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Environmental Modelling & Software xxx (2009) 1–14

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Use of environmental sensors and sensor networks to develop water and salinity budgets for seasonal wetland real-time water quality management

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ARTICLE INFO

Article history:
Received 20 April 2009
Received in revised form
29 September 2009
Accepted 28 October 2009
Available online xxx

Keywords:
Salt management
Sensors
Sensor networks
Water quality
Forecasting
Environmental decision support

ABSTRACT

Management of river salt loads in a complex and highly regulated river basin such as the San Joaquin River Basin of California presents significant challenges for current Information Technology. Computer-based numerical models are used as a means of simulating hydrologic processes and water quality within the basin and can be useful tools for organizing Basin data in a structured and readily accessible manner. These models can also be used to extend information derived from environmental sensors within existing monitoring networks to areas outside these systems based on similarity factors – since it would be cost prohibitive to collect data for every channel or pollutant source within the Basin. A common feature of all hydrologic and water quality models is the ability to perform mass balances. This paper describes the use of a number of state-of-the-art sensor technologies that have been deployed to obtain water and salinity mass balances for a 60,000 ha tract of seasonally managed wetlands in the San Joaquin River Basin of California. These sensor technologies are being combined with more traditional environmental monitoring techniques to support real-time salinity management (RTSM) in the River Basin. Two of these new technology applications: *YSI-Econet* (which supports continuous flow and salinity monitoring of surface water deliveries and seasonal wetland drainage); and *electromagnetic salinity mapping* (a remote sensing technology for mapping soil salinity in the surface soils) – have not previously been reported in the literature. Continuous sensor deployments that experience more widespread use include: *weather station sensor arrays* – used to estimate wetland pond evaporation and moist soil plant evapotranspiration; *high resolution multi-spectral imagery* – used to discriminate between and estimate the area of wetland moist soil plant vegetation; and *groundwater level sensors* – used primarily to estimate seepage losses beneath a wetland pond during flood-up. Important issues associated with quality assurance of continuous data are discussed and the application of a state-of-the-art software product AQUARIUS, which streamlines the process of data error correction and dissemination, is described as an essential element of ensuring successful RTSM implementation in the San Joaquin River Basin.

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1. Introduction

Real-time water quality management (RTWQM) is a strategy for meeting downstream water quality objectives by making use of river assimilative capacity and improving coordination of upstream contaminant loading from point and non-point sources with dilution flows. In California and other western States (within the United States) as well as other arid river basins around the world (such as the Murray Darling River Basin in Australia) – salinity is treated as a pollutant and its concentration in rivers used for agricultural, municipal and industrial water supply regulated (Murray Darling Basin Commission, 2005). The assimilative capacity for a pollutant such as salinity in a water body is defined as the maximum loading of that contaminant that can be accommodated by the water body without exceeding water quality objectives (or standards). These objectives are typically defined at a downstream compliance monitoring location. In the case of California's San Joaquin Basin – reservoir releases from tributaries on the East-Side of the River Basin (mostly snow-melt from the granitic Sierra Nevada mountains) and return flows from east-side irrigation districts provide dilution for west-side San Joaquin Basin drainage flows, derived mostly from west-side San Joaquin Valley irrigated agricultural

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doi:10.1016/j.envsoft.2009.10.011

Please cite this article in press as: Quinn, N.W.T., et al., Use of environmental sensors and sensor networks to develop water and salinity budgets..., Environ. Model. Softw. (2009), doi:10.1016/j.envsoft.2009.10.011

crop land, municipalities and seasonally managed wetlands. West-side soils derive from eroded sediments from an uplifted marine and are high in naturally occurring salts. Water supplies for irrigation of west-side agriculture, some urban areas and for seasonally managed wetlands (Fig. 1) derive from the Sacramento–San Joaquin River Delta and contain salt – most often in the range of 300–600 ppm TDS. West-side agricultural return flows are at their highest during the summer irrigation season. Seasonal wetland salt loads are highest during the months of March and April when the majority of the seasonal wetland ponds are drawn down to promote establishment of moist soil plants and other native grasses that provide a protein source to overwintering waterfowl.

Salt export from agricultural, wetland and municipalities is regulated as part of a comprehensive Total Maximum Daily Load (TMDL) for the San Joaquin River Basin (CEPA, 2002; CRWQCB, 2004; Quinn and Karkoski, 1998). The TMDL is intended to identify, quantify and control sources of pollution that affect attainment of water quality objectives and full protection of identified beneficial uses of water. The TMDL includes both point and non-point sources of salt loading. Point sources of salinity, such as discharges from wastewater treatment systems, are regulated using Waste Load Allocations (WLA). These WLAs are usually concentration based and allow the entities regulated to enter into a marketplace with other regulated entities to trade their allocations. Non-point sources of salinity (LA) are not typically amenable to the establishment of fixed monthly or seasonal salt load allocations because of the diffuse nature of these non-point source loads in the watershed (which makes it difficult to assign responsibility), the technical challenges of monitoring individual discharge points, and the high seasonal variation in export flows and salt loads.

The loading capacity for a TMDL is determined by multiplying the water quality objective (WQO) at the downstream compliance monitoring location by the available flow in the river or stream, Q (CRWQCB, 2004):

$$\mathrm{TMDL} = Q^{*}\mathrm{WQO} \tag{1}$$

This total loading capacity (TMDL) equals the sum of the waste load allocations from point sources (WLA) and non-point sources (LA) and includes an appropriate margin of safety (MOS) (CRWQCB, 2004).

$$\mathrm{TMDL} = \mathrm{LC} = \sum \mathrm{WLA} + \sum \mathrm{LA} + \mathrm{MOS} \tag{2}$$

where LC = salt load capacity, WLA = point-source salt load allocation, LA = non-point source salt load allocation, MOS = margin of safety (%).

These allocations are calculated based on the lowest anticipated flow condition in the River and the River's assimilative capacity during these periods. Point-source salt loads (WLAs), are subtracted from the total assimilative capacity of the River to determine the salt load allocation to all non-point sources. These non-point source loads of salt include both background salt loads (salt loads imported with surface water supply and not controllable by landowners) and salt loads contributed by groundwater return flows (CRWQCB, 2004).

$$\mathrm{TMDL} = \sum \mathrm{WLA} + \sum \mathrm{LA} + \sum \mathrm{BG} + \sum \mathrm{GW} + \mathrm{MOS} \tag{3}$$

where GW = groundwater salt loading, BG = background salt loading.

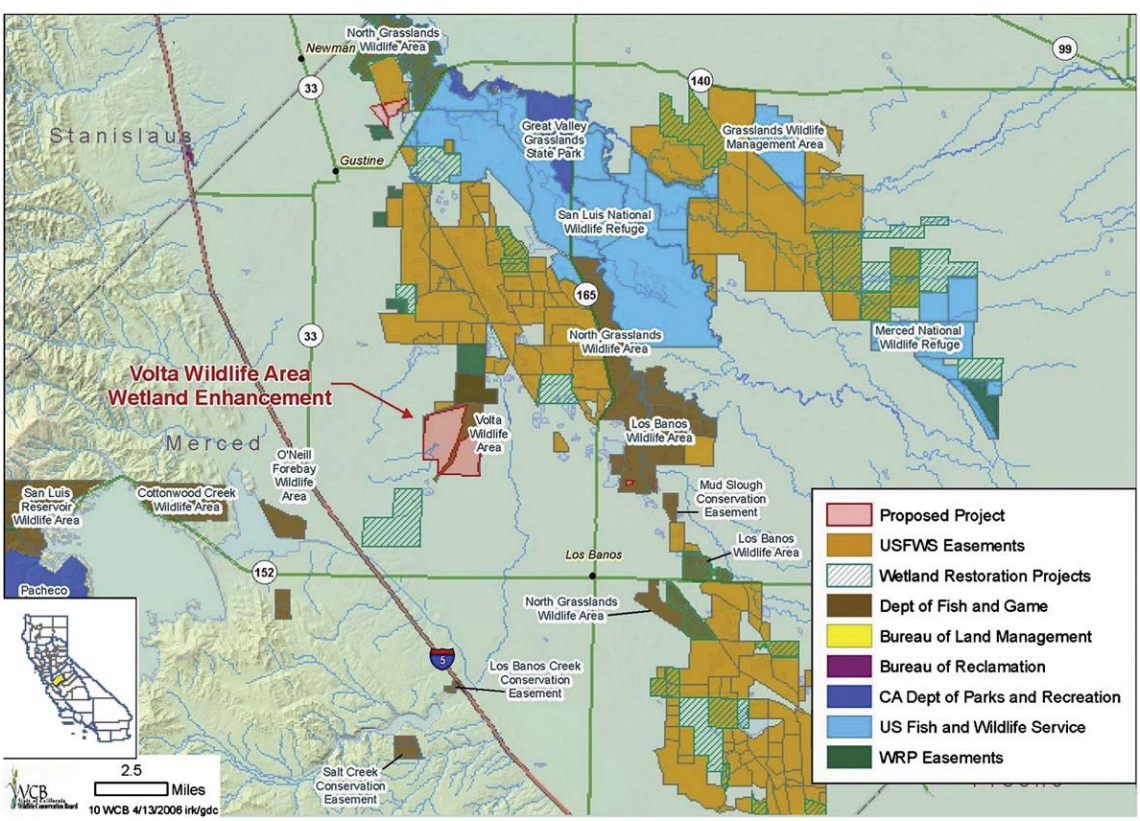

Fig. 1. Project area which contains approximately 60,000 has of seasonal wetland habitat collectively known as the Grasslands Ecological Area (GEA). It comprises Federal, State and private wetlands and conservation easements to form the largest contiguous area of waterfowl habitat in the western United States. The GEA is subject to EPA mandated salinity regulation which is best met through an innovative salt management technique, now under development, known as real-time salinity management (RTSM).

