Evaluation of dike-type causeway impacts on the flow and salinity regimes in Urmia Lake, Iran

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A R T I C L E   I N F O

Article history:
Received 11 August 2007
Accepted 5 August 2008

Communicated by Dr. Ram Yerubandi

Index words:
Urmia Lake
Hydrodynamic
Advection-dispersion
Salinity
MIKE software

A B S T R A C T

Urmia Lake, located in a closed basin in north-west Iran, is the largest lake (5000–6000 km²) in the Middle East. It is very saline with total dissolved salts reaching 200 g/l compared with a normal seawater salinity of about 35 g/l. The construction of a causeway, which was initiated in 1979 but then abandoned until the early 2000s, is near completion and will provide road access between the western and eastern provinces. The causeway has an opening 1.25 km long and divides Urmia Lake into a northern and southern basin and restricts water exchange. The flow and salinity regimes are affected by the presence of this new causeway, and there are concerns over the well being of the Artemia population. This study investigates the effects of the construction of the causeway on flow and salinity regimes, considers remedial actions, and examines the effects of climatic variability on salinity and flow. Flow and salinity regimes were numerically simulated by using a commercially available two and three-dimensional (2D and 3D) MIKE model. The validity of the numerical model was assessed through sensitivity analysis of the model and comparing the simulated results against field measurements; the 3D model provided the higher correlation between simulated and actual data. Wind input was the main climatic and hydrologic factor influencing flow regime while river discharge, evaporation and rainfall were the key parameters affecting salinity distribution in the lake models. The 3D model was subsequently used to predict lake conditions in typical dry, wet and normal climates, to examine the environmental impacts from the new causeway, and to evaluate possible improvements that some remedial measures may provide.

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Introduction

Urmia Lake is one of the largest salt lakes in the world and is located in a closed basin in north-west Iran (37°4′–38°17′N and 45°–46°E). The lake has a semi-rectangular shape, a maximum length of 135 km, and a surface area between 5000 and 6000 km² (Shabestari, 2003). A general map of Urmia Lake is presented in Fig. 1 and shows its bathymetry (Sadra, 2003) based on a water datum of 1275 m above the Persian Gulf Mean Sea Level (MSL). The mean water level varies seasonally (yearly) by about 1 m, with greater variations in water level occurring over longer time spans. For the 1930–2007 period, the extreme low of 1273.5 m occurred in 2002 and the extreme high of 1278.4 m in 1994. From 1979 to 1992, a 15.4 km dike-type causeway was gradually constructed to cross the lake width at its narrowest part (Fig. 1) and to provide road access between the western and eastern provinces. This rubble mound embankment was built by direct dumping of the quarry run materials, concurrently, from the eastern and western shores with a 1.25 km long opening left in the causeway to provide for connection between the northern and southern parts of the lake. In the early 2000s, construction was accelerated to build a bridge to span this opening and thus complete the causeway. Thus this east–west running dike-type causeway essentially divides the lake into northern and southern parts with a single opening allowing limited water flow between the two basins.

Several rivers flow into Urmia Lake (Fig. 1) and, with an average annual inflow of about 4.6 billion m³, are the main source of water to the lake. Some rivers flow over saline soils, picking up dissolved salts which are discharged with their flow into the lake; salinity is 6 g/l around some river mouths. Evaporation rates are high averaging 1200 mm/year for a 50 year record. As a result, the lake is highly saline with salinity averaging 225 g/l but may reach 280 g/l when the lake water level declines during dry years. Salinity is approximately 60% higher in the northern basin of the lake because of higher evaporation rates and lower water river inflows than in the southern basin. Salinity and lake level have declined over the past 20 years although salinity did increase over 2003–2004 with favorable climatic conditions (Eimanifar and Mohebbi, 2007). Construction of the causeway may also have contributed to a higher salinity in the north and lower salinity in the south by reducing the normal exchange of water between the northern and southern parts of the lake.
Urmia Lake is registered under RAMSAR Convention as an area of international importance for birds. The brine shrimp *Artemia urmiana* is one of the few organisms inhabiting the lake and can tolerate a salinity range of 40 to 250 g/l although may be stressed by the higher salinities (Csvas, 1996). The increasing salinity in the northern basin of the lake, if exacerbated by the causeway, may have an adverse impact on the *Artemia* populations if their salinity tolerance range is exceeded. Various remedial actions have been considered to reduce the salinity of the northern basin. One option is to construct additional openings in the causeway to improve water exchange between and mixing within the north and south basins. This would be an expensive and technically demanding solution as relatively long overpass rail/road bridges would have to be built on top of each new opening. Moreover, the causeway bed is very loose and, after about 30 years, is still subsiding. This subsiding substructure would have adverse effects on a rigid bridge structure and on its long-term performance. Another option being considered is moving the mouth of the Nazloochi River so that it discharges into the northern basin. Therefore, additional openings and/or relocating the Nazloochi River mouth would only be considered feasible if comprehensive hydrodynamic modeling studies proved them to be essential measures to reducing the increased salinity of the northern basin.

