A METHODOLOGY FOR WATER QUANTITY AND QUALITY ASSESSMENT FOR WETLAND DEVELOPMENT

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ABSTRACT. A methodology is presented for water quantity and quality assessment for wetland development which enables planners to evaluate the results of restoring and managing a large wetland complex based on a set of criteria developed under multi-disciplinary guidelines. The methodology includes addressing temporal and spatial variability of climatic data for determination of wetland water requirements; determination of wetland evapotranspiration; determination of critical areas for wetland and agricultural development using GIS; modelling the water delivery system (quantity, quality, location, and timing) of a wetland complex using HEC-5 and WASP; and water management using the GAMS/MINOS optimization program. The methodology is applied through the use of a Decision Support System (DSS). The goal of the DSS is to provide tools for spatial and temporal simulation, evaluation and management of a wetland system. The user has access to a common analysis environment consisting of models and data within a Graphical User Interface (GUI). Simulation and optimization modules, combined with a graphical user interface, permit efficient and convenient study of various resource management scenarios.

1 - BACKGROUND

Once considered noxious, unprofitable places, wetlands are now prized as one of the richest ecosystems on earth (Mitchell et al., 1992). Some of the valuable resources that wetlands provide include wildlife and fish habitat, flood control, clean water, and beauty. Wetlands can range from moist prairie depressions of less than half a hectare to flooded grasslands stretching out for hundreds of hectares such as the Florida Everglades. Wetlands appear in every region and climate of the United States. Rivaling tropical rain forests in productivity, wetlands have been comparably exploited and diminished by development (Mitchell et al., 1992).

Over a 200-year period, wetlands have been drained, dredged, filled, leveled and flooded (Dahl, 1990). At the time of Colonial America, the area that is now the bordering United States contained an estimated 90 million hectares of wetlands (Dahl, 1990). By the mid-1980's, an estimated 42 million hectares of wetlands remained in the continental United States (Dahl and Johnson, 1991)Twenty-two States have lost 50 percent or more of their original wetlands since the 1780's. Fig. 1 shows states that lost more than 50 percent of their wetlands between the 1780's and mid-1980's (Dahl 1990). Ten States (i.e. Arkansas, California, Connecticut, Illinois, Indiana, Iowa, Kentucky, Maryland, Missouri and Ohio) have lost 70 percent or more of their original wetland area. The increase in the appreciation of the ecological and economical value of wetlands, combined with the awareness of how much area has been converted or damaged, has resulted in wetland protection legislation and programs.

Maintaining these wetlands has become difficult because of changes in water quality and availability. High evapotranspiration of polluted drainage water in some areas has resulted in wetlands with high concentrations of selenium and other trace elements. A prime example of where this problem has occurred is the Kesterson Refuge area in the San Joaquin Valley located in California. The possibility exists for similar water quality problems to occur elsewhere with an increasing demand for water and land, and water rights conflicts.

The study area located in the San Joaquin Valley is made up of 9,315 hectares of land with many unique landuse and vegetation types.

2 - MODELLING LANDUSE

The United States Bureau of Reclamation (USBR) Mid-Pacific Geographic Information System Group (MPGIS) has developed extensive and detailed maps for a portion of the San Joaquin Valley of

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California in ARC/INFO (ESRI, 1992), a GIS system. An example map is given in Fig. 2. These maps were imported from ARC/INFO into Geographical Resources Analysis Support System (GRASS) (USACERL, 1993). This information serves as the basis for developing the water features and management development plans.

The GIS provides tools for analysis and display of spatial data, allowing users to model complex resource and environmental systems. The GIS contains wetland use data for the areas being studied for development, and manipulates the spatial data in order to obtain information required for wetland development.

Suitability maps available from the Denver office of the USBR were used as a framework for creating maps of wetland potential and irrigation suitability in ARC/INFO. These maps were labelled and classified using a general soil classification scheme. The maps were indexed to represent different levels of wetland potential and irrigation suitability, and then imported into GRASS. These maps are then used to examine the consequences of spatial requirements of management objectives. By manipulating several layers of spatial data the manager is able to determine the best areas as well as identify problem areas for wetland development.