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For a successful TMDL, the actual sum of loads from tones all point and non-point sources, background loads, groundwater loads, and margin of safety must be less than or equal to the TMDL. The margin of safety is typically set at 15–20% of the total salt load and takes account of the hydrologic variability of the system and the technical inability to use 100% of the assimilative capacity of the River, even under near-perfect management.

The salinity TMDL limits both agricultural and wetland discharges of salt loads to the San Joaquin River. During dry and critically dry years the salinity TMDL is especially restrictive curtailing salt load from irrigated agricultural land during the summer months when drainage return flows are highest. Under these hydrologic conditions the total volume of dilution flow from Sierran tributaries to the San Joaquin River diminish – River assimilative capacity is likewise reduced, resulting in more frequent violation of the CRWQCB water quality objectives for salinity.

Real-time salinity management has been advocated as a means of improving compliance with San Joaquin River salinity objectives by improving the coordination of west-side agricultural and wetland dischargers of salt with reservoir releases flows made along east-side tributaries (Quinn and Hanna; 2002, 2003; Quinn et al., 2005). RTSM is a concept that relies upon access to real-time flow and electrical conductivity data from networks of sensors located along the San Joaquin River and its major tributaries (Quinn and Karkoski, 1998). RTSM provides timely decision support to agricultural water districts and seasonal wetland managers – allowing them to improve the coordination of salt load export with the available assimilative capacity of the San Joaquin River (Quinn and Hanna; 2002, 2003). An Environmental Decision Support System (EDSS) is under development which combines watershed flow and water quality monitoring, modeling, salt assimilative capacity forecasting and web-based information dissemination and sharing. The published literature contains examples of similar, although less ambitious, EDSS projects for adaptive management of salinity and other water quality contaminants (Zhu and Dale, 2001; Janssen et al., 2005; Garcia and Lange, 1993).

1.1. Wetland salinity management

Seasonally managed wetlands in the western San Joaquin Basin of California's Central Valley provide overwintering habitat for migratory waterfowl and hunting opportunities during the annual duck hunting season. Wetland water supply from the Sacramento–San Joaquin River Delta contains inorganic salts which evapoconcentrate in the man-made, seasonally managed ponds, before being drained into channels that discharge into the San Joaquin River. This seasonal wetland drainage, produced within a 60,000 ha wetland Grasslands Ecological Area (GEA) of the San Joaquin Basin (Fig. 1), must be eliminated to preserve salt balance and sustain habitat conditions that make these wetlands the most important migratory bird resource in the western United States. Unfortunately wetland drainage schedules often coincide with periods of low assimilative capacity in the San Joaquin River as well as the germination period of salt sensitive agricultural crops in the southern Delta. These southern Delta crops are irrigated with water pumped from the River – the area in which they are grown is located approximately 100 km downstream of the major salt-load bearing tributaries to the River. Assimilative capacity, expressed in tonnes (tons) of salt, is the numerical difference between the product of the current flow and numerical water quality objective and the current salt load measured at the compliance monitoring station. A negative River assimilative capacity (Fig. 2) occurs any time the numeric water quality objective is exceeded.

Application of RTSM to seasonal wetlands in the San Joaquin Basin will likely require more intensive management of wetland hydrology which might include modification of traditional wetland drawdown schedules to better match wetland salt loads with the assimilative capacity of the San Joaquin River. Wetland drawdown schedules have been established over several decades to promote the establishment of moist soil plant habitat that provides the optimal food resource for overwintering waterfowl (Mushet et. al.,1992; Reinecke and Hartke, 2005; USFWS, 1986). Changes to this traditional schedule may come at a potential cost to the sustainability of the moist soil plant habitat resource (Fredrickson and Taylor, 1982; Quinn et al., 2005; Taft et al.,

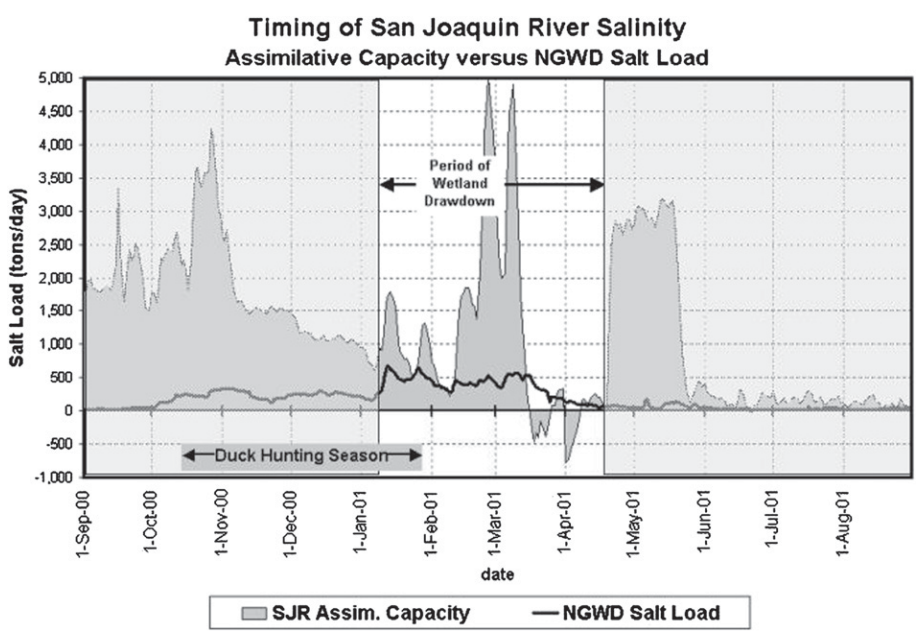

Fig. 2. Illustration of the concept of RTSM. Salt assimilative capacity (shown by the shaded grey area – tons/day) is typically high during winter months when a combination of a higher salinity river objective (1,000 μS/cm) and rainfall runoff produce high diluting flows from east-side San Joaquin River tributaries. Wetland drainage salt loads from private wetlands in the Grasslands Ecological Area are sufficient to produce negative assimilative capacity during periods in late March and early April when river salt concentrations exceed State-mandated water quality objectives. Under an RTSM scenario delaying wetland drainage drawdown until mid-April would re-schedule this salt loading to a period of high River assimilative capacity preventing exceedence of river salinity objectives.

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2002). However there exists is a dearth of field data or published studies upon which to base wetland seasonal salinity management strategies. A primary objective of the study described in this paper is to develop a quantitative approach to improve the understanding of wetland hydrology and salinity and to guide RTSM.

2. Methods

The concept of water and salt balance is fundamental to all water quality simulation models. Wetland water and salinity balances are performed by summing fluxes of water and salt entering a leaving a defined control volume, such as a single pond, resulting in an estimated rate of change in wetland water storage or salt content (Fig. 3). Implementation of wetland RTSM requires continuous updating of water and salinity balances using sensors to: measure water and salt inflow to and outflow from each pond; seepage and salt flux exchange with groundwater; surface water storage gain due to precipitation and surface water storage loss due to the sum of direct pond evaporation and moist soil plant evapotranspiration.

Sensors selected to take these measurements should have the following capabilities:

1. Provide accurate flow measurements within the range of 0.1–10 cfs – typical of wetland flow hydrology
2. Have a common data communication interface such as SDI-12 providing sensor compatibility with a number of data collection platforms
3. Fast response and capable of being telemetered in combination with other sensors through the data collection platform
4. Robust and resilient – capable of performing accurately under a wide range of environmental conditions (i.e. cold, moist winter conditions and hot, desiccating summer conditions)
5. Inexpensive and easy to deploy

The environmental monitoring systems described in this paper fall into three categories :

1. Sensors that are part of a environmental sensor network that contains master (access) nodes that directly communicate with the data storage service center and slave (data) nodes that report to the master nodes. The YSI-EcoNet environmental monitoring and web-based data dissemination system is state-of-the-art example of this type of sensor network.
2. Sensors that are not normally part of a telemetered sensor network that are interrogated at irregular intervals and data are accessed manually. The Bowen weather station and in situ groundwater elevation sensors are examples of this type of sensor deployment.
3. Sensors that are typically deployed only once at a single location as part of a system characterization procedure or experiment. Soil salinity maps based on surveys conducted using a portable electromagnetic (EM-38) instrument and wetland vegetation maps developed from high resolution, multi-spectral remote sensing imagery and spectral analysis software are examples of this mode of sensor deployment.