Several attempts have been made to quantify Urmia Lake hydrodynamics. Ab-Niroo (1995) used a 2D model and concluded that the natural mixing of the waters between the north and south parts of the lake was reduced because of the construction of the causeway. Alikhani (1997) used the HEC-5 program and a water balance approach to model water level fluctuations; the results were verified using field measurements. Modaresi (2002) used a critical meteorological approach to quantify water exchange through the causeway opening and the widening of the opening required to obtain the desired water exchange. Abrari (2003) used 2D hydrodynamics modeling to investigate water circulation patterns (simulated data were compared to field monitoring data generated by freely travelling buoys released into the lake) and concluded that flow patterns in the lake were controlled by the wind regime. Sadra (2003) employed a 2D depth-averaged hydrodynamic model to investigate design improvements in the causeway and for the design of a bridge to span the existing opening; they also performed one-year simulations of the flow and salinity circulation in the lake. They recommended that a

Fig. 1. (a) A general map of Urmia Lake, its bathymetry, the crossing dike and the major river entries; (b) distribution of salinity in May 1987 (see also Table 4); (c) measurement stations (see also Table 1).
new 500-meter long opening be constructed in the west arm of the existing causeway and predicted that this would result in a 40% increase in water exchange between the south and north basins. Parts of this study were reported later by Shafieefar (2005) and Mohghimi et al. (2007). Tarhe-e-Noandishan (2004) employed the model proposed by Lawrence (1990) for two-layer flows and described stratified flow through the causeway opening. Fallah (2004) used a 2D model for predicting wave conditions in four locations of the lake, studied the seasonal flow patterns, and reported independent flow circulations in the northern and southern basins which varied seasonally. More recently, Eimanifar and Mohebbi (2007) presented a general literature review on various aspects of the lake such as its geology, sediments, hydrology, morphology, hydrochemistry, Artemia biology, ecology and bacteriology.

The current work aims to present a new, comprehensive and more realistic prediction of the hydrodynamics and salinity distribution in Urmia Lake. A numerical approach is used and several simulation scenarios considered including natural conditions (pre-causeway construction), current conditions (post causeway construction), and conditions were extra openings introduced into the existing causeway. For long term predictions, normal, wet and dry weather conditions were considered.

**Model description**

**Generals**

Commercially available MIKE hydrodynamic models are general numerical modeling systems, developed by DHI Water and Environment (DHI 2005a,b), for simulation of flows in estuaries, bays, coastal areas and oceans. MIKE 21 and MIKE 3 HD/AD (HydroDynamic/Advection-Dispersion) modules were used in this work. MIKE 21 HD simulates unsteady 2D flows in one-layer (vertically homogenous) fluids. Conservation of mass and momentum equations are integrated over the vertical to define flow and water level variations. MIKE 3 (HD) module simulates unsteady three-dimensional flows taking into account density variations. The model uses a multi-level coordinate system in the vertical direction and a rectangular coordinate system in the horizontal direction. The mathematical foundation in MIKE 3 is the mass conservation equation, the Reynolds-averaged Navier-Stokes equations in three dimensions, including the effects of turbulence and variable density, together with conservation equations for salinity and temperature:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = SS
\]