3 - MODELLING THE WETLAND EVAPOTRANSPIRATION

Wetland water losses to the atmosphere occur from the water and soil (evaporation) and from emergent portions of plants (transpiration), with the combination termed evapotranspiration (Jensen et al., 1990). It is assumed that, for a wetland system, although the presence of vegetation retards evaporation, by increasing shade and humidity and reducing wind near the surface, transpiration by the vegetation compensates for the difference. Wetland evaporation is computed using the Penman (1948) equation. Penman derived the equation assuming a thin free-water surface without heat storage or conduction from below.

$$E = \frac{\Delta}{(\Delta + Y)} R_n + \frac{Y}{(\Delta + Y)} E_a$$

where R_n is the net radiation exchanged, γ is the psychrometric constant (defined by the Bowen Ratio equation), Δ is the slope of the saturation vapor pressure vs. temperature curve at air temperature , T_a, E_a is the evaporation given by $E= (e_o – e_a)(a+bv)$ [Dalton type equation], e_o is the vapor pressure at the water surface, e_a is the vapor pressure at some fixed height in the overrunning air, and v is the wind speed at some fixed height.

Vegetation type is assumed not to be a significant factor in wetland water loss determination. For a crop coefficient, Kc, rice is assumed to be the best representation of a wetland system. The California rice reference (two years of Bowen ratio measurements of rice ET) is 2 to 5% more than grass (Lourence et al., 1970), therefore the (wetland) crop coefficient, Kc, rice/ETo is approximately equal to 1.05.

Calculated values of evaporation for wetlands were compared with historical values of ETo in California at Los Banos Reservoir, as shown in Fig. 3. GIS is then used to determine the spatial water requirements for wetlands based on existing landuse. GRASS calculates the areas for each landuse type in each management unit. The areas are then multiplied by the corresponding wetland evapotranspiration rate to determine the spatial wetland evapotranspiration requirements.

MODELLING THE WATER DELIVERY SYSTEM

The GIS coverages containing the landuse types together with maps of existing canals and aerial photos, are used to delineate a water delivery network. Wetland areas are lumped together into a management unit which is treated as a reservoir for water quantity and quality simulation. The network of management units that is being used to model the San Joaquin Valley is shown in Fig. 4.

HEC-5 (U.S. Army Corps of Engineers, 1982; and U.S. Army Corps of Engineers, 1989) is used to operate the system and determine how water is allocated to the management units. Each management unit is treated as a shallow reservoir. The models attempts to satisfy the constraints at individual management units, to maintain specified flows at downstream control points, and keep the system in balance. The results from HEC-5 are imported into the WASP (EPA, 1991; Abrose et al., 1991; and Abrose et al., 1993) model for water quality simulation (total dissolved solids) throughout out the system.

WATER MANAGEMENT USING MATHEMATICAL OPTIMIZATION

Once inflow amounts and concentrations for each Management Unit (MU) are calculated, it is necessary to determine how to operate the system. For each management unit, it is necessary to develop how much water should be provided and drain from each landuse type such that water quantity and quality requirements for each habitat are satisfied. An example of five representative MUs is given in Fig. 5. In addition, standards for effluent from the wetland system into the San Joaquin River must be satisfied.

The problem formulation requires inclusion of several water exchange processes taking place in a wetland system. Exchanges occur to the atmosphere through vapor losses, which affect water quality by increasing concentration. Losses occur to groundwater through seepage. Incoming flows increase the volume of a wetland and may increase or decrease existing concentrations, depending of the quality of the incoming water. There are system limitations on conveyance and maximum and minimum amounts to each wetland. The hydrological complexity and temporal variability of the variables results in a large scale model with more than a thousand variables and constraints. The program selected to solve the wetlands water management model is GAMS/MINOS (Brooke, 1988) which uses MINOS 5.2 as the solver and GAMS as the preprocessor and compiler. MINOS 5.2 (Modular In-Core Nonlinear Optimization System) is a FORTRAN-based system designed to solve large-scale optimization problems that can be expressed by smooth, linear and/or nonlinear functions (Murtagh and Saunders, 1987). The problem is essentially a nonlinear problem because the concentrations can change. The problem is solved by successive approximations. There is a successive recalculation for updated concentrations until convergence is achieved. Based on Fig. 5, the general formulation of the linear programming problem is given as follows. The objective function of the problem is:

$$Min\left(\sum_{i=1}^{5}\sum_{j=1}^{3}\sum_{t=1}^{12} c1\bullet(SHORT_{i,j,t}+EXCESS_{i,j,t})+\sum_{i=1}^{5}\sum_{j=1}^{3}\sum_{t=1}^{12} c2\bullet MMAX_{i,j,t}\right)$$

where: i = management unit number (1: China Island; 2: Freitas; 3: Salt Slough; 4: East Gallo; 5: West Gallo); j = landuse type (1: permanent wetlands; 2: seasonal wetlands; 3: agricultural areas); t = time period (1: january,., 12: december)