2.1. Monitoring system design

For the seasonal wetland application an integrated suite of environmental sensors were deployed to develop accurate water and salinity balances for individual wetland ponds and extrapolate these results over the GEA. With over 300 wetland ponds, ranging in size from a few hectares to several hundred hectares, the annual cost of providing telemetry to each inlet and outlet of every pond within the entire 60,000 ha GEA would be in excess of $270,000 (assuming an average of $450 per site per year and no scale-up cost offsets). This figure would exceed the annual salinity monitoring budgets of the wetland entities combined. Hence the environmental monitoring system was designed to provide characterization at both individual pond and sub-watershed scale. At the scale of the individual wetland pond – inlets and outlets were continuously monitored for flow and salinity during the period of flooding. High resolution imagery was analysed of each of the wetland pond sites and the resulting classification used to determine the relative proportion of each pond area vegetated with desirable moist soil crops that provide superior wetland habitat such as swamp timothy (*Crypsis schoenoides*), watergrass (*Hydrochloa caroliniensis*) and smartweed (*Polygonum lapathifolium*).

Sub-basin scale characterization was accomplished by subdividing the entire Basin into subareas that shared a common water supply (i.e. were flooded up together and hence were provided similar quality water) and subareas that drained through common drainage outlets (drainage water quality expected to be similar). Flow and salinity monitoring stations were installed at these major inlets and outlets, within several of the major wetland supply and drainage canals and also at the inlets and outlets of carefully selected individual ponds. In the GEA it was fortunate that the footprint of the larger flooded sub-basins and the drainage sub-basins were most often closely matched. A certain amount of redundancy was built into the monitoring system to act as checks when extrapolating the data derived from individual ponds to the larger drainage subareas. This also assisted in validation of model hydrologic and water quality assumptions.

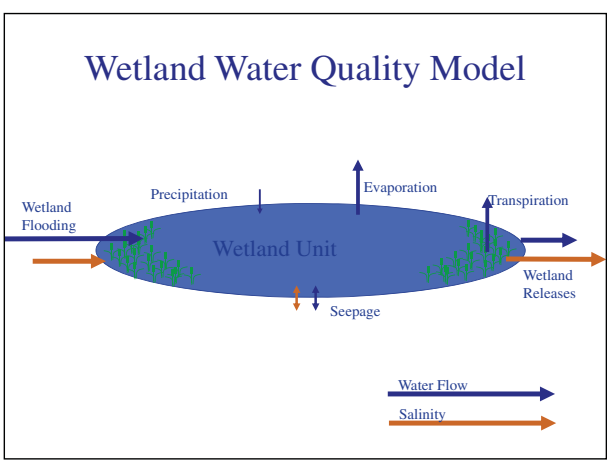

Fig. 3. Conceptual wetland hydrology and salinity model showing component processes.

3. Results

Implementation of the monitoring system design and the data reporting and visualization system began in 2005 and the system continues to evolve and expand in coverage and capability. The timing of the project was fortuitous in one aspect that it coincided with the commercial release to market of a suite of innovative sensor technologies some of which have been exploited in the project application. The downside of being the first in line to apply new technology was that our project became the de-facto alpha test platform for several of the technologies that still contained software bugs and hardware components that had not been adequately tested.

3.1. Data collection, dissemination and visualization

The technology for telemetry of environmental monitoring data has been available for several decades. Supervisory Control and Data Acquisition (SCADA) systems provide not only continuous monitoring of flow and water quality for their client municipalities and water districts but also have the ability to adjust control settings of pumps and other flow devices according to preset logic or specific control-feedback algorithms. These systems typically utilize radio or cellular telemetry to transmit data to a central base station, are complicated to program and are rarely accessible to outside monitoring networks. Skilled technicians are often required to install, reprogram and administer these systems – although new SCADA software is now available, such as Control Microsystem's ClearSCADA product (http://www.clearscada.com/), which makes this technology more accessible. Commercial vendors such as Campbell Scientific Inc. (http://www.campbellsci.com), Vaisala Inc. (http://www.Vaisala.com), Design Analysis Associates Inc. (http://www.daa-utah.com) manufacture open-architecture data logging systems that are somewhat easier to program but which rely on custom software to communicate with the datalogger and download data. Campbell Scientific Inc., in particular, developed complementary software known as (RTDM – Real-Time Data Management) as an add-on to their popular LoggerNet datalogger programming software, which allows post-processed data to be posted on a web-server as image files. Experience with this software was positive although frequent hiccups in the batch processing system did not eliminate the need for human system oversight. Water district

personnel were reluctant to take time away from their busy field activities to keep the system current leading to sensor malfunctions going unreported until the next quality assurance check of the instruments. The Water District was not able to justify hiring a full-time staff member whose time was devoted to monitoring system administration and data quality assurance. A system design that eliminated all manual data downloading and processing while and providing reliable web access to both downloaded and quality-assured data was sought for the GEA wetlands application.

The advent of YSI-EcoNet (YSI, 2007, https://www.ysi.com/ysi) in 2004 provided the capability to provide web delivery of the wetland flow and water quality monitoring data. YSI-EcoNet integrates sensor hardware (acoustic flow probes, pressure and water quality sondes), dataloggers and software that perform local data storage, telemetry and visualization (Fig. 4). The YSI-EcoNet architecture comprises a mixed mesh of Data Nodes (that collect data from flow and water quality measuring sensors) and Access Nodes (that have the added capability of collecting data, via a low power radio interface, from surrounding Data Nodes) (Fig. 4). The Access Node transmits logged data to a remote Data Center (NIVIS) via CDMA cellular phone or satellite modem – the data is made accessible to the world-wide web through the NIVIS Data Center. The NIVIS Data Center is a remote data storage and processing facility, located on the east coast of the US, that initiates each call to the Access Node network at 15 min intervals through a service contract with YSI Inc, maintains all data collected by the monitoring network and allows customized web access and downloading of the data.

The wireless mesh network topology of YSI-EcoNet allows "point-to-point" or "peer-to-peer" connectivity within an ad hoc, multi-hop network. The mesh network is self-organizing and self-healing – hence loss of one or more nodes does not necessarily affect its operation. This has helped to increase the overall reliability of the system by allowing a fast local response to critical events in the rare event of communication problems. Elimination of tedious data acquisition and processing procedures through adoption of YSI-EcoNet has worked well with our wetland manager client base by eliminating the tedium of downloading and processing environmental data. It has also allowed wetland managers to perform daily oversight of the system and to devote more time to perform bi-weekly sensor quality assurance checks including cleaning of sensors and checking the accuracy of staff gauge data (used in the computation of flow) and to prepare for contingencies such as sensor failure prior to travelling to the site. Project monitoring sites were up to 30 km apart.

3.2. Precipitation and evapotranspiration process sensors

A Bowen weather station (Radiation & Energy Balance Systems, Inc. model CR10-3C) with a continuously recording datalogger was installed centrally within the GEA in the State Wildlife Management Complex (Fig. 5). The Bowen ratio-energy balance method indirectly estimates evapotranspiration (ET) (combination of direct evaporation and emergent moist soil plant transpiration) using micrometeorological sensors (Radiation and Energy Balance Systems, 2004)– it does not directly measure actual ET. Nevertheless, it is considered to be an accurate method for obtaining ET values if net radiation, soil heat flux, and vertical gradients of temperature and humidity can be accurately measured (ASCE, 1996).

The Bowen ratio method derives from the basic surface energy balance equation:

$$R_n = G + H + \lambda E + W + M + S \tag{4}$$

where R_n is the net radiation (incoming–outgoing), G is the surface soil heat flux, H is the sensible heat flux, λE is the latent heat flux, W is the surface water heat flux, M is the energy flux used for photosynthesis and respiration (metabolism), and S is the energy flux into and out of plant tissue, with each term expressed in W/m^2 (Radiation and Energy Balance Systems, 2004). When no standing water is present, the water heat flux term can be removed. In their review of numerous ET estimation methods, Drexler et al. (2004) concluded that the method can produce good results in wetlands that are relatively smooth and uniform (i.e. aerodynamic resistance over the surface is not highly variable) as well as large in area allowing for adequate "fetch" distances. The sensors are powered by two 6 V deep-cycle batteries, connected in series, which are

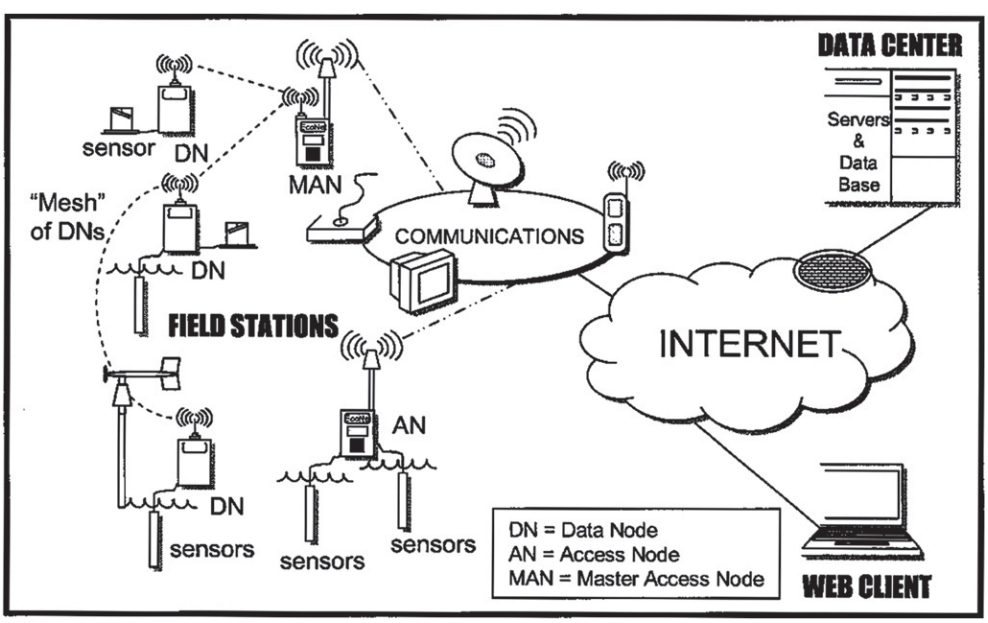

Fig. 4. Environmental sensor network showing how individual sensors at each monitoring site report to local data nodes and communicate to each other through radio frequency telemetry. Master (access) nodes poll each data node and report data from multiple data nodes to the NIVIS data center. The NIVIS Data Center posts sensor data every 15 min to the web – allowing near real-time retrieval of preliminary data. Continuous data processing is required to produce data suitable for public access and retrieval (YSI Inc., 2007).