\[
\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla p + \mathbf{g} + \nabla \cdot \left( \mathbf{v}_T \left( \frac{\partial \mathbf{u}}{\partial x} + \frac{\partial \mathbf{u}}{\partial y} \right) - \frac{2}{3} \Omega k \right) + \mathbf{u}'
\]

\[
\frac{\partial S}{\partial t} + \nabla \cdot (S \mathbf{u}) = \frac{\partial}{\partial x} \left( D_s \frac{\partial S}{\partial x} \right) + SS
\]

\[
\frac{\partial T}{\partial t} + \nabla \cdot (T \mathbf{u}) = \frac{\partial}{\partial x} \left( D_T \frac{\partial T}{\partial x} \right) + SS
\]

Where \( \rho \) is the local density of the fluid, \( c_i \) the sound speed in the lake water, \( u_i \) the velocity in the \( x_i \)-direction, \( \Omega \) is the Coriolis tensor, \( P \) the fluid pressure, \( g_i \) the gravitational vector, \( \mathbf{v}_T \) the turbulent eddy viscosity, \( \delta \) Kronecker’s delta, \( k \) the turbulent kinetic energy, \( S \) and \( T \) for the salinity and temperature, \( D_s \) and \( D_T \) the associated dispersion coefficients and \( t \) denotes the time. \( SS \) refers to the respective source-sink terms and thus differs from equation to equation.

**Model inputs**

Urmia Lake, as a closed-basin lake without a natural outlet, has its flow and salinity regimes highly dependent on the annual climate conditions. For long term simulation of the lake under dry, wet and normal climates, field data from a representative extremely dry, wet and normal year was used.
extremely wet and a normal year respectively from past records were used in the simulations.

Wind speed/ direction time histories are important inputs for the simulation of the flow and salinity distribution in the lake. Wind data in 1987 and 1999 were found to be more representative of the long term (44 years) wind field over the lake; therefore these two years were regarded as representatives of a normal climate. Based on a statistical investigation, Tarh-e-Noandishan (2004) reported a good agreement between the evaporation, rainfall, river discharge and the lake level fluctuations in 1979, 1987 and 1997. Some field measurements on the water density and its distribution for May and September 1987 were also available. Long term simulations of the lake under a normal climate were therefore, based on yearly input data starting from October 1986 to September 1987. This also provides the possibility of verifying the numerical models against the best field data available.

The Urmia Lake hydrodynamic model includes the river discharge, precipitation and evaporation, surface shear stress (due to wind) and lake bed resistance. The model incorporates modified monthly average values for the river discharge. These values were collected by the Iranian Ministry of Power and were introduced into the model for 21 main rivers. For precipitation and evaporation data, modified monthly average values from the nearest meteorological stations to the lake were used. Wind speed and direction inputs were in 3-hour time intervals and from the synoptic station of the Urmia airport. A rectangular mesh grid was used to represent the bathymetry of the lake; bathymetry was based on hydrographical surveys around the causeway and remote sensing measurements by Sadra (2003). Four main southern islands and the existing causeway were incorporated into the model geometry. Some small islands in the lake and caisson piers for a viaduct bridge under construction, which are situated in the existing opening, were not included in the lake models.

Calibration/verification

Typically, a numerical model has to be first calibrated using a series of field data. The calibrated model is then compared to other field measurements for verification purposes. Unfortunately few field studies have been performed on the lake to provide those data which are normally required for the full calibration/verification of the numerical model. The available field data seemed insufficient and far from comprehensive.

One set of concurrent measurements of the wind speed over the lake and the flow velocity was reported by Water Research Center of the Iran Ministry of Power (Table 1). However, the duration of the data was very short and insufficient for verifying long term model results. Furthermore, the stations were close to the causeway. Water salinity was measured by lake authorities on a regular basis at one point near the causeway and reported as the monthly average. Another series of field measurements on density and salinity throughout the lake was performed on two occasions in 1987 (Table 2).

