Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

ISSN: 0972-6268	Vol. 14	No. 1	pp. 149-152	2015

Original Research Paper

Quasi-3D Numerical Simulation of Salinity Transport for Reservoir Initial Impoundment

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Nat. Env. & Poll. Tech.
Website: www.neptjournal.com
Received: 9-1-2015
Accepted: 10-2-2015

Key Words:
Initial impoundment
Salt transfer
Quasi-3D numerical simulation
Estuarine reservoir

ABSTRACT

In the special geological and water environment of estuarine reservoirs, salt water in the deposits will intrude into the overlying freshwater and affect the water quality and normal operation of the reservoir. It is, therefore, important to identify the spatial extent of salt. Based on site survey, drilling and laboratory data, a quasi-3D model was established, simulating the migration of salt in the initial impoundment of the reservoir. As a result, if the impoundment happened in the normal water year, when the water level rose to 0.5m, salinity ranged from 0.3g/L to 2.8g/L on the surface; at the level of 1.5m, salinity ranged from 0.3g/L to 1.3g/L; and at the level of 4.5m, salinity varied between 0.3g/L and 1.55g/L. This will lead to a better understanding of the implications of groundwater hydrology and improve protection of surface water quality during the extraction of water resources.

INTRODUCTION

The estuarine reservoir has attracted much attention as one of the important approaches to freshwater shortage on the coast. But one problem is that in some man-made estuarine reservoirs, the storage water becomes salty and the surface water contains a greater amount of salt than the standard level due to sea water contained in the storage and salt released from the bottom sediment. Therefore, a model is established to simulate the changing process of water quality under the effect of release of endogenous salt in initial impoundment, founding a sound basis for desalinization of the water.

The simulation of salt transfer is a worthy topic of research. The quality of storage water is related to the water brought in by the rivers, in addition, after the completion of the reservoir (especially in the initial stage), the disposal of residual sea water and dispersion of salt from the bottom sediment determine the desalinization process and future water quality (Zhang et al. 1999, Higashino et al. 2003, Portielje & Lijklema 1999).

As tidalite laden with salty water is at the bottom of the reservoir, the diffusion of the salt from the bottom and the change process will determine the desalinization speed and water quality. With impoundment in the reservoir, particularly in the initial stage, we shall carry out research on salt transport under different hydrodynamic and engineering conditions. For this purpose, a simulation model has to be established to build up the basis for predicting water quality and desalinization operations. The fresh storage water will reach the porous material laden with salty water and initiate a complex physical and chemical exchange between them. Under such a water environment, salt content varies vertically, and with the effect of seasons, inflow, outflow and wind, salt content reveals dynamic changes at the surface and different sections. The model shall reflect the variation of salt migration in time and space.

OVERVIEW OF THE STUDY AREA

Location: The reservoir is located to the southwest of Boli town, Jiaonan city, at the estuarine area of the Henghe River. Jiaonan city is situated in the southwest of the Shandong Peninsula. The main dam is about 7km long with a maximum height of about 13m, a planned dam crest elevation of about 8m and a crest width of about 20.0m. The estuarine area embraced by the dam is 25km^2, with the reservoir bottom at an average elevation of about -3.5m, about 7.5m deep at the normal water level of 4.0m and with a total storage capacity of 1.6×10^8m^3. The Henghe river flows into the reservoir gravitationally and other rivers will be diverted into the reservoir by structures.

Topography, geomorphology and tectonic features: The reservoir sits on a base of proterozoic metamorphic rock structure. Since the Paleozoic era, the area has gradually risen, forming an alternation of upheavals and grabens which are the basis for the estuary coast. The main formation is the Cathaysian structure conjugated with NW-SW fractures. The coastline mainly features Mesozoic fractures. Erosion and denudation of hills and peneplains are widely distributed along the coast with the increasing, and marine deposition plains or alluvial plains are distributed at the estuary and shore, while the seashore bottom declines southward.

