Two- and Three-Dimensional Hydrodynamic Modeling of the Salton Sea, California

Christopher B. Cook, Student Mem. and Gerald T. Orlob, Fellow, ASCE

Abstract

The Salton Sea, the largest surface water body in California, faces a myriad of problems related to rapidly changing water levels, rising salinity, accelerated eutrophication, fish kills, and potential physical alteration of its bathymetry. In the initial phase of a comprehensive study to resolve these problems two- and three-dimensional hydrodynamic models have been applied to characterize circulation and transport processes. Because of the Sea's large size, relatively shallow depth, exposure to perennial winds, and small hydrologic influxes, the hydrodynamics of the system have been assumed initially to be driven solely by wind and Coriolis forces. Wind-induced friction on the Sea's surface was generated by imposing a representational steady regional wind derived from statistical analysis of observations at three weather stations situated on the north, west, and southeast shores of the Sea. Initial simulation results suggest the presence of several large gyres within the water body, located within the northern and southern basins. A comparison of two- and three-dimensional representations is provided. Preliminary studies of proposed salinity control barriers that would isolate portions of the Sea indicate potential adverse effects of physical modification of the Sea's bathymetry. Critical concerns for future control of water levels and salinity focus on wind-induced circulation, water and salt balances, and pollution by tributary sources.

Introduction

The modern day Salton Sea, often referred to as the largest "man-made" water body in California, was formed late in 1904 as the result of a temporary levee break along the Colorado River. For a period of about 16 months thereafter water flowed through this break into the below-sea level depression, then known as the Salton Sink, filling it to a depth of more than 24 meters above its lowest elevation, approximately 85 meters below mean ocean sea level (msl). Since that time the water level in the Salton Sea has been seeking a balance between the harsh desert forces that extract water by evaporation, the only mechanism for removal of water from this land-locked depression, and inflows of water from surface and subsurface sources. For a time following closure of the levee break, water levels declined rapidly, as evaporation greatly exceeded inflow. A minimum level was reached in the 1920's, after which the level of the Sea once again began to rise, due in major part to importation of water for agriculture. By the 1990's water level elevations were recorded exceeding -69.6 meters msl. Rising water levels encroached onto private property, causing loss of usable land and damage to property by flooding.

Salinity History

During the course of historical changes in the Sea's water balance, its salinity has also changed. Initially the salinity of the Sea was about that of the Colorado River at the time of the levee break, but because of evaporative concentration, the salinity began to rise as water levels fell toward the minimum of the 1920's. Subsequently, with the importation of water for irrigation, salt loads from irrigation drainage, and return flows added salt to the water body. As agriculture expanded and water importation increased, not only did the Sea's water level increase, but salinity also rose steadily, surpassing that of the ocean. Today it is at its highest historical level about 30 percent higher than the ocean, about 44 parts per thousand.

To address these concerns, the Salton Sea Authority is supporting investigation of alternative measures to control water levels and salinity concentration in the Sea that will preserve its intrinsic values. Among possible alternatives are those that would physically alter the configuration of open water areas in parts of the Sea, and thereby alter its natural circulation and water quality characteristics. Before such physical alterations are made in the Sea's configuration and bathymetry, it is necessary to determine the effects these changes may have on circulation patterns and how these may in turn influence water quality and the indigenous ecosystem.

Model Representation of the Sea

An excellent detailed database containing over 133,000 measured bathymenty points was obtained from the US Bureau of Reclamation (USBR). This bathymetry file provides the basis for formation of a finite element network. The two-dimensional horizontal grid was initially constructed conforming to isobaths within the basin of the Sea. Later, this grid was extended to three dimensions, considering a single element in the vertical. The unusually high level of detail, allowed by the USBR data, provided for construction of a network closely approximating the real basin, although to minimize computational effort detail was reduced in areas of lesser interest, such as along the shorelines.

California Irrigation Management Information Stations (CIMIS) located close to the shore of the Sea provide excellent point measurements of wind magnitude and direction. Wind friction boundary conditions were developed by statistical analysis of continuous measurements for March and April 1995 at the CIMIS stations. For initial studies, a mean representational wind of 10.5 kph with an average prevailing direction of west-northwest (azimuth of 292.5 degrees) was applied over the entire surface of the Sea. Due to the absence of direct measurements of circulation velocities and limited geographic coverage of wind conditions at this stage of the investigation, wind stresses were applied uniformly, both in magnitude and direction, assuming frictional stress proportional to the square of wind velocity. Coriolis accelerations were intrinsically included in the model formulation corresponding to the geographic location of the Sea.

Hydrologic fluxes, primarily from the runoff of the New, Alamo, and Whitewater Rivers, and Salt Creek, plus dispersed irrigation drainage returns, were evaluated with respect to their potential influence on the Sea. From published reports of the US Geologic Survey, the average yearly inflow from the rivers and the creek determined from gages close to the Sea was estimated to be about 1.41 x

10^9 m^3/yr. Using an empirical relationship between sea volume and surface elevation (Hely et al., 1966) it was estimated that the impounded volume under average conditions for September 1993 (surface level = -69.5 meters msl) was about 9.87 x 10^9 m^3/yr. Thus, only about 0.00039 of the volume of the Sea enters on a daily basis and annually these sources amount to about one-seventh of the Sea's volume. Because the hydrologic fluxes from these sources are so small, it was considered reasonable in initial simulations of large scale circulation to neglect momentum transfer at the points where they enter. However, these fluxes will be considered in future extensions of the models to simulate water quality responses to loadings from polluted sources.

