr^{-1}), animal manure P inputs (P_{am}) (kg P km^{-2} yr^{-1}), and four calibrated coefficients defining the shape of the runoff response curve for weathering and non-point DIP sources (*a*, *b*, W_{max}, and L_{max} ; constrained to observation-based ranges). As with NEWS-DIN, sinks include consumptive water use, calculated as the ratio of contemporary river discharge (Q_{act}) to pre-dam river discharge (Q_{nat}), and within-basin DIP retention due to DIP trapping in reservoirs (*D*) (0-1). As with NEWS-DOC and NEWS-DIN, input variables for global application consisted mainly of spatially explicit, 0.5º x 0.5º resolution gridded datasets, which were used to compute area-weighted, basin wide means. This approach was applied at the global level because of a lack of higher resolution data. Application to CV watersheds will allow for a higher resolution analysis.

Like NEWS-DOC, and NEWS-DIN, NEWS-DIP can be used to calculate the percent contribution from various land-based sources, including point sources of P, naturally weathered P, fertilizer P, and Manure P. For more detailed information on the NEWS-DIP model, see Harrison et al. (in Press), available at: (http://marine.rutgers.edu/globalnews/data/NEWS_Papers_Submitted_2005/2004GB002357R.pdf ; username: globalnews, password: gl0balnews). When applied at the global scale, NEWS-DIP explains 74% and 61% of the variability in per-basin DIP export (DIP load) in calibration and validation basins respectively.

2.3.4 Accounting for Human Modification of CV Hydrology

The SJR system has at least 25 major reservoirs, 13 major agricultural diversions, and many more minor reservoirs and diversions (Krazer and Sheldon 1998), and the Sacramento system, though somewhat less altered, is still largely a human-regulated system with respect to water. NEWS models currently account for dam and diversion impacts on quantity of water discharged through rivers by correcting for consumptive water use and, in the case of NEWS-DIN and NEWS-DIP, by accounting for DIN and DIP removal in reservoirs as a function of water residence time. We will therefore need to estimate the magnitude of human influence on discharge in each study basin (potential (pre-dam and diversion) discharge minus actual discharge) and reservoir residence time for major reservoirs in each basin). We have already succeeded in attaining information on diversions accounting for approximately 65% of the agricultural diversions in the SJR Basin (Table 1), and will work with the appropriate agencies to attain the necessary data on reservoir inflows and mean water residence times, and additional agricultural diversions.

2.4. Q1. What are the relative contributions of various land-based sources of DIN, DIP, and DOC to nutrient and DOC loads in Sacramento and San Joaquin River systems?

In a recent report Kratzer et al. (2004) used nutrient concentration and isotope data to suggest likely sources of nutrients to land-use types within the SJR system, but did not quantify the relative contribution of different land use types to nutrient and DOC export from the SJR system. To do this would have required the application of a model. However, such models do not currently exist for CV basins. We will take monitoring data to the next step by applying NEWS-DIN, NEWS-DIP, and NEWS-DOC to sub-basins of the San Joaquin and Sacramento rivers where validation data are available. We will also apply these models to the entire Sacramento and SJR basins to estimate total DIN, DIP, and DOC flux and land-based DIN, DIP, and DOC sources to the Bay-Delta. For all of these initial runs, we will use higher spatial resolution input datasets than were used for global model runs. Rather than the 0.5 degree input data (approximately 2500 km^2/grid cell), we will use 30m to 1km resolution input datasets (Table 1). To distinguish region-specific versions of NEWS models from the Global NEWS models, we will hereafter refer to the regional models as CV-NEWS-DIN, CV-NEWS-DIP, and CV-NEWS-DOC. In addition to predicting annual average fluxes and sources, we will explore the possibility of using CV-NEWS models to estimate seasonal DIN, DIP, and DOC fluxes.

After running our models, we will compare model estimates with measured nutrient fluxes. We will also compare model-estimated sources with field-based estimates of DIN, DIP, and DOC leaching to surface waters. Additionally, where possible, we will compare CV-NEWS predictions with source apportionment estimates based on isotope data (e.g. Kratzer et al., 1998).

We will also evaluate seasonal and inter-annual patterns in nutrient fluxes from several "indicator" watersheds in the SSJ system, watersheds that have a dominant land use type (generally urban or agricultural; Domagalski and Dileanis 2000). We will compare these fluxes with temporal patterns in nutrient inputs to the landscape (using data in Table 1), and use the results of this analysis to evaluate a) whether this approach gives additional information about the magnitude of urban and agricultural C, N, and P sources to surface waters and b) whether our models are attributing sources correctly on the landscape. For example, in an agriculture-dominated watershed, it should be possible to use a correlation between increased N or P application over the past 20 years with increases in N and P fluxes to develop a relationship between N and P loading and nutrient loss to surface waters (mass balance analysis). It should also be possible to see pulses of N and P following major irrigation and fertilization periods, whereas urban sources should be relatively constant (e.g. Harrison et al., 2003).

With respect to our analysis of DOC, we will pay particular attention to the role of wetlands, which are thought to be a major source of DOC on the landscape both in the SJR system (Kratzer et al. 2004) and more generally (Mulholland 2003; Harrison et al. In Press a). However, there has not yet been an effort to quantify the amount of DOC coming from wetland sources in either the Sacramento or SJR systems, and therefore how sensitive DOC fluxes are to potential future changes in wetland extent. We will use CV-NEWS-DOM to carry out this analysis.

With respect to DIN, past work suggests that a recent increase in subsurface drainage from agricultural fields (tile drainage) is largely responsible for the observed increase in river-borne DIN (Kratzer and Sheldon 1998), but other factors could be contributing as well. For example, manure production, N-deposition, and human population density have all increased substantially over the period of observed increase in DIN. We will use CV-NEWS-DIN to evaluate the potential contribution from each of these sources to SJR and Sacramento River DIN fluxes.