Sensitivity experiments

As those available field data did not seem to be sufficient for both the calibration and verification purposes, a number of sensitivity analyses were performed to evaluate effects of different modeling parameters on both hydrodynamic and salinity distribution results. The sensitivity analysis thus, assisted in choosing appropriate values for some modeling parameters.

Rainfall, evaporation, and river discharge were not included in the model used in the sensitivity study. This is because short duration models were used for the sensitivity analyses. Two sets of models were employed. In one set, a constant wind speed of 15.3 m/s with a direction of 170° was used; this corresponds to an extreme wind condition, observed in the representative year (from October 1986 to September 1987). It should be noted that the mean seasonal wind speed over the lake is about 4.1 m/s with maximum of 9 h duration (Fallah 2004). In the second set, a variable wind time series was used. The wind speed/directions were in 3-hour time intervals and corresponded to the recorded data for July 1987. The July wind data appeared comparable to the overall wind regime in the representative year.

Table 3 gives a summary of the sensitivity analysis results. Each individual parameter was varied between its upper and lower limits and the maximum effect on the output flow velocity evaluated. The velocities at 10 arbitrary locations across the lake (some within the existing opening, where higher velocities are expected) were

<table>
<thead>
<tr>
<th>Month in 1991</th>
<th>Position (Fig. 1.b)</th>
<th>Density/(kg/m³)</th>
<th>Salinity/(g/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>North</td>
<td>1146±2</td>
<td>235±3</td>
</tr>
<tr>
<td></td>
<td>South–West</td>
<td>1140±2</td>
<td>225±4</td>
</tr>
<tr>
<td></td>
<td>Center &amp; East</td>
<td>1138±4</td>
<td>211±16</td>
</tr>
<tr>
<td>September</td>
<td>All</td>
<td>1159±1</td>
<td>251±2.5</td>
</tr>
</tbody>
</table>
monitored. The percentages given in Table 3 denote the maximum variations observed in the flow velocity amongst the 10 locations. Salinity results in Table 3 are from AD modules. They were obtained from longer simulations covering the whole representative year. In this case, Table 3 gives the effects of variations in dispersion coefficients on the salinity diversity between two arbitrary points in the southern and northern parts of the lake. By varying the dispersion coefficient in the model, notable changes in the salinity values were observed at those two arbitrary points in the lake. However, the difference of salinity between those two points remained small.

Amongst parameters listed in Table 3, water density can be seen to have had fewer effects on flow velocity. The results were not significantly affected by variations in grid spacing, initial conditions for water density and dispersion coefficient. The 2D model was less responsive to variations in the mentioned parameters compared to the 3D model. Both the 2D and 3D models were sensitive to variations in the wind friction coefficients. Values selected, out of the sensitivity analyses, for long term simulations of the lake are also given in Table 3. For the Manning number and dispersion factors, values recommended by DHI were used (DHI 2005a,b). Constant eddy viscosity coefficients were chosen instead of velocity based coefficients since they are less time consuming to compute with similar effects on the results. With a velocity based coefficient option, these coefficients vary with time and location, and are calculated at each time step, from the velocities obtained.

It should be mentioned that in MIKE 3, the UNESCO formula is incorporated for the relationship between the salinity-temperature and the water density (DHI 2005a,b). A range of 0 to 45 PSU (Practical Salinity Unit) and a range of temperatures from −2.1 to 40 °C can be defined as initial conditions in the program. With these limits, the UNESCO formula gives a range of water density between 992 to 1.037 g/ml. These values of density are far below the water densities in a velocity based coefficient option, these coefficients vary with time and location, and are calculated at each time step, from the velocities obtained.