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Fig. 5. Bowen weather station showing the solar panel, 6 V batteries (inside the cooler below to prevent contact with moisture), cable box with datalogger, rain gauge, and anemometer. Two net radiometers (left side of photo) are held at approx. 1.5 m over the surface. The air exchangers (right side of photo) face the prevailing winds and are spaced 1 m apart, with the lower exchanger positioned approximately 25 cm above the surface.

continually recharged by a 53-W solar panel. The station includes (Fig. 5):

- two double-sided total hemispherical radiometers, two vertically-separated air exchangers (automatic exchange mechanism) with temperature and humidity probes, three soil heat flux measurement disk, soil moisture plate, and soil temperature probes, one anemometer, a barometer and a rain gauge.

The net radiometers, placed at approximately 1.5 m above the vegetation, record both incoming and outgoing radiation to produce a single net radiation value at each time step. The air exchangers were separated vertically by a distance of 1.0 m and the lower radiometer was mounted about 1.5 m above the vegetation – these instruments measure vertical gradients of temperature and vapor pressure within the equilibrium boundary layer that forms over the swamp timothy. Ground sensors were inserted into the soil at shallow depths to record heat flux, moisture, and temperature. In order to capture the "average" soil environment, sensor groups were placed in locations with slightly varying microscale moisture conditions and topography, as assessed from field observation. The Bowen weather station was positioned so that at least 100 m of upwind fetch existed for the 1 m of separation between the air exchangers as suggested by protocol (ASCE, 1996). This helped to ensure that flux measurements represented the underlying surface and that the measured boundary layer were not contaminated by fluxes from distant surfaces (Drexler et al., 2004). A number of factors affect the rate of evapotranspiration from a given surface, including solar energy, humidity, soil moisture, extent of open water, solar albedo, vegetation density, species composition, growth stage, heat advection, wind speed and salinity.

Data from the Bowen weather station was reported at 15 min intervals to a Campbell Scientific Inc. datalogger housed in the white, air-tight, metal enclosure (Fig. 5). Data was downloaded daily to the remote project computer workstation by means of a cellular modem located within the enclosure. Upon download termination a number software programs were initiated in batch mode to error check the data, flag out-of-range or potentially erroneous values and parse the data into hourly and daily data reports. The daily mean values of wetland evapotranspiration were used in the wetland water balance.

During wetland annual flood-up and drawdown pond surface area varies over time as the pond floods or is drawn down. Hence evapotranspiration rates are a function of pond surface area – the surface area needs to be determined continuously to measure the daily volume of evapotranspiration loss from the pond surface of each wetland. Detailed pond bathymetric surveys were made using an ATV-mounted differential GPS instrument and relationships developed using ESRI's Arc-GIS (3-D analyst – http://www.esri.com) to develop functional relationships between pond stage and pond surface area. Slices of a three dimensional volume rendering of each pond were made at 1/10th ft (0.03 m) increments and the surface area and cumulative volume were recorded at each depth increment. Polynomial curves were fitted to the data to allow pond surface area to be calculated from the continuous stage data recorded at each pond outlet. Pond elevations were referenced to the deepest point in the pond which was typically the bottom of each culvert at the outlet weir box for each pond. As each wetland pond was drawn down – evapotranspiration losses were determined as the sum of direct water evaporation, evapotranspiration from emergent moist soil plants and grasses (such as cattail and skirpus – these losses can exceed potential evapotranspiration), direct soil evaporation and evapotranspiration from germinating grasses (such as swamp timothy and watergrass). Germinating grasses provide increasing soil cover as they spread and mature.

Development of ET estimates for the entire GEA required maps of wetland ponded area and emergent wetland vegetation during the flooded season and maps of the area of moist soil plant habitat post wetland drawdown. Evapotranspiration rates exhibit significant variation for various wetland moist soil plant types – ET was calculated by applying specific crop coefficients, representative of the wetland moist soil plant vegetation, by potential wetland evaporation (California Irrigation Management Information System, 2009).

3.3. Remote sensing of wetland moist soil vegetation

Estimation of the area of moist soil plant habitat was made using high resolution remote sensing imagery, supported by field surveys of wetland moist soil habitat plant associations. The QuickBird satellite (Digital Globe, Longmont, Colorado) was tasked to provide high resolution, multi-spectral imagery to capture the spatial variability of the patchy and irregularly shaped vegetation communities typical of these wetlands. The imagery provided bands in the blue, green, red and near-infrared (NIR) spectra. Image collection was timed to record the different stages of growth of the dominant wetland moist soil plants throughout the growing season. A late April image typically captures seedlings and perennials in wetland

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basins, and verdant uplands vegetation. May imagery usually coincides with the maximum growth period for the wetland basins, following the first summer irrigation, usually late May to early June. For field data collection and ground-truthing of the imagery, a modified version of the California Native Plant Society's Rapid Assessment Protocol (CNPS RAP) was used. The CNPS RAP employed a community-based approach to surveying, and provided a methodology for collecting basic quantitative information sufficient for identification and verification of habitats. Parameters collected included composition and abundance information on the sampling locations' plant species, their state of health and growth stage. General site environmental factors were also tabulated, including litter cover, anthropogenic disturbances, the presence of visible salts, and soil cracking. A Trimble GeoExplorer 3 GPS was programmed to include sufficient of these factors as data fields to define a vegetation community. Data was post-processed via differential correction to increase on-ground accuracy to less than 2 m. Data was collected with a single point representing a community of vegetation. Field personnel worked in teams, defining the boundaries of a homogenous area, visually estimating the size and shape of the area, and then characterizing it according to the field protocol.

Pixels and ground truth points were assigned to one of twenty land cover classes. Vegetation land cover classes were developed from observations of the dominant species in each vegetation assemblage at ground sample points. The decision to combine two or more dominant land cover classes into a single class was based on the similarity of their habitat, the frequency of their co-occurrence on the landscape, and the amount of spectral confusion between the classes that was observed in the check point dataset. The complexity of the seasonal wetland landscape intensified the difficulty inherent in developing a representative classification schema – given that the twenty land cover classes in this schema did not represent the entire diversity of plant species that exists in these wetlands. Rather, it represents the most commonly observed dominant plant species.

Pixel-based image processing was performed on the high resolution imagery using ERDAS (Leica Geosystems, Norcross, Georgia) Imagine Professional. A maximum likelihood classifier, which has been found to give superior results in mapping wetlands (Ozesmi and Bauer, 2002), was selected for analysis of the images. This technique required the input of the training data, used by algorithms to define statistically based spectral bounds for each class. After the training area was defined, the image processing software compiled statistics that described the spectral values for those pixels. This process was repeated until a signature for each ground truth point was determined. The final result was a compilation of 262 spectral signatures used by the classification algorithm. A pixel-based land cover map for the North Grassland Water District and San Luis National Wildlife Refuge (approximately 50% of the land area of the GEA) is shown in Fig. 6. The legend shows the sixteen wetland moist plant associations that were used to classify the vegetation and that were also used to assign wetland crop coefficients to calculate wetland ET for the flow and salinity mass balance model.

3.4. Groundwater water table sensors

Monitoring of the depth to the water table below each pond is important to the estimation of water loss through seepage, especially during initial pond flood-up when the underlying clay soils are desiccated and fissured with deep cracks – causing high initial seepage losses. During early September, when wetland flood-up typically begins, seepage losses to groundwater have been estimated to be as high as 30% of applied surface water. Wetland pond soils desiccate during the summer months in the San Joaquin Valley when temperatures can exceed 40 °C and fissure to depths of up to 1 m owing to the high clay content of the soils. Water fills the cracks in the soil and the soil swells – closing the fissures and slowing down infiltration. Infiltrating water fills pore spaces causing a rise in the water table. For many ponds that are not subjected to regional drainage gradients (which relieve groundwater mounding below the pond) the vadose zone can become completely saturated. Pond seepage can be estimated by the rate of rise of the water table using estimates of shallow aquifer porosity.