Though phosphorus concentrations in the SJR have declined since the onset of widespread sewage treatment in the late 1960s, loading of non-point P to basin land surface has continued to increase (e.g. from 17,900 ton P/yr in 1970 to 24,200 kg P/yr in 1990; Kratzer and Sheldon 1998), suggesting that P concentrations may soon begin to rise again as non-point sources increasingly contribute P to CV river systems. This change could play an essential role in SJR ecosystem function, as preliminary analysis of SJR N:P ratios suggests that algal productivity is limited by P availability (median TN:TP at Maze Rd. = 38; Fig 2a; Dahlgren Unpublished data). We will use CV-NEWS-DIP to evaluate the relative importance of non-point P sources in contributing to river-borne DIP in CV river systems.

2.5. Q2. How can we improve our ability to predict river DOC, DIN, and DIP export and sources?

The work outlined in the previous section will constitute the first step in what will be an iterative process of model application and model refinement. After each model run, we will compare model predictions with measured annual and seasonal fluxes at each gauging station for which there is sufficient measurement data. We will evaluate outliers on these plots for consistent traits, and will consider accounting for those traits in subsequent versions of CV-NEWS models.

We will not initially recalibrate the original Global NEWS models to CV fluxes for the reasons outlined in section 2.3. However, if concerns over model accuracy dictate that we re-calibrate CV-NEWS models specifically for Central Valley Regions, then we will re-validate CV-NEWS models as well. To accomplish this, we will reserve at least 25% of the basins for which we have nutrient flux data, and not use them in model calibration. We will then test the ability of CV-NEWS models to predict DIN, DIP, and DOC export in the basins that were not used for model calibration. We will also evaluate the ability of both un-calibrated and calibrated CV-NEWS models to predict nutrient and organic matter fluxes from basins with newly collected data. Throughout first two years of our proposed three-year project, collection of additional data will be occurring. We will not initially use these data in our model runs, but will reserve them as a model validation dataset. At beginning of third year, we will test CV-NEWS models against the newly-collected validation data.

Eventually, it is our aim to incorporate higher temporal resolution, within sub-basin dynamic interactions of elements and water, and estimates of DOC quality as well as bulk quantity in CV-NEWS-models. We have recently developed the capacity to simulate within-basin nutrient transformation for global models (Wolheim et al., Submitted). However, even without these refinements, the work that we have proposed represents a significant advance over the state of nutrient export modeling in the CV region. Nonetheless, as time permits, we will also work to incorporate the aforementioned improvements. With respect to the incorporation of a DOC quality component, we will work with Dr. Brian Bergamaschi to incorporate growing understanding of DOC sources and composition (gained through intensive study of the Willow Slough watershed) into future versions of our DOC model. We will also explore opportunities for collaboration with the group at the California Department of Water Resources that is developing the Delta Simulation Model II (DSMII; http://modeling.water.ca.gov/delta/models/dsm2/), to see whether there is a potential to combine the biogeochemical sophistication of the NEWS models with the high spatial and temporal resolution and computing power associated with DSMII.

2.5.1 Error, Efficiency, and Sensitivity Analyses

In addition to attempting to reduce model error by exploring other potential controlling variables and higher resolution input datasets, we will also explicitly quantify model uncertainty. Three aspects of uncertainty will be explored: 1) uncertainties associated with river nutrient export observations (sampling approach: tools and techniques, sampling locations, and sampling rate) leading to quantification of uncertainties associated with interpolation and extrapolation both in space and in time; 2) uncertainties associated with model boundary conditions (upscaling and downscaling issues associated with climate data, digital elevation models, nutrient inputs, and other parameters as noted above); and 3) uncertainties associated with models (parameterization of processes, propagation of errors through uncertainties in boundary conditions). Every effort will be made to ensure that the best available data is used for model validation or model input.

Once we are satisfied with model performance, we will evaluate the contribution of individual model components to model predictive capacity as in Harrison et al. (In Press a). To accomplish this, we will evaluate change in model efficiency (a measure of deviation from the 1:1 line of measured vs. modeled nutrient export; Nash and Sutcliffe 1970) upon removal of model components (e.g. in the case of the DIP model point sources, non-point sources, weathering sources, consumptive use, and reservoir DIP retention).

We will also subject the CV-NEWS models to sensitivity analyses in which we vary each model input and coefficient and each combination of inputs and coefficients and quantify model response to these variations. This analysis will indicate how sensitive our models are to errors in input data or parameter estimation. Together, these analyses will suggest how accurate CV-NEWS-based estimates are likely to be, and where our understanding of DOC, DIN, and DIP transport is lacking and must be improved as in (Harrison et al., In Press a and b).

2.7. Q3. How are river DOC, DIN, and DIP loads and sources likely to change as a function of climate, population growth, and land-use change in the next few decades?

To this point there has not been an effort to forecast how river nutrient or DOC fluxes the SSJ system will respond to likely future changes in climate, water consumption, fertilizer application, or population growth. The understanding we gain by addressing questions 1 & 2 will poise us to make the first quantitative, spatially explicit predictions as to how nutrient fluxes and sources in CV river basins are likely to change as a function of these potential anthropogenic perturbations.

We will use the models developed to address Q1 and Q2, in conjunction with estimates of water availability (due to climate change), population growth, water-use, and fertilizer use to estimate likely future rates and sources of DOC, DIN, and DIP transport through the CV rivers.

Before running future projections, we will first test model response to multiple simultaneous changes in model inputs by using 1975 input data (Table 1) to hind-cast to 1975. We will then test model performance in basins for which sufficient validation data is available (at least 20 sub-basins; C. Kratzer Pers. Comm.).

We will then apply our CV-NEWS models to several possible future scenarios, including: 1) a business as usual (BAU) projection of 2030 land-use, population-density, and fertilizer inputs (e.g. Bouwman et al., 2004), 2) a projection with current nutrient inputs and hydrology consistent with global warming predicted reductions in snow-pack and water availability, and 3) a projection incorporating both the BAU projection of nutrient loading to the landscape and projected climate change and resultant reduced snow-pack. We already have datasets required for a coarse-scale (0.5 degree) land-use change projection, but will use finer resolution data as available (e.g. 30 m resolution land-use data from NLCD-USGS and county-level population projections; Table 1). Data for climate projection will be similar to that presented in Miller et al. (2003) and Snyder et al. (2004).