The objective function is composed of two terms. The first term attempts to meet, as closely as possible, the required volumes in the wetlands by minimizing any shortage or excess. The second term minimizes the variable MMAX, representing any deviation from achieving salt mass balance.
The constraints of the problem are the following for any management unit "i", landuse "j", and time "t":

1. The existing volume should satisfy bounds on minimum and maximum allowable volume:

$$VMIN_{i,j,t} \leq VE_{i,j,t} \leq VMAX_{i,j,t}$$

2. The volume mass balance should be satisfied which equates volume at the next time period (t+1) to volume at period (t), plus the inflow volume, less evapotranspiration losses, less seepage losses, and less the outflow volume:

$$VE_{i,j,t+1} = VE_{i,j,t} + VIN_{i,j,t} - ET_{i,j,t} \cdot acoeff \cdot VE_{i,j,t} - S_{i,j,t} \cdot bcoeff \cdot VE_{i,j,t} - VOUT_{i,j,t}$$

The required volume should equate the existing volume, plus any shortage, or minus any excess:

$$VE_{i,j,t} + SHORT_{i,j,t} - EXCESS_{i,j,t} = VRGIVEN_{i,j,t}$$

4. The mass (concentration times volume) at period (t+1), minus the mass at period (t), minus the mass input, plus the mass outflow, plus the mass lost to seepage should be bounded by [-MMAX, MMAX]:

$MMAX_{i,j,t}\ ^{3}\ VE_{i,j,t+1} \cdot CE_{i,j,t+1} - VE_{i,j,t} \cdot CE_{i,j,t} - VIN_{i,j,t} \cdot CIN_{i,j,t} + VOUT_{i,j,t} \cdot CE_{i,j,t} +$
$S_{i,j,t} \cdot VE_{i,j,t} \cdot CE_{i,j,t}\ ^{3}\ -MMAX_{i,j,t}$

Notice that minimization of MMAX results in minimizing the maximum deviation in salt mass balance.

5. The sum of volumes from all landuse "j" should not exceed the maximum conveyance capacity:

$$\sum_{j=1}^{3} VOUT_{i,j,t} \leq VOUTMAX_{t}$$

6. Initial volumes for any management unit "i", landuse "j" is given by:

$VE_{i,j,jan} = VEINIT_{i,j}$

where: VOUTi,j,t=outgoing volume from management unit "i", landuse "j", time "t"; VEi,j,t =existing volume in management unit "i", landuse "j", time "t"; VINi,j,t =incoming volume into management unit "i", landuse "j", time "t"; VEINITi,j=initial volume for management unit "i", landuse "j"; VMAXi,j,t=maximum allowable volume for management unit "i", landuse "j", time "t"; VMINi,j,t=minimum allowable volume for management unit "i", landuse "j", time "t"; EXCESSi,j,t =excess volume in management unit "i", landuse "j", time "t"; SHORTi,j,t=shortage volume in management unit "i", landuse "j", time "t"; VOUTMAXi=maximum conveyance capacity outside management unit "i"; COUTi,j,t=concentration of drainage water leaving management unit "i", landuse "j", time "t"; CEi,j,t=existing concentration of water in management unit "i", landuse "j", time "t"; MMAXi,j,t=upper bound for the salt mass balance at management unit "i", landuse "j", time "t"; -MMAXi,j,t=lower bound for the salt mass balance at management unit "i", landuse "j", time "t"; Si,j,t=seepage coefficient at management unit "i", landuse "j", time "t"; ETi,j,t =evapotranspiration coefficient at management unit "i", landuse "j", time "t"; C1 and C2=weights in the objective function.