Schlumberger Diver pressure sensors (http://www.swstechnology.com/equipment_product.php?ID=5) were attached to 4 m lengths of plastic-coated cable and fixed to the well cap of each monitoring well (Fig. 7). Although technology exists to telemeter the pressure and temperature data that are produced by each sensor – the fact that groundwater levels change slowly and incrementally over time – made it more cost effective to make periodic downloads of the data during each field site visit. Inexpensive Bluetooth and radio telemetry options are being considered to improve the efficiency of data collection from remote groundwater monitoring locations. RTSM, which is concerned with wetland drawdown and drainage volumes, is not impacted by changes in water table – however these data are critical for estimates of annual water and salt balances.

3.5. Remote electromagnetic sensing of wetland soil salinity

Remote sensing of wetland soil salinity content was used as an indirect check on wetland salt balance – and to assess the distribution of salts within each wetland pond. Ponds managed for swamp timothy production (the most productive of the moist soil plants used to provide waterfowl habitat) are typically drawn down in mid-March – a schedule that appears to favour swamp timothy dominance. RTSM solutions would suggest that wetlands be drained later, in mid-April, since San Joaquin River assimilative capacity is higher during this period when major releases are made from east-side reservoirs to aid fish migration. The impact of a delayed drainage hydrology on the ecological health and productivity of these wetlands as a food source for migratory waterfowl are not well-established although experience suggests a vegetation shift from swamp timothy dominance to watergrass dominance as the most likely long-term outcome (Mushet et al., 1992). The warmer temperatures in April result in increased pond evaporation which produce higher concentrations of salts in those ponds still inundated. Higher concentrations of salt in the water column will affect soil salinity as saline water infiltrates or diffuses into the wetland soil.

An electromagnetic sensing instrument (EM-38 Geonics Ltd. – http://www.geonics.com) was used to estimate bulk soil salinity in the wetland ponds (Fig. 8). The EM-38 instrument utilizes dual coil electromagnetic induction to obtain a signal response which is a function of both bulk soil salinity and soil moisture content. When water content is controlled – the instrument can be used (McNeill, 1980) to map near-surface soil salinity (Suddeth et al., 2005; Williams and Hoey, 1987). The EM-38 can be used in two different orientations; vertically or horizontally. The peak signal strength for the horizontal and vertical orientations are between 0–0.3 m and 0.3–0.6 m respectively. Software has been developed by the US Department of Agriculture Salinity Laboratory (ESAP – http://www.ars.usda.gov/Services/docs.htm?docid=8918) to convert the raw EM-38 signal to electrical conductivity (EC) after soil cores have been drawn and the saturated soil extract salinity determined at sample sites chosen by the program to conform to a normal distribution within each pond (Cassel, 2007; Corwin et al, 2003; Rhoades et al., 1989). The EM-38, along with a backpack GPS system (Trimble Inc. – www.trimble.com) was deployed with a hand-held PC (Juniper Systems, Allegro Cx – http://www.junipersys.com/products/products.cfm?id=99). Data logging was performed with

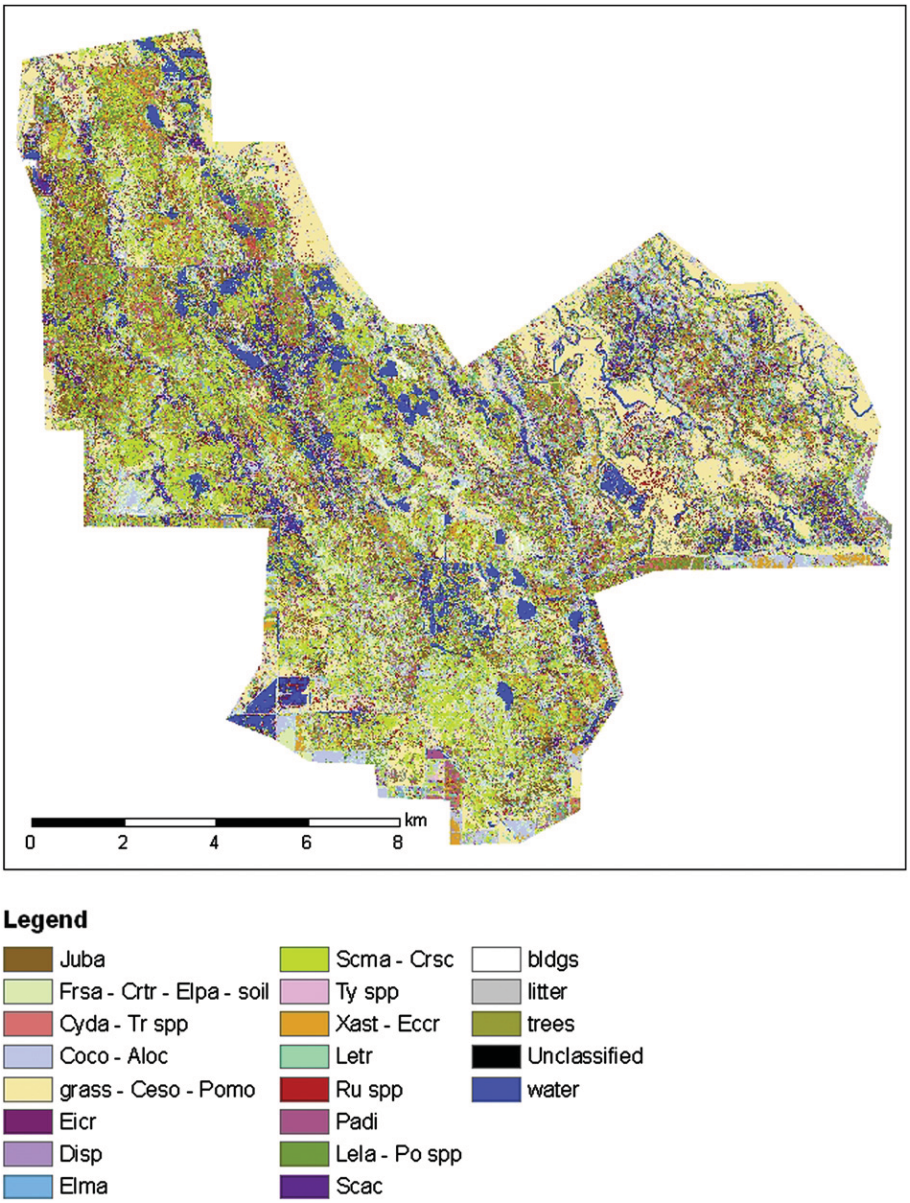

Fig. 6. Moist soil vegetation map derived from high resolution remote sensing imagery and analysis using ERDAS-Imagine software. Ground-truthing provided the spectral signatures associating spectral data and specific wetland moist soil plant associations (shown in legend).

the aid of TrackMaker software (http://www.kdjonesinstruments.com/uploads/files/pdfs/TrackMaker31.pdf) which helps the field analyst visualize each transect of the field survey while being performed by foot or GPS-enabled ATV. The EM-38 instrument has been widely used to assess soil salinity in agricultural areas (Corwin and Lesch, 2003, 2005a,b; Isla et al., 2003; Lesch and Corwin, 2003; Lesch et al., 2005; Cassel, 2007) though its use in wetland soil applications has not been previously reported. Factors to be considered in wetland soil salinity remote sensing include variations in soil texture and taxonomy, soil moisture, topography, vegetation and litter cover which all affect electromagnetic response (Hanson and Kaita, 1997; Suddeth et al., 2005; Brevik et al., 2006).

The instrumentation used in the field survey and its deployment is shown in Fig. 8. The right-hand panel in Fig. 8 shows the individual survey points along each transect for two adjacent wetland ponds. Readings were taken every 2 s and the transects were spaced approximately 5 m apart. The results of the survey of the Ducky Strike Duck Club south pond (one of twenty four ponds surveyed) are shown in Fig. 9. Fig. 9 shows the raw and model-derived (based on the regression model between laboratory saturated extract soil salinity and field EM readings) sensor data from the EM-38 instrument. Fig. 9 also shows the frequency distribution of salinity measurements over the wetland area and the control measurements made at selected sample sites to represent the full range of wetland soils salinity readings.

Data collected over a period of 3 years for ponds subjected to late wetland drawdown has shown a statistically significant increase in soil salinity due to the practice of delayed wetland drawdown in those ponds subjected to the highest influent salinity concentration. Water delivery to ponds in the south of the Grassland Water District is typically higher in EC than those Northern Division owing to the fact that the Northern Division receives

Fig. 7. Deployment of pressure sensors in shallow groundwater monitoring wells to measure changes in water table depth and to estimate pond seepage losses during fall flood-up.

a better quality water supply than the Southern Division. Evapoconcentration of salts leads to higher soil concentrations in those areas where influent salinity is highest. This also suggests that adoption of RTSM should require rotating a particular wetland back to a more traditional hydrology after two seasons of delayed drainage drawdown or in instances where the salinity of influent water supply becomes elevated.

4. Discussion

Integration of the sensor technologies described in section 3 into a fully functional EDSS is work in progress, although in reality, successful EDSS projects are rarely finished if they continue to innovate. New sensor technologies and improvements to data management and visualization software are embraced when trained personnel can be assigned to take on new tasks and fiscal budgets allow this expansion. Budgets need to be justified in terms of long-term resource management efficiency and economies of innovation. Institutional changes will also be required over the longer term to accommodate the reality of Basin-wide RTSM.