2.8. Schedule of Tasks and Feasibility

We will spend the first six months of the project gathering, collating, and quality controlling nutrient concentration and water discharge data, delineating watersheds at the appropriate scale (or attaining existing watershed delineations from the USGS, as shown in Kratzer and Shelton 1998; Domagalski and Dileanis 2000), associating land-uses with sub-basin watersheds, and gathering as much information as possible regarding the amounts and timing of nutrient and water dynamics in the CV river systems.

Over the subsequent year of the project (5/2006-5/2007), we will use data collected during the initial six months, along with CV-NEWS models, to develop estimates of current DIN, DIP, and DOC fluxes through the SJR and Sacramento River systems, as well as the relative importance of various land-based sources of those nutrients. We will also use this time to refine, validate, and evaluate model uncertainty, model efficiency, and model sensitivity. In addition, we will be gathering (or creating based on past trends) additional input data necessary to run model projections, and preparing a manuscript reporting the results of our data-mining exercise (Section 2.4), quantifying patterns and controls of DIN, DIP, and DOC export in the Sacramento and SJR systems.

From June 2007-June 2008, we will focus our efforts on developing and running model forecasts for DIN, DIP, and DOC export and sources. We will simultaneously be preparing a paper on our efforts at present-day source estimates, with a planned submission date of December 2007. Finally, from June 2008-August 2008, we will prepare the future projection manuscript(s) for submission. Throughout the duration of the project, R. Dahlgren will continue to collect additional bi-weekly water quality samples that can be used in model validation.

We anticipate that the work we have proposed is feasible given that it includes no fieldwork or laboratory-based experiments and the majority of the required datasets are either publicly available or already in our possession (Table 1). In addition, Harrison has recently carried out an analysis of similar scope at the global scale in a similar time frame.

3. Anticipated Products and Benefits

3.1. Benefits to CALFED

The research we have proposed specifically addresses two of CALFED's main objectives: 1) improving ecosystem quality, and 2) improving water quality. Nutrients and DOC affect both water and ecosystem quality in fundamental ways. By increasing our understanding of the land-based controls of nutrient and DOC inputs to the Bay Delta system, this work will contribute to CalFed's ability to manage water quality and ecosystem function effectively. This work also directly addresses CALFED's three priority topic areas by: 1) improving the understanding the relationship between water operations and biological resources (e.g. dam releases and management of irrigation waters likely have a huge impact on nutrient and organic matter transport, which in turn affects downstream ecosystems), 2) improving understanding of ecological processes and their relationship to water management and key species (e.g. the relationship between nutrient loading and DO in the lower SJR), and 3) developing an analytical framework (i.e. models) to improve understanding of the implications of future changes.

The work outlined above will also lead to: 1) an updated and consolidated water quality and discharge database for Sacramento and San Joaquin systems 2) models relating land-use to nutrient and DOC loads to CV rivers and to the Bay Delta; 3) estimates of current and future (2030) DIN, DIP, and DOC loading as well as estimates of the major land-based sources contributing to this loading; 4) scholarly articles published in peer-reviewed journals; and 5) training for at least one postdoctoral scholar and one undergraduate researcher.

The quality of California's surface waters is essential to the health and well-being of CA's citizens. The Sacramento and San Joaquin systems provide drinking water to over 22 million Californians and habitat for multiple threatened fish species. However, DIN, DIP, and DOC loading brought on, in part, by CA's intensive land-use and urbanization, and rapid economic development threaten both. The nutrient export models we propose to develop and apply to the SSJ system will constitute a step towards a system of models that can contribute to the protection of CA's rivers and Bay-Delta region while still allowing for continued economic growth. Specifically, the models we are proposing to develop will provide managers with initial insight into what land-uses sources in specific watersheds are most important in contributing to water quality degradation. As such, these models will eventually grant insight into potential eutrophication-mitigating activities that managers and policy makers can encourage or enforce. This insight will likely be applicable to the agricultural water quality waiver currently in force in California (California Regional Water Quality Control Board, 2004). In addition to contributing tools that can help direct the reduction of N, P, and C loading to coastal systems, these models will also likely provide managers and policy-makers with a tool to forecast how different development scenarios are likely to affect river and delta water quality. Such information may help managers and policy makers set priorities. Finally, as there is no field-work associated with the work we have proposed, it presents a cost-effective project that utilizes historic datasets and ties together multiple existing CALFED-funded projects.

3.2. Benefits to Fellow

The proposed research will benefit the fellow in several ways, including: 1) career development by providing resources required for peer-reviewed publications; 2) continued training and experience working with regional scale nutrient transport modeling; 3) development of professional relationships between fellow and CV/CALFED scientists and policy-makers; and 4) providing the fellow with experience administering a grant.

3.3. Benefits to Research Mentor

The proposed research will benefit the research mentor (Dr. R. Dahlgren) in several ways, including 1) adding value to R. Dahlgren's current research efforts by providing a way to extrapolate from water quality monitoring data (collected as part of a CALFED grant to monitor SJR water quality) to basin-wide patterns of nutrient and DOC transport; 2) contributing experience and expertise on aquatic biogeochemical processes and modeling to R. Dahlgren's lab group; 3) co-authorship with fellow on peer-reviewed publications that substantially utilize the aforementioned water quality monitoring dataset or to which R. Dahlgren makes a substantive intellectual contribution; 4) contact with a likely future collaborator; and 5) an additional link to the CALFED community.

3.4. Benefits to Community Mentor

The proposed research will benefit the CALFED community mentor in several ways, including: 1) adding value added to B. Bergamaschi's current research efforts by providing a tool to explore regional-scale implications of CALFED-funded, catchment-scale Willow Slough experiment; 2) contributing expertise and experience to B. Bergamaschi's group; 3) co-authorship with fellow on peer-reviewed publications to which B. Bergamaschi makes a substantive intellectual contribution peer-reviewed publications; and 4) contact with a likely future collaborator.