Table 3
Some results from the sensitivity analysis on major calibration parameters and values selected for them

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Module</th>
<th>Exercised range</th>
<th>Effect (percent)</th>
<th>Selected value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>Constant</td>
<td>Variable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grid spacing</td>
<td>21(HD)</td>
<td>Hor. 300–900 m</td>
<td>1</td>
<td>H: 450 m</td>
</tr>
<tr>
<td></td>
<td>3 (HD)</td>
<td>Hor. 300–900; ver. 0.5–2 m</td>
<td>25</td>
<td>Hor. nested 900+300; ver.:6 layers</td>
</tr>
<tr>
<td>Bed resistance</td>
<td>21(HD)</td>
<td>Manning (20–40 m1/3/s)</td>
<td>1</td>
<td>32 m1/3/s</td>
</tr>
<tr>
<td></td>
<td>3 (HD)</td>
<td>0.01–0.3 (m)</td>
<td>80</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Eddy viscosity</td>
<td>21(HD)</td>
<td>Relative to method</td>
<td>0.3</td>
<td>0.5 m/s Constant value</td>
</tr>
<tr>
<td></td>
<td>3 (HD)</td>
<td>Relative to method</td>
<td>50–100</td>
<td>Smagorinsky 0.088H0.576V</td>
</tr>
<tr>
<td>Wind friction</td>
<td>21(HD)</td>
<td>0.0026,0.005,Variable</td>
<td>20</td>
<td>Proportional to the wind speed</td>
</tr>
<tr>
<td></td>
<td>3 (HD)</td>
<td>0.0026,0.005,Variable</td>
<td>150</td>
<td>Proportional to the wind speed</td>
</tr>
<tr>
<td>Density</td>
<td>3 (HD)</td>
<td>0.992–1.037 (g/ml)</td>
<td>2</td>
<td>1.037 g/ml</td>
</tr>
<tr>
<td>Dispersion factor</td>
<td>3 (HD)</td>
<td>0–0.2</td>
<td>0.02</td>
<td>0.1</td>
</tr>
<tr>
<td>Dispersion coefficient</td>
<td>21(AD)</td>
<td>Relative to method</td>
<td>3 in salinity</td>
<td>Proportional to current 0.1 m2/s</td>
</tr>
<tr>
<td></td>
<td>3 (AD)</td>
<td>Relative to method</td>
<td>&lt;1 in salinity</td>
<td>Independent of current 4 m2/s</td>
</tr>
</tbody>
</table>

1–Hydrodynamic Module 2–Advection-Dispersion Module.
3–In MIKE 21/3 the dispersion coefficients can be introduced to model as: proportional to local effective eddy viscosity or local velocity component in each grid direction or local current vector.

Urmia Lake (see Table 2). So, real initial density of the lake water cannot be introduced to the model. Excluding areas close to the river mouths, the maximum difference of water density is about 8 g/l and this occurs in spring. Therefore, while it is not possible to introduce real initial values of the water density in the model, variations in the water density within the range observed inside the lake can be modeled. Moreover, the hydrodynamic model has been found less sensitive to the initial water density.

Separate models (i) with the minimum allowable initial density; (ii) with the maximum allowable initial density; and (iii) with the maximum difference in the initial density, reported between the northern and southern basins, were developed and their effect on wind-induced current monitored across the lake. Time series of the flow velocity, at an arbitrary point across the causeway opening are given in Fig. 3. The figure shows an insignificantly difference in the flow velocity produced with different initial densities.

Model verification

One-year simulations were the primary ones performed in model verification. Figs. 4 and 5 show time series for the flow velocity and its direction from the 2D and 3D models, respectively and are for a location half-way through the causeway opening where higher flow velocities are anticipated compared to other parts of the lake. No concurrence of events can be judged between the velocities in Figs. 4 and 5. The range of velocities predicted by the 3D models however, agrees well with that from measurements in similar conditions (for example to those in Table 1). In general, the 2D model yielded to higher flow velocities (around 57% for the maximum velocity) compared to those from the 3D model. The majority of the river discharge is into the southern part of the lake and water flow through the causeway opening is predominantly northward and is confirmed by the 2D and more consistently by the 3D models (Figs. 4 and 5). The 3D model demonstrates that the velocity/direction of the flow varies
Fig. 5. Flow speed and its direction at different water depths, halfway through the causeway opening, from the 3D model for 1986–1987. The bottom chart shows the results in September 1987. The order of the layers is from surface to bottom.
in depth (Fig. 5). This allows a more realistic simulation of the fresh and saline water mixing in the lake. However, stratification induced by variations in salinity and density with water depth was not demonstrated in the 3D models. The available data do not support the existence of stratification in Urmia Lake in areas far from the river inlet.