4.1. Data quality control and assurance of continuous data

A common weakness of many environmental decision support projects that rely on the telemetry of continuously monitored data is data quality assurance. Data quality assurance is easier to provide for discrete or periodic monitoring where adequate time exists between sample collection events to analyze data and make corrections to the instrument software, in the case of sensor drift, or replace a sensor in the case of irreversible sensor failure. Data quality assurance protocols established for discrete environmental sampling are well-established and data quality control plans are integral components of most environmental monitoring projects. However in the case of continuously recorded and reported data – the logistics of monitoring site visitation, data management, processing and error correction become more onerous. Until recently, few software tools existed to facilitate and guide these tasks – even the task of migrating preliminary data from one internet-accessible location to another (after data quality assurance tasks have been performed) has not been routinely practiced. Inaccurate or absurd data posted to a project website can do irreparable harm to a project and can quickly lead to a loss of confidence in the stakeholder community. In our wetland salinity management project cumulative flow calculations, which were performed by our acoustic Doppler instrument, were accurate when downloaded directly from the data collection platform through the output data processor but were 100 times too high when intercepted prior to output processing using an SDI-12 device (these readings should be identical). The issue was eventually resolved and turnedout to be a programming error in the firmware – a decimal point was omitted in the program and re-inserted during output processing. This error was caught by one of our project cooperators, who had become a routine user of project real-time data. Our close working relationship prompted early feedback from this cooperator and relatively quick recognition and resolution of the problem. This is not typical – problems such as these often fester within the stakeholder community before coming to light – by which

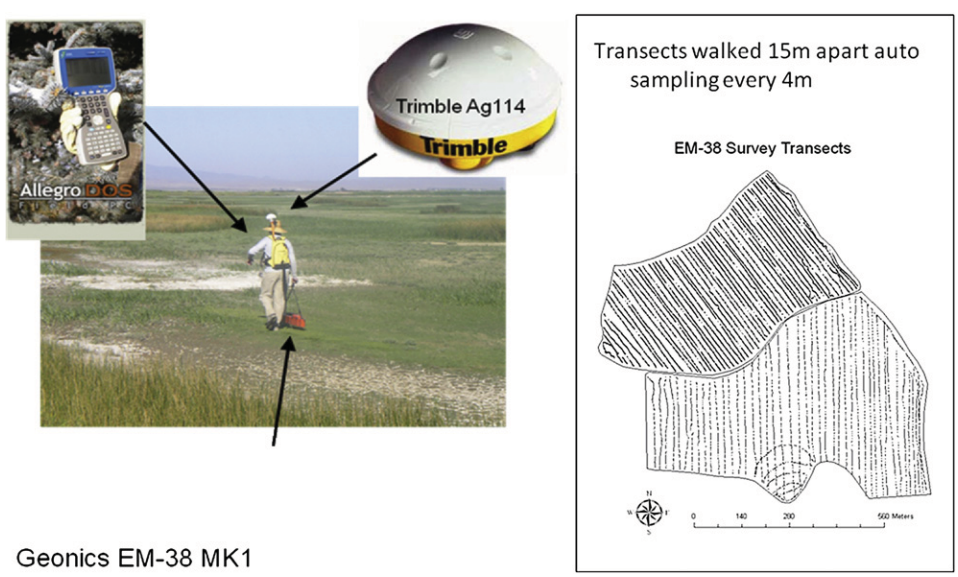

Fig. 8. Instruments used to perform soil salinity mapping of wetland soils in the Grasslands Ecological Area. Image shows the field analyst traversing a large area of swamp timothy, a non-native grass that is nevertheless regarded as highly desirable as waterfowl habitat. A patch of salt efflorescence appears in front of the field analyst – high soil salinity limits moist soil plant growth in these areas.

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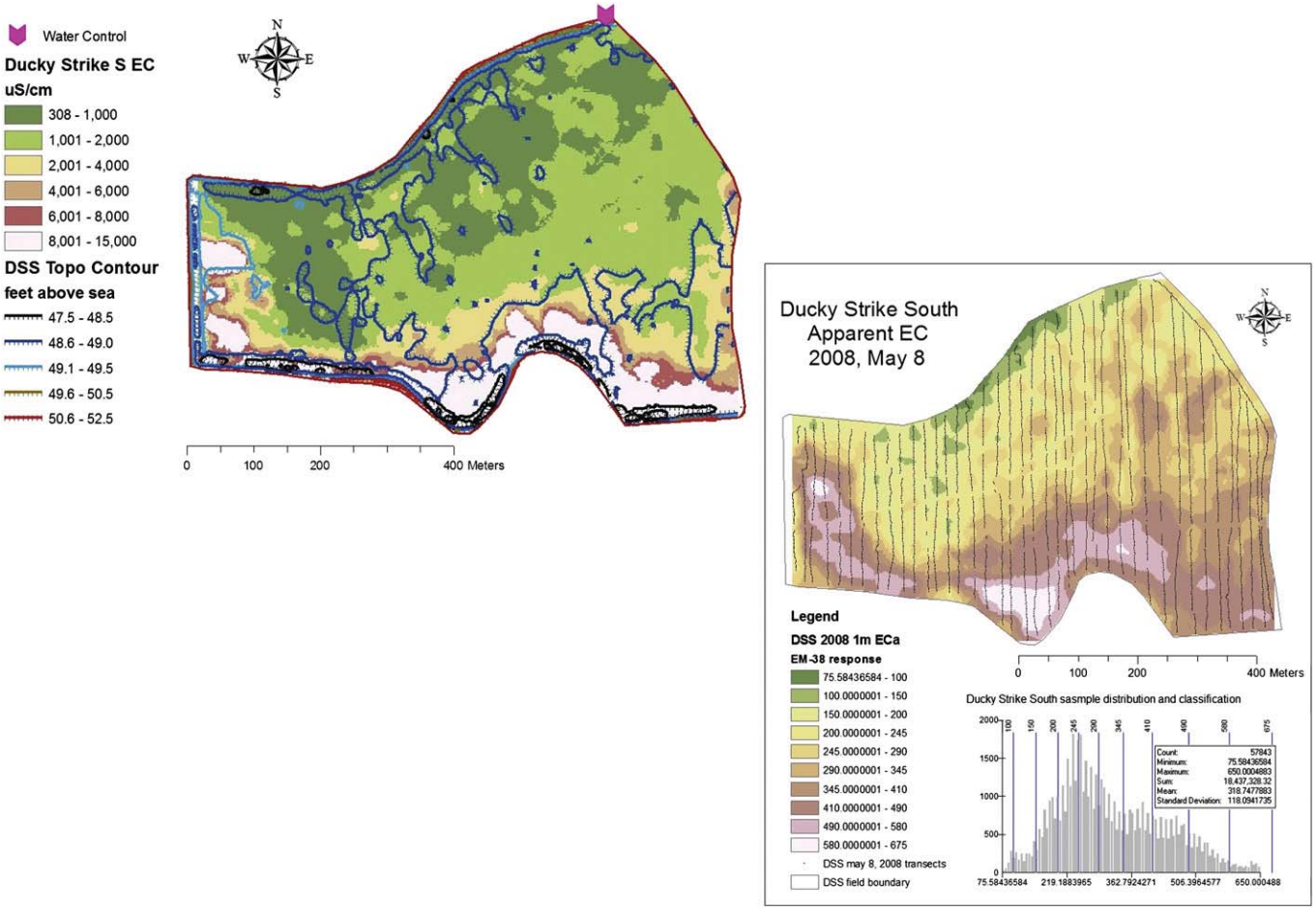

Fig. 9. Map of EM-38 response developed from a soil salinity survey of a wetland pond. These readings are converted into soil salinity estimates based on a regression model developed between instrument readings and saturated extract soil salinity from field samples. The sample locations are chosen using software which ensures that the sample values fall across a normal distribution.

time enthusiasm for the project and trust between project proponents and the stakeholder community has been eroded.

4.2. Software tools for continuous data quality assurance

The Aquarius Environment Toolbox (Aquatic Informatics Inc., 2009) is a suite of software object modules used to manage the entire data processing workflow from the project flow and water quality monitoring stations. The software object modules relevant to the wetland salinity management project include those responsible for: *Data Pre-Processing; Data Correction; Modeling;* and *Output Visualization and Reporting*. The Aquarius Whiteboard environment is used to assemble the sequence of object modules that comprise the data processing workflow (Fig. 10).

The *Data Pre-Processing* module comprises software objects for *Signal Joining* and *Signal Trimming*. The *Signal Joining* object is used to append multiple time series data files during each data download so that a complete data record can be compiled within a local database. Storing the data in a local database after performing data quality assurance allows the certified data to be uploaded routinely to the NIVIS Data Center, which previously provided access to uncensored real-time data. The *Signal Trimming* object is used to trim outliers and periods of incomplete data records from the data record before being stored in the database. At the beginning of the project technical problems such as bad circuit boards and poorly sealed acoustic Doppler sensors produced periods of incomplete or suspect records which had to be removed from the data record.