The optimization model is run using monthly intervals for a total period of 12 months. The model was tested to determine how it allocates water under stress conditions, that is, when supply of water is limited in quantity and/or quality. The model effectively allocates water based on availability of supply water and existing conditions and requirements of the wetlands. These requirements include both the quantity and quality of the water allocated. The criteria used to allocate water depends on the objective of the manager. The coefficients in the objective function allow the user to prioritize and to define whether the model will first satisfy the required volumes in the wetlands, or emphasize the concentration times volume mass balance equation at each wetland. Priorities for which management unit and/or landuse type should be supplied and/or drained can also be specified in the constraints of the model. Application of linear programming guarantees a feasible and globally optimal solution to this problem and the ability to perform sensitivity analysis. The successive approximation procedure represents a decided advantage over solving a large-scale nonlinear problem with volumes and concentrations all considered variables.

CONCLUSIONS

A methodology is developed through a graphical user interface to anticipate the effects of management scenarios for wetland resources. GIS is used to model the landuse to determine the areas most suitable for wetland development, and to spatially determine the wetland water demands. Wetlands are lumped together into management units for water quantity and quality simulation. Water supply quantities are simulated using the U.S. Army Corp. of Engineers HEC-5 model. The water quality of the area is simulated using the U.S.Environmental Protection Agency WASP model. Once the inflow amount and concentration of each management unit is determined, an optimization model is developed to assist in managing the water to the various wetland types within a management unit, and to keep the effluent standards of the whole system within desired levels. The model takes into consideration the several water exchange processes taking place in the wetland system including losses, dilution and concentration.

The methodology is developed by blending the following technologies: decision support theory, geographic information systems (GIS), spatial modeling, water demand estimation, surface water modeling, water quality modeling, habitat management, and mathematical programming. The methodology allows the integrated analysis of physical, biological and chemical interrelations for an ecological systems that varies in time and space. It provides the ability to create different landuse scenarios and explore development alternatives.

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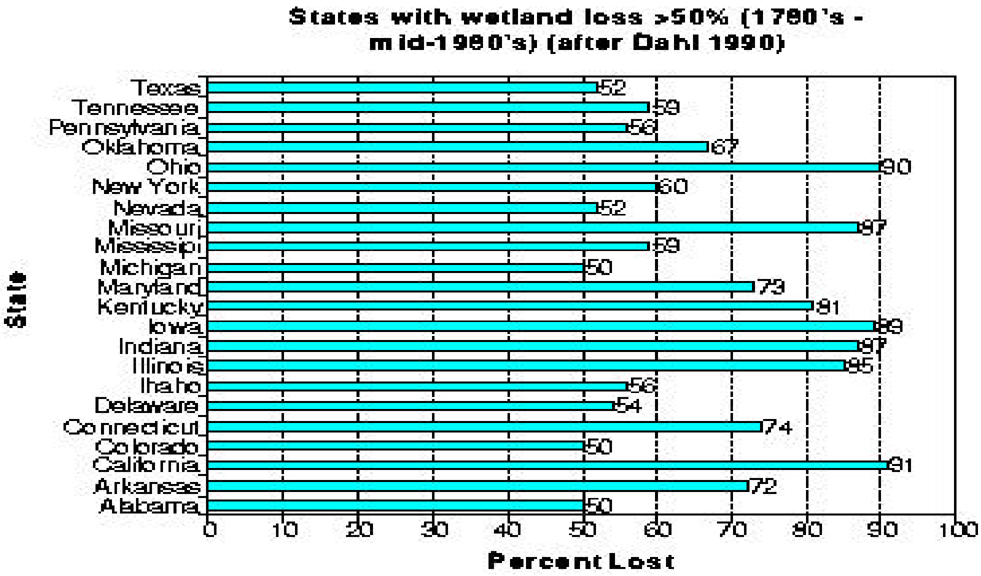

Figure 1. States with wetland loss > 50% (1780s – mid-1980s)(after Dahl, 1990)