Table 1. A subset of the datasets (currently in our possession) that will be employed in analysis of land-use-river DOC, DIN, and DIP-loading relationships, current, historical, and future estimates of DOC, DIN, and DIP export and concentrations.

Dataset	***Brief Description and Source***
River nutrient and water discharge data	US Geological Survey WQN (Alexander et al., 1996), US Geological Survey NAWQA (http://water.usgs.gov/nawqa/), National Water Information System (NWIS), US-EPA Storage and Retrieval (STORET), UC-Davis water quality dataset (R. Dahlgren Pers. Comm.)
30 m land use	Land use in 24 classifications, including wetlands, irrigated and dryland agriculture, forest, pasture, and urban classifications (National Land Cover Characterization 1992-USGS)
County-level N and P fertilizer use	Fertilizer use by county for the years 1945-1991 (http://spo.nos.noaa.gov/projects/cads/description.html)
County-level manure N and P production	Agricultural census data (http://spo.nos.noaa.gov/projects/cads/description.html)
1 km basin delineations	Hydro 1k (Verdin et al., 1996)
Water Diversion Data	http://esd.lbl.gov/people/nwquinn/Grassland_website/sanjoaquin/agdiversion/index.htm
County-level historic and projected population data	http://www.dof.ca.gov/HTML/DEMOGRAP/DRU_Publications/Projections/P3/P3.htm
0.5º gridded N-fixation	N-Fixation estimate (Cleveland et al., 1999)
0.5º gridded N fertilizer application	Fertilizer application by crop type for 1975, 1995, and 2030
0.5º gridded N manure	Manure application by land-use type for 1975, 1995, and 2030
1º gridded NHx and NO$_y$ deposition	NHx and NOy deposition by decade (1860-2000) and projected N deposition (2025 and 2050) (Fig. 3)
Sewage treatment plant discharge	Discharge for major wastewater treatment plants (Kratzer and Sheldon 1998)

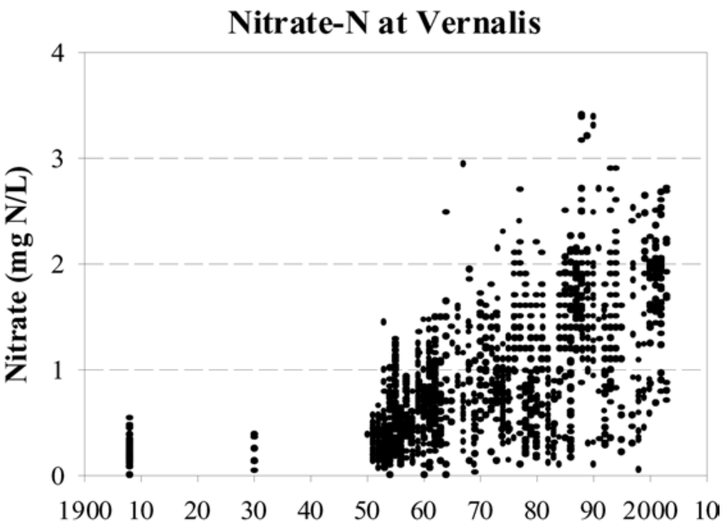

Figure 1. Nitrate (NO_3^-) concentrations (mg N/L) as measured near Vernalis (one of the most downstream water quality monitoring sites on the San Joaquin River; Figure 2a), showing an order of magnitude increase in recent years over pre-industrial levels (Data from R. Dahlgren).

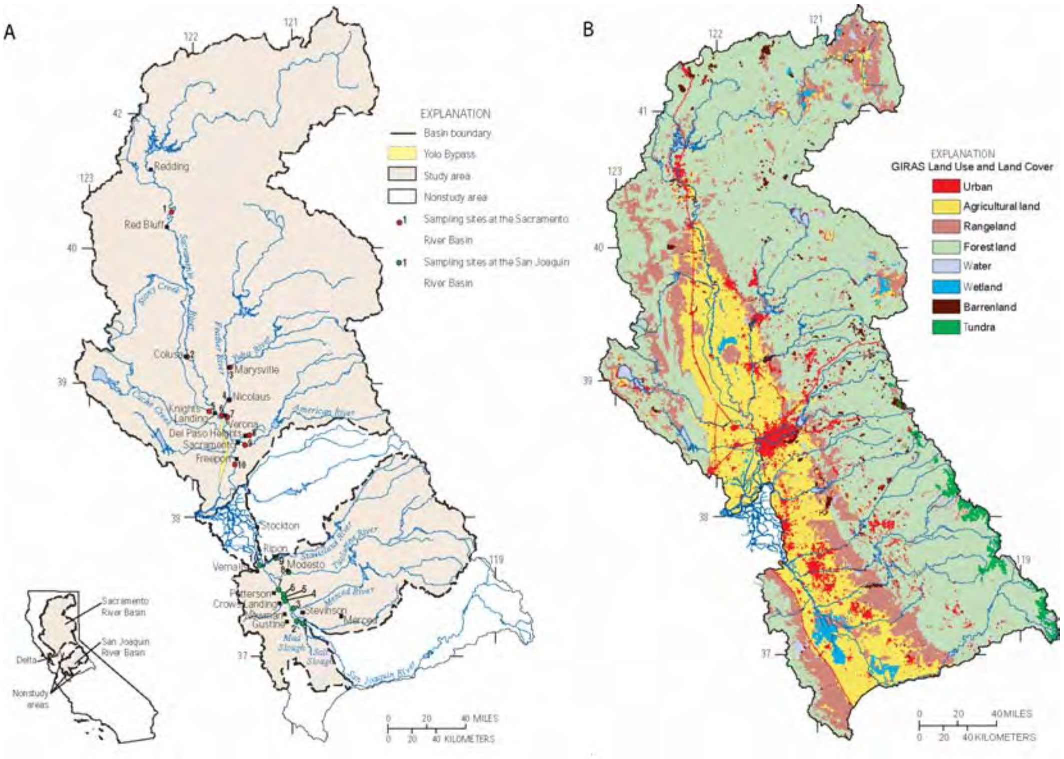

Figure 2. A) Study basins and a small fraction of the sampling sites that will be included in the study, and B) Land use in California's Central Valley from EPA GIRAS (Redrawn from Saleh et al. 2003).