The *Data Correction* object is used to apply manual adjustments to time series datasets. Autonomous collection of data results in anomalies such as biases, drifts, outliers, and non-physical data. Hence, the *Data Correction* object is used to apply corrections for sensor drift (not typically a problem with the water quality (YSI) or acoustic Doppler (MACE) instruments) or sensor fouling (a significant problem in the wetland environment of the project). For example a *Fouling Drift* correction is used routinely to compensate for biological fouling or scaling of the water quality sensor that tend to skew readings in a progressive fashion as the biological film or scale develops. Standard practice for quality assurance is to take a single measurement from a sensor immersed in a control solution both before and after cleaning. A more time and cost effective protocol, practiced in the current project, was to calibrate a portable YSI sonde (comprising EC, temperature and pressure sensors) in the laboratory before and after each day in the field. The sonde at each monitoring station was calibrated against the ambient portable sonde sensor reading. The sonde EC sensor was recalibrated if the readings differed from the value of the standard solution by 5% or greater. Pressure transducers in both the water quality sonde and acoustic Doppler instrument remained stable requiring little adjustment. Monthly removal of biological growth surrounding the pressure transducers was sufficient to keep the transducers from drifting – except in the

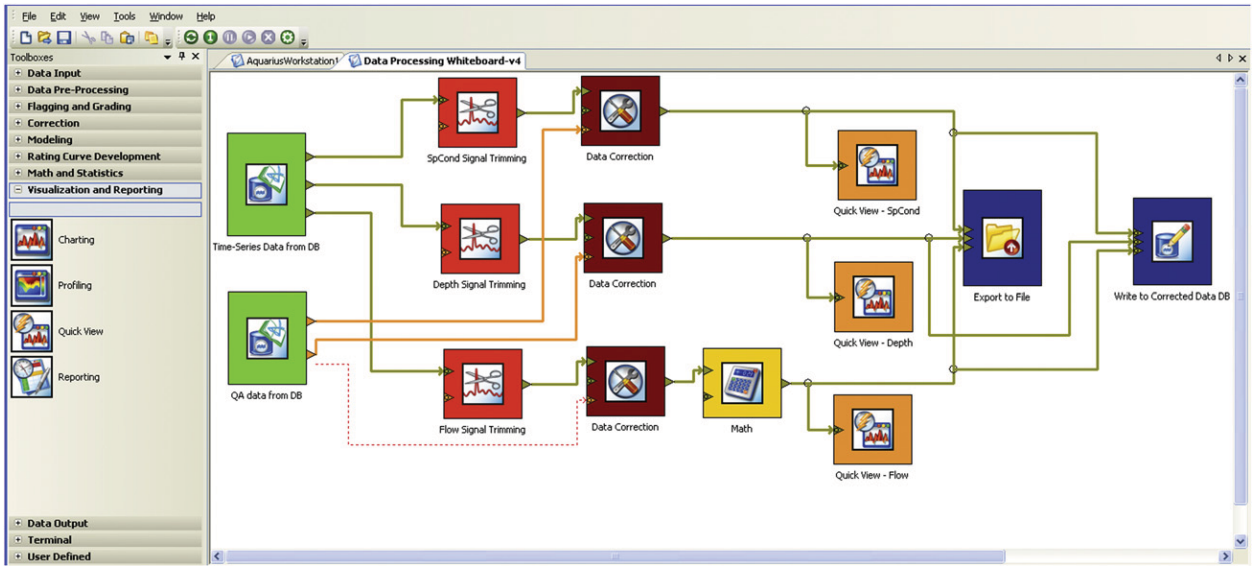

Fig. 10. Data processing whiteboard within the Aquatic Informatics Aquarius software. Continuous environmental monitoring data is merged with weekly quality assurance data collected at each monitoring station to allow continuous error checking and data corrections to take place. RTSM requires continuous data processing to allow daily salinity assimilative capacity forecasts to be made.

instances of catastrophic failure where improper sealing with epoxy allowed moisture migration into the sensor housing.

When using the Aquarius software each correction made to the time series data was recorded in the Correction History Manager which logs information about the correction and makes an entry in the correction history (Aquatic Informatics Inc., 2009). Comments describing the correction appeared in small text that is auto generated and can be modified, if necessary, to increase the amount of information for a subsequent correction audit. Offset adjustments were made to correct for any constant (throughout time) bias in the target time series data. Offset adjustments were necessary when a sonde had to be replaced or a sonde moved higher within the stilling well as a result of sediment accumulation around the base of the stilling well. This accumulation of sediment affected water circulation around the electrical conductivity and temperature sensors. Within the Aquarius software the *Mark Region* tool was used to select a section of the target time series where the *offset correction* could be used to adjust readings upwards or downward. The *percent correction* featured in the correction control pane of the software allows the user to apply a calculated known percentage correction to the signal at either the beginning of the data sequence or at the end. Data outliers were be removed using these tools and short data gaps were interpolated without resorting to a model based correction approach. Data gap interpolation controls provided options that include the application of a *linear spine*, which simply draws a straight line in between the endpoints of the gap; or a *cubic spline,* which uses up to 5 data points outside the range of the marked gap to guess at the curvature of the time series plot using a best-fit polynomial or other non-linear expression. The automated interpolation control options within the Aquarius toolbox were a significant technical advance over existing software and were critical for the anticipated expansion of existing sensor networks necessary to fully implement RTSM. Manual as well as automated interpolation changes was all noted in the *Correction History Manager*. Each time a correction is applied to a section of target time series data the *Correction History Manager* was invoked to capture details about the user performing the correction and the rationale for performing the correction.

The *Modeling* object within the Aquarius toolbox has proved useful in the application of calibration factors to discharge data derived from acoustic Doppler velocity sensors and pressure sensors. Acoustic Doppler velocity devices sample the flow volume either approaching or moving away from the sensor. In open channels with fluctuating stage or in culverts which can flow partially full – it is difficult to obtain a true mean area-velocity owing to the friction along the perimeter of the conveyance structure. Flow rating relationships between reported and actual flow have been developed for each monitoring site and the rating equation built into the modeling object to transform the reported flow value to an actual flow. At a number of monitoring sites weir boards (flash board risers) provide the means of controlling wetland pond stage and pond outflow – at these sites the *modeling object* was first used to calculate discharge using the weir equation which is a function of board dimensions (width and height) and water stage over the weir boards. However the difficulty of maintaining continuous records of weir board adjustments proved too onerous for wetland managers and became a bottle-neck for real-time data reporting. Acoustic Doppler flow sensors were retrofitted at each wetland drainage site to address this issue.

The Aquarius toolbox contains a full suite of *Output Visualization and Reporting* tools that allow easy review and auditing of any data sequence within the time series database at each monitoring site. The *Quick View* object displayed time series data in a spreadsheet format which facilitated plotting and charting and was used to provide descriptive statistics of each sensor time series record. It has been used to create overlay multiple data traces within a single window in order to check the functioning of suspect sensors in the monitoring network as part of the data quality assurance program. Reporting the quality certified data back to the NIVIS website was a feature initially lacking in the commercial release of YSI-EcoNet. The NIVIS Data Center did not permit client access to the data except as served through the NIVIS EcoNet website – rather the Data Center provided a means of discriminating between public and private (password protected) access to the website. This had the unfortunate consequence of restricting public access to current data only, given our cooperators reluctance to share potentially flawed data with the general public, as discussed at the beginning of this paper. Only project personnel and cooperators were provided with private user access allowing these clients to download the time series data record. In late 2009 a solution was negotiated between YSI Inc. and

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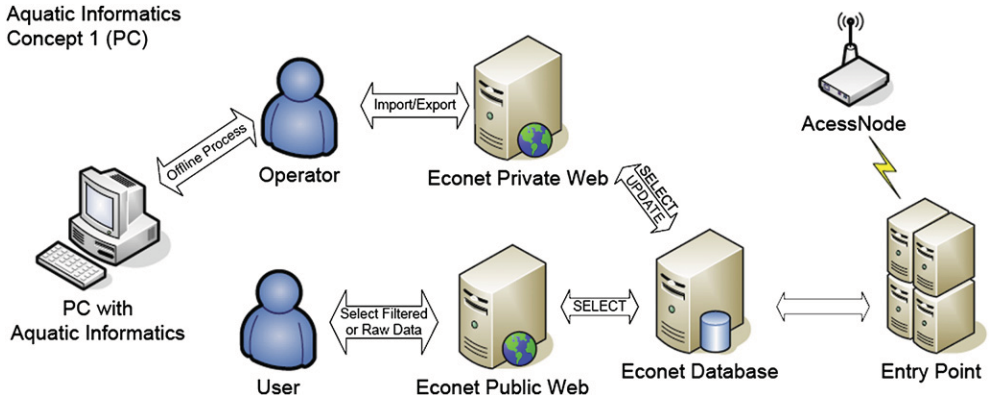

Fig. 11. Protocol for replacing preliminary data on the NIVIS public website with data after quality assurance filtering has been completed.

the NIVIS Data Center that provided a data export wizard and the ability to add a second data column paired with each of the web-reported sensor outputs. The schema for the protocol is shown in Fig. 11. Under this protocol public access clients can view all historic data once they have been migrated into the second column after having undergone data quality assurance procedures.