Although hydrological and meteorological data were acquired from many different sources, information on concurrent measurements of current velocities and water quality characteristics were not immediately available for these preliminary studies. These will be needed for extending the models and for their calibration and verification. Succeeding phases of the comprehensive investigation will provide for development of the needed data.

Preliminary Model Application

Two unique hydrodynamic models, RMA-2 and RMA-10, both formulated for finite element solution, were applied to simulate circulation in the Salton Sea. RMA-2 is designed to simulate two-dimensional, depth-averaged hydrodynamics for surface water systems in which external forcing, e.g., wind stresses and tides, induces vertical mixing. Turbulent energy losses, traction forces due to bottom friction, Coriolis forces, and surface wind stresses are represented in the model. It is capable of simulating both steady and unsteady state conditions. The model is well documented (King, 1994) and has been widely applied to estuarine systems.

RMA-2 was applied to the Salton Sea in a steady state mode, assuming negligible momentum inputs from tributary flow, a steady wind stress proportional to a mean wind at 10.5 kph from the northwest, and Coriolis acceleration corresponding to the location of the Sea. Results of the simulation are shown in Figure 1. It is noted the wind-induced circulation produced by the model is characterized by distinctive gyres in the southern basin, comparatively high velocities along the shorelines, and a lower velocity return flow opposed to the wind along the central portion of the Sea. Momentum conservation in the shallower waters near the shoreline results in higher velocities in these areas than in the deeper waters. Mass continuity requires the observed lateral circulation, the movement of water from shallow to deep areas, and the formation of the typical two-dimensional gyres.

Not available.

Figure 1 Two-Dimensional Circulation Results

RMA-10 is a model designed for the simulation of hydrodynamic circulation where vertical velocities are important and densimetric stratification may be an important factor. The model describes the state variables of pressure and velocity in three dimensions by solving a set of equations derived by combining the Navier-Stokes equations, volume continuity, advection-diffusion, and an equation of state relating water density to salinity, temperature, and suspended sediment. As with RMA-2, friction losses, Coriolis effects, and surface wind stresses are also represented. The model may be used to simulate time-dependent or steady-state simulations. RMA-10 has been utilized in similar hydrodynamic systems and is well documented (King, 1994b). Although the model is capable of simulating stratification due to water quality gradients along the vertical axis, all results presented in this paper assumed the fluid to be homogenous. Boundary conditions for the three-dimensional case were identical to those noted previously for RMA-2.

Three dimensional results from RMA-10 at the mid-depth elevation are shown in Figure 2. Surface layer velocity vectors are higher than the mid-depth results and are generally orientated in the direction of the wind. Flow near the surface of the Sea is seen to travel southeast until it comes near the shoreline. At the southeastern end of the Sea, the water surface level rises slightly due to the flow along the surface, generating an increased hydrostatic pressure and a resulting downward flow. Near the bottom of the Sea, velocity vectors are approximately equal in magnitude to the mid-depth results and the flow is for the most part in a direction opposite to the wind, returning water back toward the northwest part of the Sea. As the flow approaches the northwest boundary, water rises upward to the surface, creating an upwelling. At mid-depth in the Sea, the flow is generally in a

Not available.

Figure 2 Three-dimensional Circulation Results: Mid-Depth Velocity Vectors

direction opposite to the wind. It is in this mid-depth region that gyres are the most visible. These gyres can be seen at several locations, the strongest of which are found in the southeastern part of the Sea. Flow in these gyres not only circulates horizontally around the center of the gyre, but also vertically.

Results presented in these figures are for uncalibrated models. Calibration to different meteorological conditions, water quality parameters (such as gradients of temperature and salinity) and turbulence exchange coefficients could change the results presented here. However, given the limitations of measured data presently available and the approximations described above, the results are encouraging. There is no evidence of behavior that is inconsistent with the fundamental principles of hydrodynamics as they apply to surface water systems.

Conclusions

Problems of increasing water levels and salinity are threatening the viability of the Salton Sea as a recreational and ecological resource. Solutions are being proposed that may alter the configuration of the Sea by isolating certain portions with physical barriers. Possible consequences of such alterations include changes in circulation and related redistribution of nutrients, sediments, and water quality constituents that affect ecological and recreational values.

To examine effects on the Sea's circulation, two finite element models were adapted to the bathymetry of the Sea and used to simulate circulation patterns induced by wind friction on the surface. Both models indicated the likely presence of large scale gyres which could result under conditions of a steady wind from the west northwest. The three-dimensional model provided the most credible results, from a fundamental hydrodynamic viewpoint, that is, return flows opposite to the wind were observed to occur in deep portions of the Sea.

Additional improvements are needed to account for the effects of stratification related to vertical differences in temperature and salinity, to accommodate the influences of inflow on water quality, and to consider variations in wind strength and direction of the Sea's surface. There is a need to obtain direct measurements of water currents, wind and other atmospheric characteristics, and water quality in support of model development and application.

Appendix. References

Hely, Allen G., G.H. Hughes, and B. Ireland (1966). *Hydrologic Regimen of Salton Sea, California,* Geological Survey Professional Paper 486-C. US Department of Interior.

King, Ian P. (1994a). *RMA-2 : A Two Dimensional Finite Element Model for Flow in Estuaries and Streams - Update Documentation*, Version 5.1, Department of Civil and Environmental Engineering, University of California, Davis.

King, Ian P. (1994b). *RMA-10 : A Finite Element Model for Stratified Flow. Users Guide*, Version 5.0, Department of Civil and Environmental Engineering, University of California, Davis.