Flow regimes simulated by the 2D and 3D models were then used to model salinity in the lake. An initial salinity condition corresponding to that from spring conditions (Table 2) was used in the AD module. In order to monitor the convergence of the advection-dispersion model, this module was used to simulate about 7 additional years. The same inputs used for the main one-year simulation period were repeated through the 7-year period. With the 3D model (AD), salinity distribution patterns throughout the lake during the last 4.5 years simulation were found to be identical and mostly a repetition of the results from the main simulation period. For the 2D model, however, this was only observed for the middle part of the lake. The 3D model showed a reasonable level of convergence after 3.5 years, while the 2D (AD) model did converge after 8 years, particularly in the northern part of the lake. This is most probably because the 2D (depth-averaged) model overlooked variations in the flow velocity/direction in vertical direction and so had some limitations in properly simulating fresh and saline water mixing in the lake. As a result, at the end of each simulation year, the salinity in the northern part increased more than that from the 3D model. The salinity predicted by the 2D model, conversely, decreased in the southern part of the lake.

Table 4
Comparison between the salinity contents predicted by the 2D and 3D models and those from field measurements

<table>
<thead>
<tr>
<th>Point (Fig. 1a)</th>
<th>Field data (PSU)</th>
<th>MIKE 21 (PSU)</th>
<th>MIKE 3 (PSU)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>May</td>
<td>Sep</td>
<td>May</td>
</tr>
<tr>
<td>1</td>
<td>235</td>
<td>251</td>
<td>366</td>
</tr>
<tr>
<td>2</td>
<td>235</td>
<td>251</td>
<td>368</td>
</tr>
<tr>
<td>3</td>
<td>235</td>
<td>251</td>
<td>364</td>
</tr>
<tr>
<td>4</td>
<td>235</td>
<td>251</td>
<td>344</td>
</tr>
<tr>
<td>5</td>
<td>211</td>
<td>251</td>
<td>343</td>
</tr>
<tr>
<td>6</td>
<td>211</td>
<td>251</td>
<td>241</td>
</tr>
<tr>
<td>7</td>
<td>225</td>
<td>251</td>
<td>221</td>
</tr>
<tr>
<td>8</td>
<td>211</td>
<td>251</td>
<td>43</td>
</tr>
<tr>
<td>9</td>
<td>225</td>
<td>251</td>
<td>160</td>
</tr>
<tr>
<td>10</td>
<td>6–232</td>
<td>36</td>
<td>154</td>
</tr>
</tbody>
</table>

Fig. 6. Distributions of salinity content (PSU) from the 2D (left) and 3D (right) models well after expected convergence time.

Fig. 7. Wind forcing effects on the Practical Salinity Unit from the 3D model (for 1986–1987).
**Table 5** Effects of meteorological parameters on the flow velocity and the salinity distribution

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Wind</th>
<th>Rivers</th>
<th>Precipitation</th>
<th>Effects relative to the real condition (when all three parameters are included)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>✓</td>
<td>x</td>
<td>✓</td>
<td>Similar fluctuation but lower velocity Instability in model</td>
</tr>
<tr>
<td></td>
<td>✓</td>
<td>x</td>
<td>✓</td>
<td>Lower velocity and different values Little reduction in the south</td>
</tr>
<tr>
<td></td>
<td>✓</td>
<td>x</td>
<td>✓</td>
<td>Similar fluctuation but different values Little fluctuation</td>
</tr>
<tr>
<td></td>
<td>✓</td>
<td>x</td>
<td>✓</td>
<td>Similar fluctuation but lower velocity Instability in model</td>
</tr>
<tr>
<td></td>
<td>✓</td>
<td>x</td>
<td>✓</td>
<td>Velocity is about zero Homogeneity in low speed</td>
</tr>
</tbody>
</table>

✓ means the parameter has been incorporated to the model and x means the parameter has been neglected.