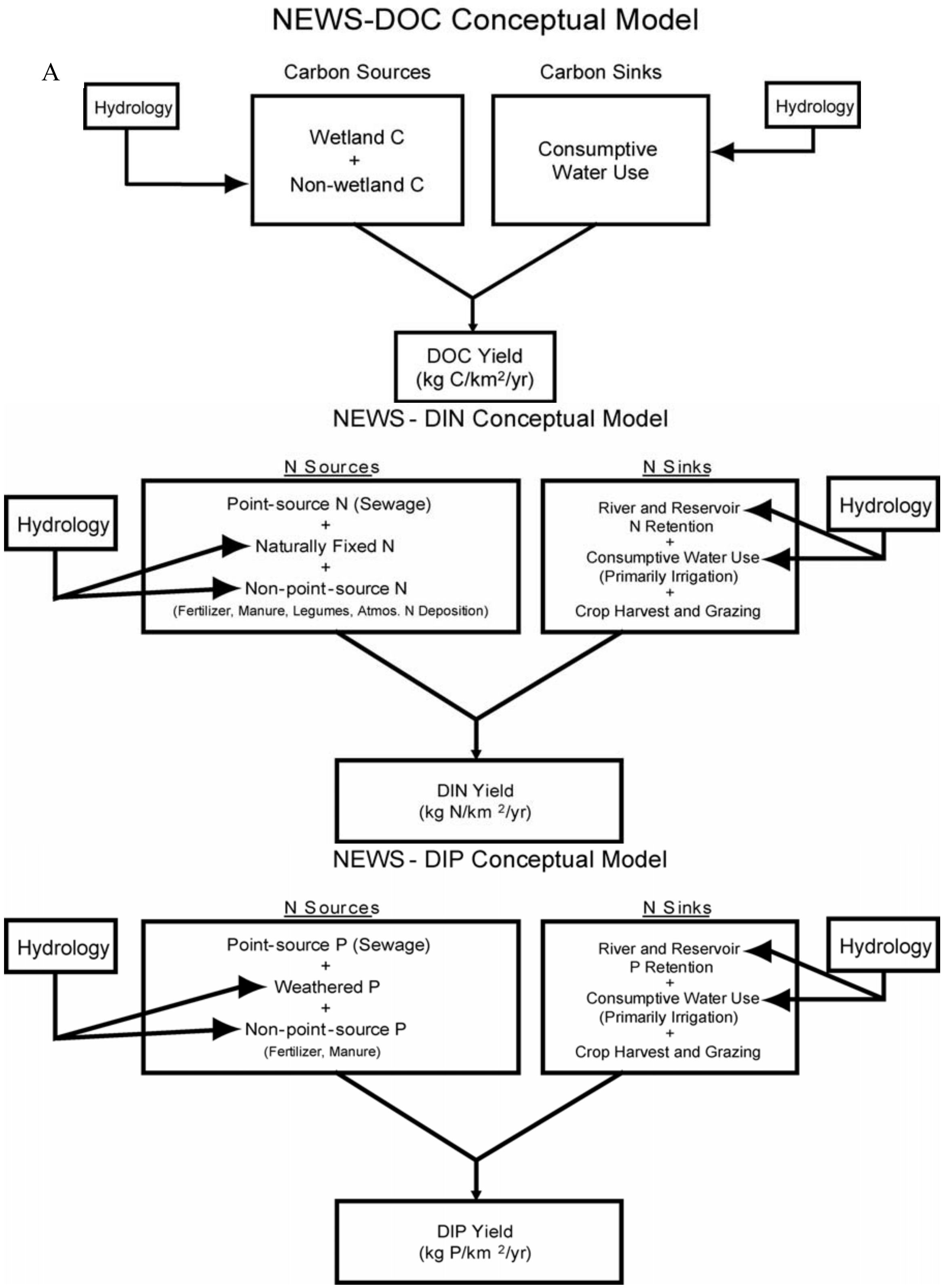

Figure 3. Conceptual models for A) NEWS-DOC, B) NEWS-DIN, and C) NEWS-DIP

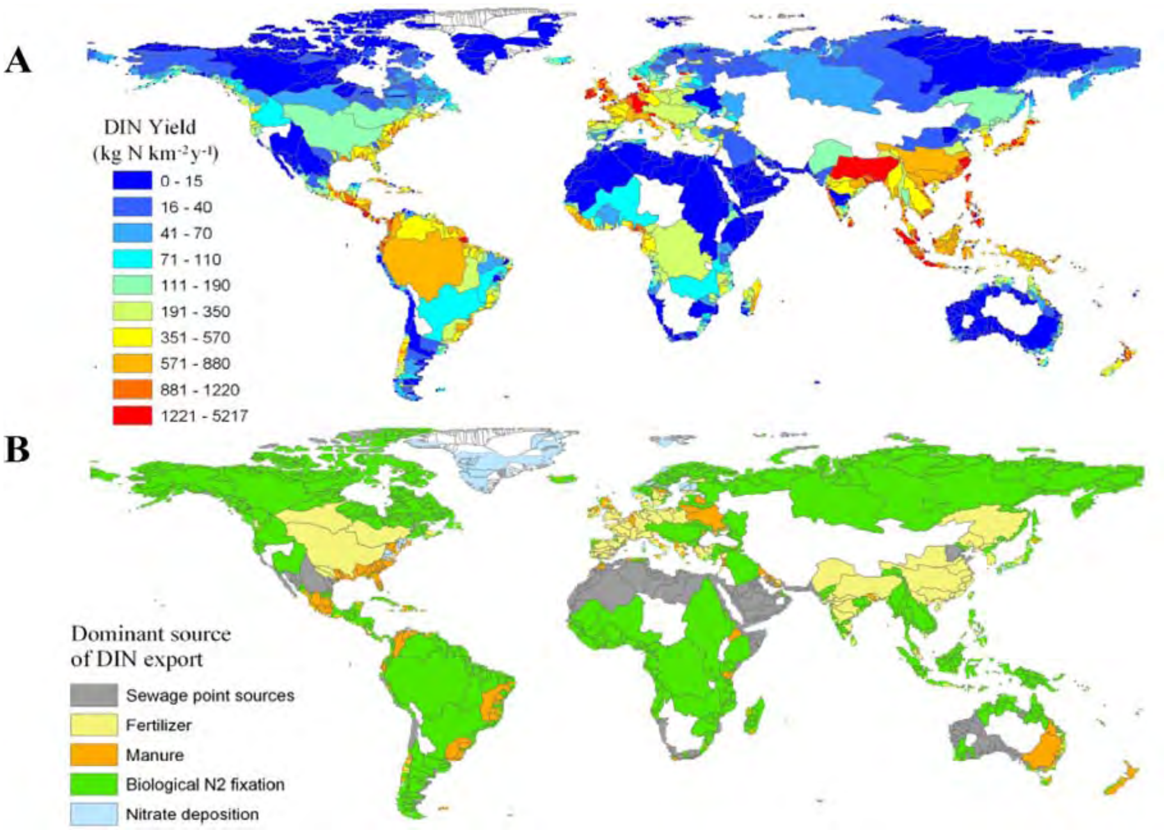

Figure 4. A) NEWS-DIN predicted DIN yield from watersheds globally, and B) NEWS-DIN predicted dominant sources of DIN to the coastal zone. Dominant sources are shown here, but NEWS-DIN can also be used to estimate percent contribution of DIN from specific land-based DIN sources. White areas flow to inland seas and were not included in this analysis. NEWS-DIP and NEWS-DOC are capable of producing similar output (Harrison et al., In Press, and Dumont et al., In Press)

Reference List

Alexander, R. B., P.J. Johnes, E.W. Boyer, and R.A. Smith. 2002. A comparison of models for estimating the riverine export of nitrogen from large watersheds. *Biogeochemistry* 57/58: 295-339.

Anderson, D. M., P. M. Glibert, and J. M. Burkholder. 2002. Harmful algal blooms and eutrophication: Nutrient sources, composition, and consequences. *Estuaries* 25:704-726.

Bennett, E. M., S. R. Carpenter, and N. F. Caraco. 2001. Human impact on erodable phosphorus and eutrophication: A global perspective. *Bioscience* 51 (3):227-234.

Bergamaschi, B. A., M. S. Fram, C. Kendall, S. R. Silva, G. R. Aiken, and R. Fujii. 1999 Carbon isotopic constraints on the contribution of plant material to the natural precursors of trihalomethanes, *Organic Geochemistry*, 30, 835-842.

Bergamaschi, B. A. and M. S. Fram. 2001. Trihalomethane formation rates of dissolved organic carbon from different carbon sources within a watershed, *Abstracts of Papers of the American Chemical Society*, 222, U451.

Bergamaschi, B. A., R. Fujii, and M. S. Fram. 2001. Understanding the sources of dissolved organic carbon in the Sacramento-San Joaquin River Delta, California, USA, *Abstracts of Papers of the American Chemical Society*, 221, U526-U527.

Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Jr., Donigian, A.S., Jr., and Johanson, R.C., 1997, Hydrological simulation program--fortran, user's manual for version 11: U.S. Environmental Protection Agency, National Exposure Research Laboratory, Athens, Ga., EPA/600/R-97/080, 755 p.

Bouwman, A. F., Van Drecht G., and K. W. van der Hoek. 2004. Global and regional surface nitrogen balances in intensive agricultural production systems for the period 1970-2030. *Pedosphere* 1-31.