Private access clients were able to view both columns of data on the project website and had full access to the time series data for all monitoring sites. Automation of the data filtering and web posting process has sped-up stakeholder access time to information needed to make RTSM decisions. These actions will help develop the assurances needed for stakeholders to fully implement RTSM within the San Joaquin River Basin.

4.3. Water quality forecasting and decision support

Successful implementation of RTSM in the San Joaquin Basin requires that salt loads exported from managed wetlands and other west-side dischargers within the Basin never exceed the calculated assimilative capacity of the San Joaquin River. River assimilative capacity (expressed as a salt mass load) was determined by the product of river flow and the ambient water quality standard for salinity, established at the downstream compliance monitoring station. A decision support tool was developed to simulate daily river assimilative capacity and permit forecasting of allowable salt loading from managed wetlands in the Basin based on real-time flow and salinity data.

The Watershed Management Framework (WARMF) model (Chen et al., 2001; Herr et al., 2001; Herr and Chen, 2006) is comprehensive decision support tool specifically designed to facilitate TMDL development at the watershed-level (http://www.epa.gov/ATHENS/wwqtsc/html/warmf.html). The San Joaquin River Basin application of the WARMF model (WARMF-SJR), shown in Fig. 12, simulates the hydrology of San Joaquin River and performs mass balances for a broad suite of potential contaminants including total dissolved solids. The model accounts for tributary inflows from the major east-side rivers, agricultural and wetland drainage return flows, riparian and appropriative diversions and uses hydrologic routing to calculate flow and water quality at approximately 0.8 km intervals along the main stem of the San Joaquin River. Wetland drainage from the Grassland Ecological Area was partitioned into component State, Federal and private wetland contributors to San Joaquin River salt load. A GIS-based graphical user interface (GUI) facilitated the visualization of model input flow and water quality data. Data templates expedited automated data retrieval from State and Federal agency hydrology and water quality databases and the automated updating of model input files. Water managers can enter daily schedules of diversions and discharges using the spreadsheet formatted model data interface. Standardized model output graphics aided the dissemination of flow and water quality forecasts.

A wetland water quality model (WARMF-WETLAND) is under development within the WARMF modeling framework. The model simulates water and salinity balances for individual (and lumped) ponded areas and aggregates wetland discharge and salt loading from all contributing areas. The model allows comparison with (soon to be established) salt loading targets for the Grasslands Ecological Area. Monthly sub-basin, seasonally-adjusted salt load targets are one of a number of salinity management strategies that could be used to encourage cooperation and coordination of wetland drawdown by State, Federal and private wetland stakeholders. Coalition building between stakeholders with like interests and who are required to comply with similar environmental regulations has been effective in California as a means of retaining local control and management flexibility. The new model application will track the salt concentration within each ponded area based on estimated wetland evaporation, seepage and cumulative inflow and outflow and the salinity concentrations of these fluxes. Output from the WARMF-WETLAND model application will overwrite estimated values for the State, Federal and private wetland salt loads in the WARMF-SJR model – to provide a more accurate assessment of San Joaquin River assimilative capacity.

4.4. Institutional accommodation

Realization of the potential of RTSM will require the formation of a watershed-level salinity management entity with the authority to encourage compliance with sub-basin salt load targets and to impose penalties for violation of these established salt load limits. A local coalition of entities discharging drainage to the San Joaquin River formed a "Drainage Authority" to coordinate flow and water quality monitoring requirements imposed by the Regional Water Quality Control Board (the State institution responsible for implementation of TMDLs in the San Joaquin River Basin). This Drainage Authority is financed by stakeholder contributions and retains a staff to oversee the activities of the agricultural, wetland and municipal dischargers of salt and other contaminants into the San Joaquin River. Oversight involves maintenance of monitoring stations, responsibility for discrete sample collection and analysis and monitoring data record keeping. Implementation of RTSM will require a similar institution though with added responsibilities of coordinating both drainage return flows and reservoir releases from east-side tributaries, synthesis of real-time data and dissemination of daily salt assimilative capacity forecasts for the San

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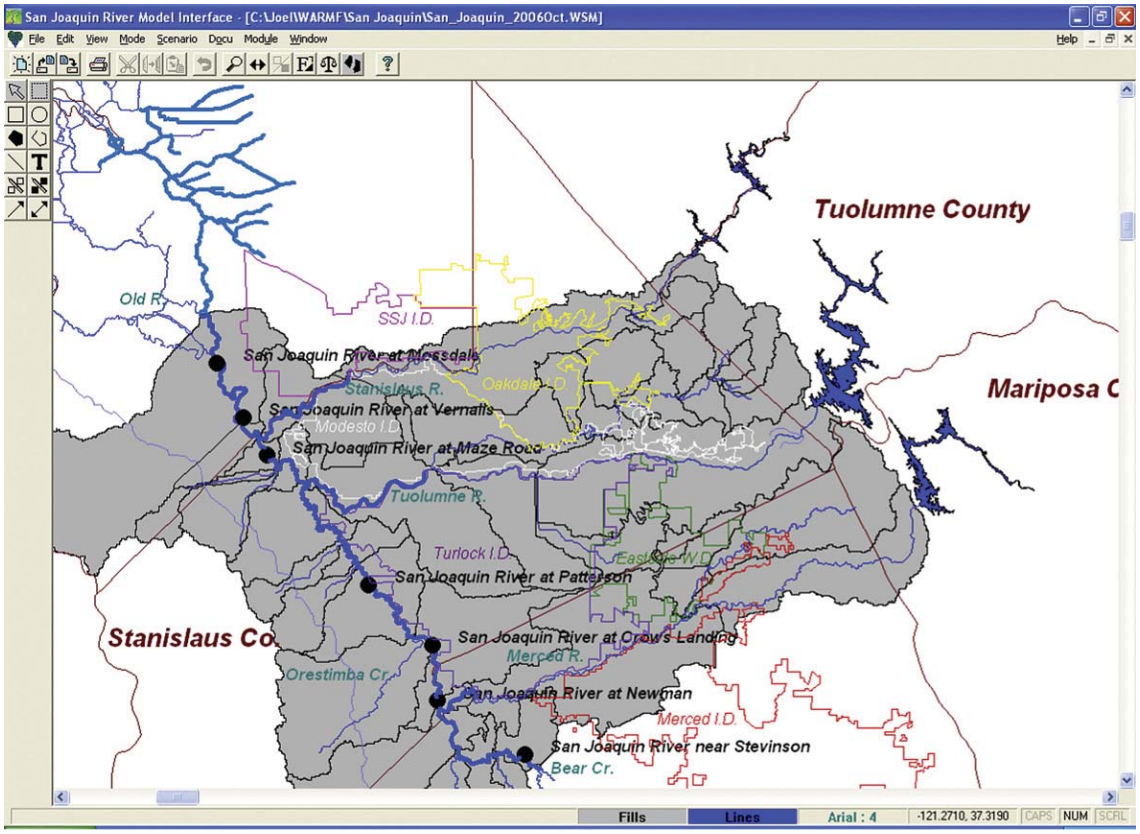

Fig. 12. The WARMF-SJR simulation model is used to develop short-term forecasts of San Joaquin River salt assimilative capacity decision support system as part of the wetland EDSS for salinity management in the GEA. Wetland drainage discharges to the River from the west between the Stevinson and Newman monitoring stations.

Joaquin River. At the present time a conceptual design of this new institution has not been formulated.

5. Summary

Technical advances in data acquisition and information dissemination technologies have made possible the implementation of an RTSM program in California's San Joaquin Basin wetlands. RTSM relies on continuously recording sensors that form the backbone of a monitoring network and simulation models that are used to forecast flow and water quality conditions in the receiving water body and the tributary watersheds that contribute flow and salt load to the river. The application discussed in this paper – RTSM of drainage from seasonal wetlands – relies on a suite of sensor technologies the data from which are used to develop water and salt mass balances. The concept of mass balance is fundamental to all flow and water quality simulation models. Models can be used to extrapolate the results of system monitoring since it is impossible to collect data for every drainage outlet and stream tributary in the Basin. Dividing the San Joaquin Basin into smaller drainage sub-basins each with a monitoring station at their outlet can provide an efficient means of characterizing salt export loading from the GEA to the River and the basis for control to meet salt loading objectives. This paper has described the use of several state-of-the-art sensor technologies that are being combined with more traditional sensor techniques to support RTSM. The paper also discussed the problems associated with continuous data quality assurance and described a new software product which streamlines the process of data error correction and dissemination that will be necessary to build stakeholder assurances key for successful implementation of the RTSM in the GEA.

Acknowledgements

This work was supported by the California State Water Resources Control Board, the U.S. Bureau of Reclamation Science and Technology Program and the California Department of Water Resources. The authors would like to thank the US Bureau of Reclamation, California Department of Water Resources and California Regional Water Quality Control Board who have funded associated research projects over the past decade directed at implementing RTSM in the San Joaquin Basin of California. Thanks also to the Grassland Water District and the California Department of Fish and Game who provide in-kind support to current projects within the GEA. YSI Inc. has provided valuable technical support for deployment of the YSI-ECONET technology in California.

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Please cite this article in press as: Quinn, N.W.T., et al., Use of environmental sensors and sensor networks to develop water and salinity budgets..., Environ. Model. Softw. (2009), doi:10.1016/j.envsoft.2009.10.011