Accumulation of these annual differences could result in divergence of the 2D salinity model over longer simulation periods.

Salinity patterns from the 2D and 3D models, after about 4.5 years, are shown in Fig. 6. Table 4 indicates that the 3D model represents a more rational and realistic simulation for the salinity in Urmia Lake than that from the 2D model. Therefore, 3D models were used for (i) simulating wet, dry and normal climate conditions; (ii) evaluation of the causeway effects; and (iii) assessment of remedial options.

**Results and discussion**

This section reports on the effects of a number of climatic and hydrologic parameters on the flow and salinity regimes in the lake using results are derived from the 3D model. The effects of the constructed causeway and the remedial actions also are presented and discussed.

**Effects of key parameters**

Effects of some key parameters such as wind, river discharge and effective precipitation (difference between rainfall and evaporation) on the response of the 3D model were investigated. These parameters were alternatively incorporated and removed from the model. A one-year period was considered for these simulations (from October 1986 to September 1987). Fig. 7 shows the wind effects on the salinity and Table 5 the overall results on flow velocity and salinity distributions. In Table 5 and Fig. 7 a real condition refers to a simulation in which all the above mentioned parameters were included in the model. From the results of these models, the wind input can be expressed as the dominant climatic and hydrologic factor affecting water flow regime in the lake. The wind input, however, has had a relatively small effect on salinity conditions in the lake. Fig. 7, for example, indicates on a maximum of 3.8% increase in the salinity when the wind input has been excluded from the model. River discharge, evaporation and rainfall are the dominant parameters affecting salinity distribution in the lake. Effective precipitation (precipitation-evaporation) is the main factor affecting the salinity increase while river discharge plays a balancing role. River discharge is a major source of fresh water input to the lake and so regulates salinity which tends to continuously increase because of evaporation.

**Causeway impacts on the flow and the salinity regimes**

The 3D model was used to evaluate the causeway impacts on the flow and salinity regimes in Urmia Lake. The model’s input and conditions correspond to those of the representative normal climate (October 1986 to September 1987). Different scenarios were considered. They were (i) natural conditions, with no causeway (as before 1978); (ii) current conditions, with the existing causeway; and (iii) remedial alternatives (for the future). The remedial alternatives studied were the widening the existing opening (making it twice as long); adding extra openings along the causeway; and moving the Nazloochi river mouth from its current position (Fig. 1), northward, so that it discharges into the northern basin. Fig. 8 shows, as an example, time series of salinity from natural and real scenarios for an arbitrary point at the southern part of the lake. Table 6 represents some of the results from all simulation scenarios. The table gives the maximum salinity difference observed (with each scenario) relative to the real conditions. The salinity was monitored at two specific but arbitrary southern and northern points in the lake, far enough from the causeway.

Results from modeling of different scenarios show that, apart from areas within ca. 2 km of the causeway, lengthening of the opening (and even removing the whole causeway) does not significantly affect the overall salinity in the lake (Table 6). While a return to natural conditions (as before 1979), would result in a improvement in current conditions as would the remedial alternatives of expanding the existing opening (Table 6), the gain would be small, i.e., a maximum change of 2 PSU (were the whole causeway removed) or around 1%, considering an average salinity of 200 PSU for the lake water; for those scenarios related to expansion of the opening, the change would be only ca. 1 PSU or 0.5%. Based on these analyses, the causeway is not...
believed to have had significant impacts on the overall salinity patterns in Urmia Lake as compared to the natural (pre-causeway) conditions. Moreover, removing the 14 km long causeway to restore the natural conditions of the lake is not feasible.

Table 6 shows that, the lake wide improvement gained by the remedial action of moving the Nazloochi River mouth to the northern basin is higher than that of removing the causeway. However, the improvement, is not substantial (5 PSU or around 2.5%). Nevertheless, relocating the Nazloochi river mouth is a more feasible alternative to reducing the salinity of the northern basin.