Boyer, E. W., G. M. Hornberger, K. E. Bencala, and D. McKnight. 1996. Overview of a simple model describing variation of dissolved organic carbon in an upland catchment. *Ecological Modeling* 86 (1996):183-188.

California Regional Water Quality Control Board. Conditional Waiver of Waste Discharge Requirements for Discharges From Irrigated Lands. Anonymous. Anonymous. San Luis Obispo, CA:R3-2004-0117:1, 2004.

Caraco, N. F., and J. J. Cole. 1999. Human impact on nitrate export: an analysis using major world rivers. *Ambio* 28: 167-170.

Caraco N. F. and Cole J. J. 2003. The importance of organic nitrogen production in aquatic systems: A landscape perspective, p. 263-283. In: S.E.G. Findlay and R.L. Sinsabaugh [eds.] Aquatic Ecosytems: Interactivity of dissolved organic matter. Academic Press.

Caraco, N.F. and J.J. Cole. In Press. When terrestrial organic matter is sent down the river: Importance of allochthonous C inputs to the metabolism in lakes and rivers. In: G.A. Polis, M.E. Power, G. Huxell [eds.] Food webs at the landscape level. University of Chicago Press

Carpenter, S.R., N.F. Caracao, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorous and nitrogen. *Ecol. App.* 8(3): 559-568.

Chapra, S., and G. Pelletier. A modeling framework for simulating river and stream water quality: documentation and users manual. Medford, MA:Civil and Environmental Engineering Department, Tufts University. 1-127, 2003.

Cleveland, C.C., A.R. Townsend, D.S. Schimel, H. Fisher, R.W. Howarth, L.O. Hedin, S.S. Perakis, E.F. Latty, J.C. Von Fischer, A. Elseroad, and M.F. Wasson. 1999. Global patterns of terrestrial biological nitrogen (N-2) fixation in natural ecosystems. *Global Biogeochemical Cycles* 13 (2):623-645, 1999.

Dillon, P. J., and L. A. Molot. 1997. Effect of landscape form on export of dissolved organic carbon, iron, and phosphorus from forested stream catchments. *Water Resources Research, 33* (11):2591-2600.

Domagalski, J. L. and Dileanis P.D. Water-quality assessments of the Sacramento River Basin, California-Water quality of fixed sites, 1996-1998. 00-4247, 1-60. 2000. U.S. Geological Survey. Water-Resources Investigations.