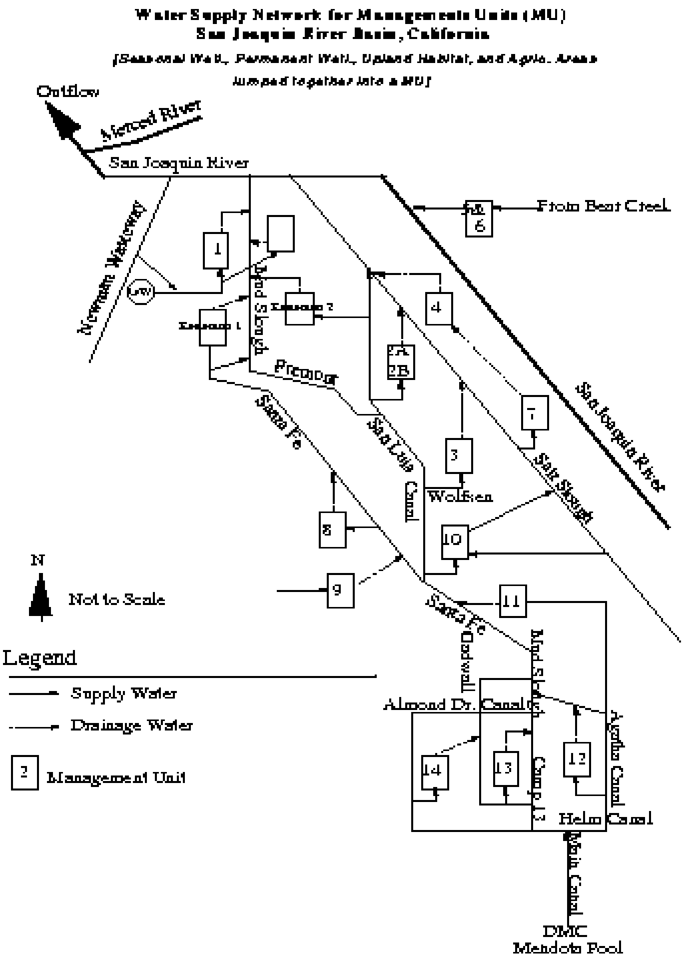

Fig. 4. Water Supply Network for Management Units (MU), San Joaquin Valley, California. (Seasonal wetlands, permanent wetlands, upland habitat, and agricultural areas lumped together into a MU).