Loose deposition at the reservoir bottom: At the elevation -3.5m of the reservoir bottom, there are three zones of argillaceous silt, medium fine sand and silty clay. The argillaceous silt zone is composed of mud, sand and silt, containing shells and broken shells, which is loose, watery and plastic in a layer of 4~10m; the silty clay zone consists of clay and sand in a layer of 0~3m, thickening towards the sea; and the sand zone consists of medium coarse sand and medium fine sand, tightly deposited. Samples were taken from the three zones for laboratory physical testing to classify the three diffusion zones (Fig. 1).

The overall thickness of the deposition is 3~17m, thickening towards the sea. It is thicker at the west of the island than at the east.

Water environment: Water analysis shows that the river water contains 0.211g/L of salt, and the shore water contains 26.705g/L. The proposed reservoir is at the tidal zone, and the bottom deposition has a high amount of chlorine and magnesium ions with high hardness. With the reservoir, the solute in the deposition will gradually diffuse into the upper freshwater, affecting the storage water.

THE MODEL

As the spatial distribution and changes of salt levels are affected by its diffusion and the convection-dispersion of water, the quasi-3D model is established by the following procedure (Chen & Chen1999, Ma et al. 2003, Ma et al. 1997, O'Connor et al. 1998, Wallach & Van Genucheten 1990).

2D Model: The 2D model (1) is used to simulate the water surface at initial reservoir storage up to a depth H. The quasi-3D model is used to simulate the distribution of solute at various depths on the basis of the 2D model by vertical linear interpolation.

$$\begin{cases} \frac{\partial C}{\partial t}=\frac{\partial}{\partial x}(D_x\frac{\partial C}{\partial x})+\frac{\partial}{\partial y}(D_y\frac{\partial C}{\partial y})-V_x\frac{\partial C}{\partial x}-V_y\frac{\partial C}{\partial y}+\varepsilon_1 C^*-\varepsilon_2 C+I & (x,y)\in G, 0<t\le T \\ C|_{t=0}=C_0(x,y) & (x,y)\in\overline{G} \\ [(V_x C-D_x\frac{\partial C}{\partial x})\cdot n_x+(V_y C-D_y\frac{\partial C}{\partial y})\cdot n_y]|_\Gamma=q(x,y,t) & (x,y)\in\Gamma, 0<t\le T \end{cases}$$

In which:

$C(x,y,t)$ - concentration of solute, M/L^3;

$C^*(x,y,t)$ - concentration of solute in atmospheric precipitation, M/L^3;

Dx, Dy - diffusion (including dispersion) coefficient respectively in the x, y directions, L^2/T;

Vx, Vy - velocity component of flow respectively in the x, y directions, L/T;

ε_1, ε_2 - respectively replenishment and evaporation per volume of water at a unit time, $L^3/T\,L^3$;

I - bottom source, M/L^3T;

q - solute flux passing the class II boundary, M/L^2T;

n_x, n_y - number of normal vectors.

With reference to the hydrogeologic and water environment, the overall reservoir boundary is taken as class II. The lateral diffusion flux, $q(x, y, t) = 0$.

For the strength of replenishment from rivers,

$$S = Q^{(in)}C^{(in)}, \quad (x,y)\in\Gamma_{in}, 0<t\le T$$

is used, in which S is strength of inflow replenishment; Γ_{in} is inflow boundary; $Q^{(in)}$ is inflow discharge; and $C^{(in)}$ is concentration of inflow.

Galerkin finite element equation: A finite element equation for model (1) is derived using the Galerkin method. Multiplying the equation with a basic function as weight, applying the integral to zone G, finding the solution by means of a partial integral or Grimn's formula, then using the functional relation of linear interpolation for a unit concentration and the trapezoidal method to finally obtain the equation for water depth H.