Dubrovsky, N. M., Kratzer, C. R., and Burrow, L. R. Water Quality in the San Joaquin-Tulare Basins, California 1992-1995. 1159, 1-38. 1998. U.S. Geological Survey. Circular.

Energy Information Administration. 2005 State Energy Data 2001 Consumption http://www.eia.doe.gov/emeu/states/sep_use/total/use_tot_ca.html

FAO, FAOSTAT. 2001. Database Collections (http://www.apps.fao.org), Food and Agriculture Organization of the United Nations, Rome.

Fekete, B. M., C. J. Vorosmarty, and W. Grabs. 1999. Global, composite runoff fields based on observed river discharge and simulated water balances; Report Number 22 (Second Edition), Global Runoff Data Center, Federal Institute of Hydrology, Koblenz, Germany.

Fenn, M. E., R. Haeuber, G. S. Tonnesen, J. S. Baron, S. Grossman-Clarke, D. Hope, D. A. Jaffe, S. Copeland, L. Geiser, H. M. Rueth, and J. O. Sickman. 2003. Nitrogen emissions, deposition, and monitoring in the western United States, *Bioscience*, 53, 391-40.

Fixen, P.E., and West, F. B. Nitrogen fertilizers: meeting contemporary challenges. *Ambio* 31(2): 169-176, 2002.

Fram, M. S., B. A. Bergamaschi, C. Kendall, S. R. Silva, G. R. Aiken, and R. Fuji, Modeling changes in the carbon isotopic composition of trihalomethane formed during chlorination of dissolved humic material, *Abstracts of Papers of the American Chemical Society*, 222, U451, 2001.

Gorham, E., J. K. Underwood, J. A. Janssens, B. Freedman, Maass W., D. H. Waller, and J. G. Ogden. 1998. The chemistry of streams in southwestern and central Nova Scotia, with particular reference to catchment vegetation and the influence of dissolved organic carbon primarily from wetlands. *Wetlands, 18* (1):115-132.

Green, P. A., C. J. Vorosmarty, M. Meybeck, J. N. Galloway, B. J. Peterson, and E. W. Boyer. 2004. Pre-industrial and contemporary fluxes of nitrogen trough rivers: a global assessment based on topology. *Biogeochemistry* 68: 1-105.

Gronberg, J. M., Dubrovsky, N. M., Kratzer, C. R., Domagalski, J. L., Brown, L. R., and Burrow, L. R. Environmental setting of the San Joaquin-Tulare Basins, California. 97-4205, 1-45. 1998. U.S. Geological Survey. Water-Resources Investigations.

Gronberg, J. M., Kratzer, C. R., Burow, L. R., Domagalski, J. L., and Phillips, S. P. Water-quality assessment of the San Joaquin-Tulare Basins: entering a new decade. 2004-3012, 1-6. 2004. U.S. Geological Survey. Fact Sheet.

Harrison, J. A. and P. A. Matson (2003) Patterns and controls of nitrous oxide (N_2O) emissions from drainage waters of the Yaqui Valley, Sonora, Mexico. *Global Biogeochemical Cycles, 17,* (3), 1080.

Harrison, J. A., S.P. Seitzinger, N. Caraco, A.F. Bouwman, A. Beusen, and C.J. Vörösmarty. 2004. Dissolved inorganic phosphorus export to the coastal zone: results from NEWS-DIP, Ecological Society of America, Ecological Bulletin.

Harrison, J.A., N.F. Caraco, and S.P. Seitzinger. In Press(a). Global distribution of DOC, DON, and DOP export to the coastal zone. *Global Biogeochemical Cycles*.

Harrison, J.A., S.P. Seitzinger, A.F. Bouwman, N. Caraco, A.H.W. Beusen, and C. Vorosmarty. In Press(b). Dissolved inorganic phosphorous export to the coastal zone: Results from a spatially explicit, global model. *Global Biogeochemical Cycles*.

Kratzer, C. R. and Shelton, J. L. Water quality assessment of the San Joaquin-Tulare Basins, California: analysis of available data on nutrients and suspended sediment in surface water, 1972-1990. 1587, 1-92. 1998. U.S. Geological Survey. Professional Paper.

Kratzer, C. R., Dileanis P.D., Zamora, C., Silva, S. R., Kendall, C., Bergamaschi, B. A., and Dahlgren, R. A. Sources and Transport of Nutrients, Organic Carbon, and Chlorophyll *a* in the San Joaquin RIver Upstream of Vernalis, Califronia, during Summer and Fall, 2000 and 2001. 03-4127, 1-113. 2004. Sacramento, CA, U.S. Geological Survey. Water-Resources Investigation Reports.

Kroeze, C., and S. P. Seitzinger. Nitrogen inputs to rivers ; estuaries and continental shelves and related nitrous oxide emissions in 1990 and 2050: a global model. *Nutrient Cycling in Agroecosystems ;* 52 (2-3):195-212, 1998.

Lee, G. F. and Jones-Lee, A. Synthesis and Discussion of Findings on the Causes and Factors Influencing Low DO in the San Joaquin River Deep Water Ship Channel near Stockton, CA: Including 2002 Data. G. Fred Lee and Associates Report to the San Joaquin River Dissolved Oxygen Total Maximum Daily Load Steering Committee. 2003. CALFED Bay-Delta Program.

Ludwig, W., J. L. Probst, and S. Kempe. 1996. Predicting the oceanic input of organic carbon by continental erosion. *Global Biogeochemical Cycles, 10* (1):23-41.

Mackenzie, F.T., Ver, L.M., and Lerman, A. 1998. Coupled biogeochemical cycles of carbon, nitrogen, phosphorous and sulfur in the land-ocean-atmosphere system, p.42-100. *In:* J.N. Galloway and J.M. Melillo [eds.]. Asian change in the context of global climate change. Cambridge University Press.

Miller, N. L., K. E. Bashford, and E. Strem. Potential impacts of climate change on California hydrology. *Journal of the American Water Resources Association* 39 (4):771-784, 2003.