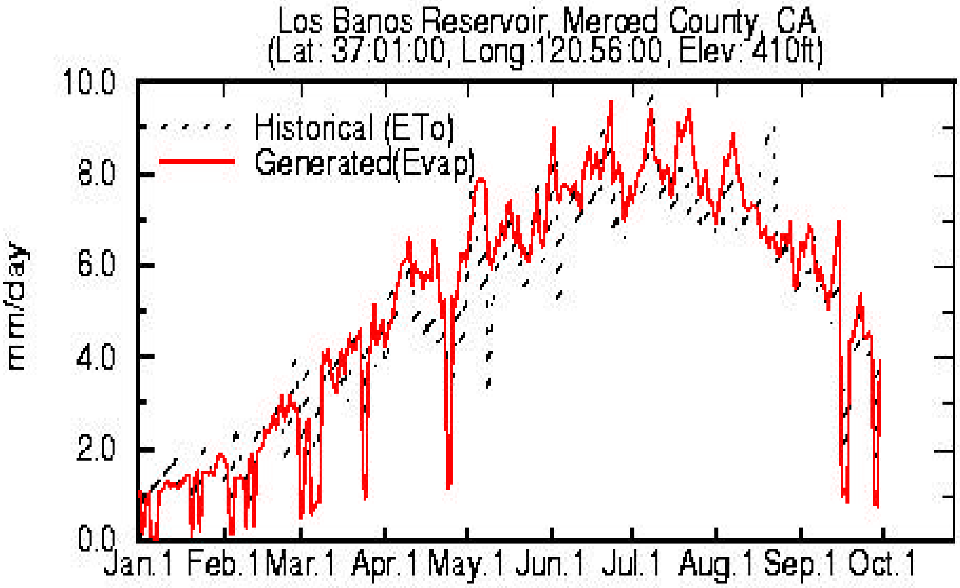

Fig. 3. ET (mm/day) for Los Banos Reservoir, Merced County, CA

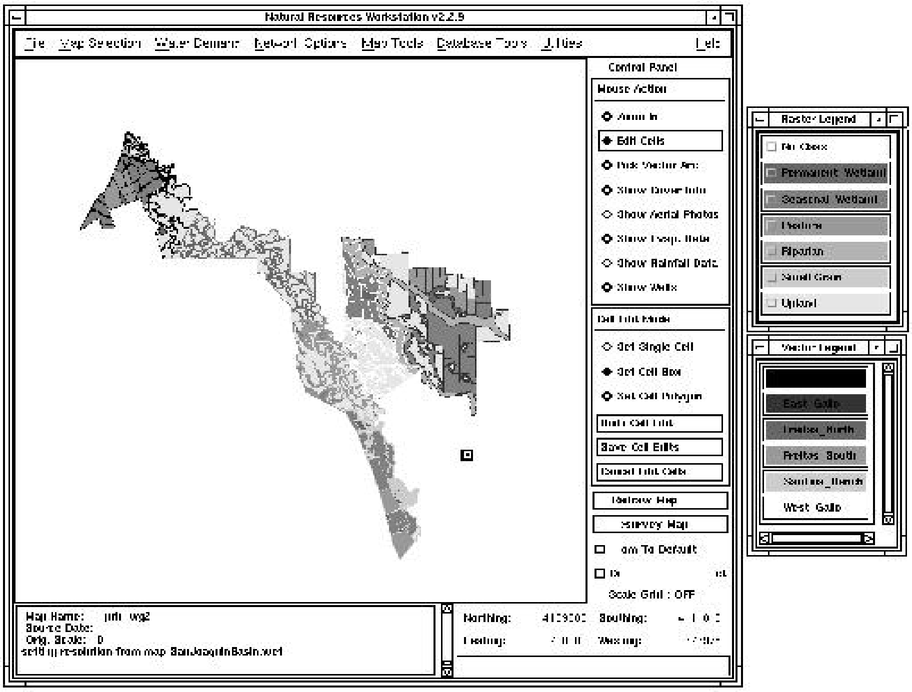

Fig. 2. Cover Types Map

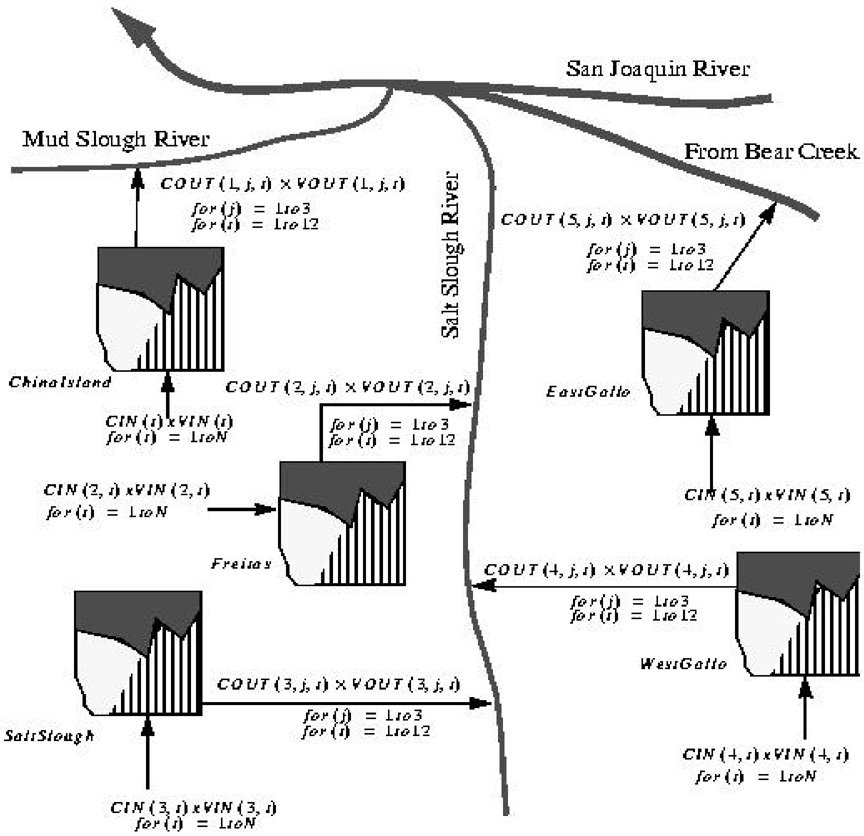

Fig. 5. Management Units - San Joaquin Valley Basin, California