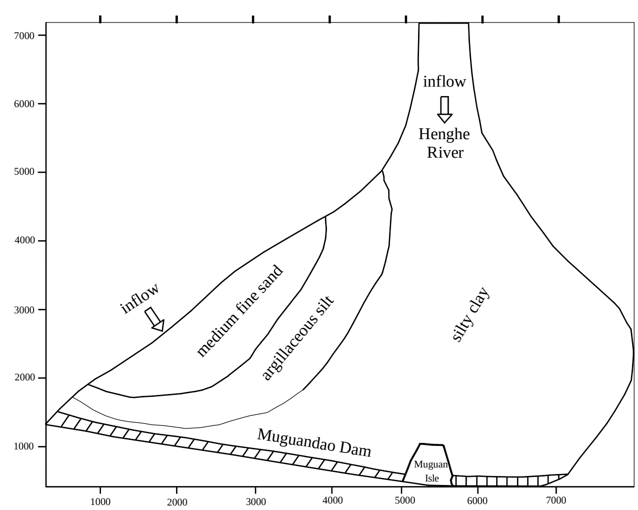

Fig. 1: Reservoir bottom material and diffusion zones.

$$\sum_{i=1}^{n_p}(M_{ij}+\frac{K_{ij}}{2}\Delta t_l)C_i^l=\sum_{i=1}^{n_p}(M_{ij}-\frac{K_{ij}}{2}\Delta t_l)C_i^{(l-1)}+\frac{f_j^l+f_j^{(l-1)}}{2}\Delta t_l,$$
$$j=1,2,\cdots,n_p, l=1,2,\cdots,n,$$
$$\Delta t_l=t_l-t_{l-1}, C_i^{(l)}=C_i(t_l)。$$

The solution is derived using the LU method.

Quasi-3D model: Besides plane simulation, finding out the concentration of salt at any other point beyond the plane is a key issue. We use the method of linear interpolation in the vertical direction in the model. The procedure includes:

Step 1: During impoundment, concentrations, $C(x_i, y_i, z_0, t)$, at all nodes of the plane at a given depth, z_0, and at the time, Δt, are derived using the 2D finite element method by defined time steps. The interpolation formula can be used for the value of any point (x, y, z_0) at the unit $\Delta\beta$;

Step 2: For the value of any point, $p(x, y, z, t)$, if the point, p, is at a given plane, step 1 applies. If not, $p_1(x, y, z_1, t)$ and $p_2(x, y, z_2, t)$ corresponding to p at the upper and lower planes are found to obtain $C_1(x, y, z_1, t)$ and $C_2(x, y, z_1, t)$. Finally, $C(x, y, z, t)$ at $p(x, y, z, t)$ is:

$$C(x,y,z,t)=\frac{[C_2(x,y,z_2,t)-C_1(x,y,z_1,t)]\cdot z+C_1(x,y,z_1,t)\cdot z_2-C_2(x,y,z_2,t)\cdot z_1}{z_2-z_1}$$

Following the above steps with the vertical linear interpolation method results in the concentration at any point, $p(x, y, z, t)$, of the storage water.

Reliability analysis: The function $C(x, y, z, t)$ can be taken as a continuous derivable function, for which linear approximation is possible using Taylor's formula. In the above model, the distance between the neighbouring two planes, $|z_1-z_2| \leq 7.5$m (storage depth) is much smaller than the length of any side of the triangular unit based on the finite element method in the actual coordinate system. The error of the linear interpolation vertically between two planes is smaller than that of the 2D linear interpolation for the triangular unit on any plane.

The linear interpolation theory shows, and it can be proved that, with a small inter-plane distance, the solution to the quasi-3D model through vertical linear interpolation is close to the solution to the actual 3D model through the finite element method. The concentration of any point in the actual water storage $C(x, y, z, t)$ would have an error in the allowable range through calculation using the quasi-3D model and the calculation accuracy is satisfactory in view of predicting water quality.

The mathematic model and the solution method are able to simulate and predict the spatial water quality of the reservoir storage through simple and explicit procedures by means of computer programming.

BASIC DATA

Plane section: The reservoir has a normal water level of 4.0m and corresponding surface area of 25km^2. The area is divided into 361 triangular units with 211 joints, including 152 internal ones and 59 boundary ones (Fig. 2).