Mulholland, P. J., Large-scale patterns in dissolved organic carbon concentration, flux, and sources. In: Aquatic Ecosystems: Interactivity of Dissolved Organic Matter, edited by S. E. G. Findlay and R. L. Sinsabaugh, San Diego, CA:Elsevier Science, 2003, p. 139-159.

Nash, J. E. and J. V. Sutcliffe. River flow forecasting through conceptual models: Part 1 - A discussion of principles. *Journal of Hydrology* 10 (1970):282-290, 1970.

Neitsch, S. L., J. G. Arnold, J. R. Kiniry, R. Srinivasan, and J. R. Williams. Soil and water assessment tool user's manual: version 2000. TWRI Report. College Station, TX:Texas Water Resources Institute. TR-192:1-472, 2002.

Raymond, P.A. and C.S. Hopkinson. 2003. Ecosystem modulation of dissolved carbon age in a temperate marsh-dominated estuary. *Ecosystems, 6* (7):694-705.

Regional Water Quality Control Board: Central Valley Region. The water quality control plan for the Sacramento River and San Joaquin River Basins for The control program for factors contributing to the dissolved oxygen impairment in the Stockton deep water ship channel. 1-104. 2004.

Reynolds, C. S. and P. S. Davies. 2001. Sources and bioavailability of phosphorus fractions in freshwaters: a British perspective, *Biological Reviews*, 76, 27-64.

Saleh, D. K., Domagalski, J. L., Kratzer, C. R., and Knifong, D. L. Organic carbon trends, loads, and yields to the Sacramento-San Joaquin Delta, California, water years 1980-2000. 03-4070, 1-77. 2003. U.S. Geological Survey. Water Resources Investigations.

Seitzinger, S. P. and C. Kroeze. 1998. Global distribution of nitrous oxide production and N inputs in freshwater and coastal marine ecosystems. *Global Biogeochemical Cycles, 12* (1):93-113.

Seitzinger, S. P., C. Kroeze, A. F. Bouman, N. Caraco, F. Dentener, and R. V. Styles. 2002a. Global patterns of dissolved inorganic and particulate nitrogen inputs to coastal systems: Recent conditions and future projections. *Estuaries* 25 (4b): 640-655.

Seitzinger, S.P., R.V. Styles, E.W. Boyer, R.B. Alexander, G. Billen, R. Howarth, B. Mayer and N. van Breemen. 2002b. Nitrogen retention in rivers: model development and application to watersheds in the northeastern U.S.A. *Biogeochemistry* 57:199-237.

Smith, S. V., D. P. Swaney, L. Talaue-Mcmanus, J. D. Bartley, P. T. Sandhei, C. J. McLaughlin, V. C. Dupra, C. J. Crossland, R. W. Buddemeier, B. A. Maxwell, and F. Wulff. 2003. Humans, hydrology, and the distribution of inorganic nutrient loading to the ocean. *Bioscience* 53: 235-245.

Snyder, M. A., L. C. Sloan, and J. L. Bell. Modeled regional climate change in the hydrologic regions of California: A CO2 sensitivity study. *Journal of the American Water Resources Association* 40 (3):591-601, 2004.

State of California, Department of Finance, July Intercensal Estimates of Total Population for California Counties, 1947-1967*, with 1940, 1950, 1960, and 1970 Census Counts. Sacramento, California, May 2005.

State of California, Department of Finance, E-4 Population Estimates for Cities, Counties and the State, 2001-2005, with 2000 DRU Benchmark. Sacramento, California, May 2005.

Stepanauskas, R., M. A. Moran, B. A. Bergamaschi, and J. T. Hollibaugh. 2003. Covariance of bacterioplankton composition and environmental variables in a temperate delta system, *Aquatic Microbial Ecology*, 31, 85-98.

United Nations. 2004. Energy Statistics Yearbook 2001. 45th Ed., United Nations, New York, NY.

U.S. Census Bureau (USCB), 2005, "Total Midyear Population for the World: 1950-2050", Data updated 4-26-2004, http://www.census.gov/ipc/www/worldpop.html

U.S.Environmental Protection Agency. Drinking water and health advisories: U.S. Environmental Protection Agency. Anonymous. Anonymous. EPA. 822-B-00-001:1-12, 2000.

Verdin, K.L., and Greenlee, S.K., 1996. Development of continental scale digital elevation models and extraction of hydrographic features. In: Proceedings, Third International Conference/Workshop on Integrating GIS and Environmental Modeling, Santa Fe, New Mexico, January 21-26, 1996. National Center for Geographic Information and Analysis, Santa Barbara, California.

Vitousek, P. M. and P. A. Matson. 1993. Agriculture, the global nitrogen cycle, and trace gas flux. The Biogeochemistry of Global Change: Radiative Trace Gases. R. S. Oremland. New York, Chapman and Hall**:** 193-208.

Vörösmarty, C. J., B. M. Feteke, M. Meybeck, and R. Lammers. 2000a. Geomorphometric attributes of the global system of rivers at 30-minute spatial resolution.. *J. Hydrol.* 237: 17-39.

Vörösmarty, C. J., B. M. Feteke, M. Meybeck, and R. Lammers. 2000b. A simulated topological network representing the global system of rivers at 30-minute spatial resolution (STN-30). *Global Biogeochemical Cycles* 14: 599-621.

Weller, D. E., T. E. Jordan, and D. L. a. L. Z. J. Correll. 2003 Effects of land-use change on nutrient discharges from the Patuxent River watershed, *Estuaries*, 26, 244-266.

Wollheim, W. M., C. J. Vörösmarty, A. F. Bouwman, P. Green, J. A. Harrison, M. Meybeck, B. J. Peterson, S. P. Seitzinger and J. P. Syvitski (In Review) A spatially distributed framework for aquatic modeling of the earth system (FrAMES), *Global Biogeochemical Cycles*.

Wool, T. A., R. B. Ambrose, J. L. Martin, and E. A. Comer. 2004. Water quality analysis simulation program (WASP): version 6.0. Anonymous. Anonymous. U.S. EPA. 1-267.