Extreme conditions

To evaluate lake salinity status at extremely wet and dry climate conditions, respectively, meteorological data for years 1994 and 2002 were respectively introduced into the 3D model. The same three different scenarios were considered. They were: (i) natural conditions (with no causeway), (ii) current conditions (with the existing causeway and its 1250 m wide opening), and (iii) remedial conditions (with an extended opening of another 1200 m, 4 km westward of the existing opening). Figs. 9 and 10 show some of the results. Fig. 9 gives the time series of the salinity during successive wet years. Under a typical wet climate, the expanded opening does not offer significant overall improvement in the salinity distribution over the lake, in comparison to that from the current conditions (Fig. 9). During dry climates salinity becomes considerably higher than during normal and wet climates (Fig. 10). However, this numerical model output may not be realistic as it does not include the salt crystallization and precipitation which occurs when salinity becomes very high, i.e., salt crystallization will begin to act as a balancing factor and, under an extremely persistent dry climate, salinity may be lower than those presented in Fig. 10.

Conclusions

The current study aimed to provide an evaluation of the flow and salinity regimes for Urmia Lake. This has become an environmentally important issue for this hypersaline lake because of its declining lake levels and because a nearly completed causeway has divided the lake into two basins with restricted flow. As the southern basin has the greater riverine input, the causeway may have exacerbated salinity increases in the north basin by restricting water flow into the north basin.

The validity of the 2D and 3D models was appraised through sensitivity analysis contrasting the numerical results against a number of available field data. Both the 2D and 3D models provided reasonable predictions for the flow characteristics in the lake. The 3D model, however, presented more reliable and rational hydrodynamic simulations. For spatial patterns in salinity in Urmia Lake, the 2D model yielded unrealistically high salinity predictions while the 3D model provided reasonable predictions. This is most likely because with a 3D model the velocity and the direction of the flow varied over the vertical, providing a better mixing simulation of fresh and saline waters. Results from the 3D models highlighted wind input as the dominant climatic and hydrologic factor influencing flow regime and the lake hydrodynamics. River discharge, evaporation and rainfall were the governing hydrological parameters affecting salinity distributions.

The effects of different remedial alternatives on the water salinity distribution in the lake were next evaluated. The 3D models were used to evaluate the impacts of additional openings in the causeway and diversion of the Nazloochi River mouth on the lake salinity compared to that of the current conditions. These remedial actions produced localized effects around the causeway but did not provide significant improvements in overall salinity conditions. The Nazloochi River diversion would be the more effective of the two remedial actions being considered.

The numerical models were also used to predict lake salinity in typical wet and dry climates and the effectiveness of introducing additional openings in the existing causeway during such periods. Based on our model results, we conclude that additional openings of causeway do not provide noticeable improvements to lake salinity and hydrodynamics regimes in wet and dry periods. Our models have not considered the considerable changes in the sedimentation and littoral drift movements/ regime, which have occurred in the lake since 1979 by the presence of the new causeway.

Several dams are planned or under construction on the rivers flowing into Urmia Lake. By holding back water, they will result in an imminent decrease in freshwater inflow, a concomitant increase in salinity, and a decline in water level. As this paper focused on the impacts from the new causeway on the salinity regime in the lake, effects from reduced water inflows, increased salinification, and declining lake levels as a consequence of dam construction were not specifically addressed in this paper. With respect to salinity patterns in Urmia Lake, it is concluded that over long term periods, the constructed causeway has not had and would not have significant impacts on the overall salinity patterns in Urmia Lake as compared to the natural (pre-causeway) conditions. Factors affecting the water balance of the lake (e.g., climatic variability, reduced river inputs) have had and will have the dominant role.

Acknowledgements

The authors would like to express their appreciation to Mr. Navidi and Mr. Tavakoli, the executives of the Urmia expressway and Mr. Borhani from IREMCo for the provision of data and technical documents about Urmia Lake. They are also very grateful to the JGLR editors and referees, especially, Dr. Marlene Evans and Dr. Ram R. Yerubandi for their insightful and astute comments on an earlier version of this paper.

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