Meteorology, hydrology, flow field and solute data: The concentration of salt applied in the model is the observed value. Precipitation, evaporation from the water surface and inflow are obtained from the monthly average data for typical years. The amount of water diversion is the planned value, and the daily average diversion is 22×10^4m^3/d. The ordinary wind is in the direction of NW 10º~50º, $f = 2\Omega\sin\varphi$, where Ω is the angular velocity of the earth's rotation, about $2\pi/(24\times3600)$1/s, and φ is the latitude of the calculated zone.

The reservoir has a flat bottom with an even and wide water surface. With impoundment, flows have a visible velocity at the intake and outlet and calm at other points. The simulation of flow fields shows the effect of the NW wind.

Model parameters: On the basis of the scale, hydrology and water environment and with reference to the observed data of other estuarine reservoirs with similar meteorology, geometry, flows and water environment, the flow velocity and parameters of the reservoir are identified. The selected transverse diffusion coefficient is $E_x = 1.5\times10^{-3}$m^2/s, longitudinal diffusion coefficient is $E_y = 7.5\times10^{-3}$m^2/s, and vertical diffusion coefficient is $E_z = 3.5\times10^{-3}$m^2/s.

ANALYSIS OF SIMULATION RESULTS

The annual rainfall varies largely and distribution is uneven throughout the year, concentrating in June to September. The annual average rainfall in these months is 562mm, 70.1% of the total. Reservoir impoundment should occur in June to September. The initiation date of June 1 and three typical years of high flow, medium flow and low flow are considered. The concentration distribution of salt is produced during simulation, that is the dynamic simulation of the water storage, to reflect the vertical diffusion of salt and provide more detailed information for the future desalinization measures, in particular during impoundment.

Taking a year of normal flow as an example, the variation of salt content in the initial stage of impoundment is analysed.

With Δt = 60s input the model, the concentration distribution of salt is obtained for the storage levels of 0.5m, 1.5m and 4.5m.

Concentration distribution of salt at 4.5m. With the initial period of 365d, the distribution is given in Fig. 3. This shows that the salt distribution at the surface is mainly in the

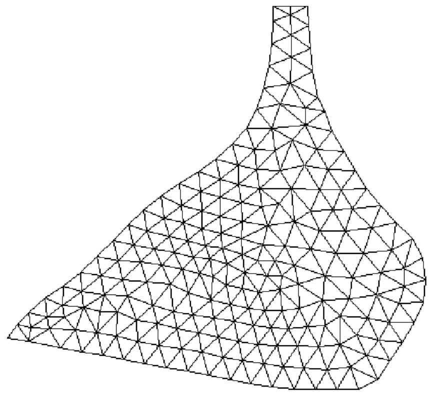

Fig. 2: Division for finite element calculation.

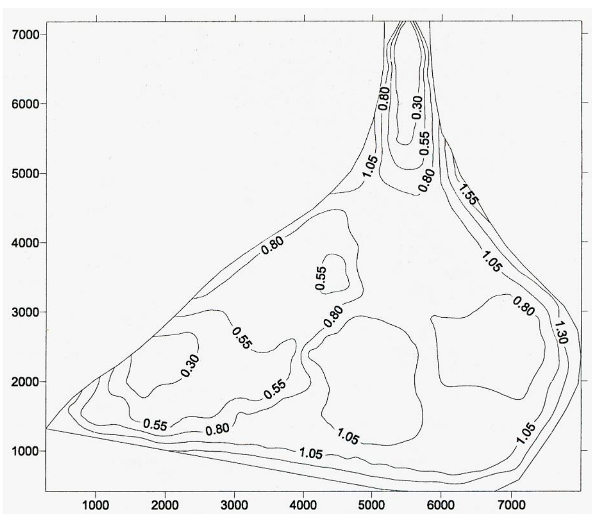

Fig. 3: Salt concentration distribution isoline at 4.5m.

range of 0.3g/L to 1.55g/L. Salt content ranges from 0.8g/L to 1.05g/L in the silty clay zone and 0.3g/L to 0.8g/L in the argillaceous silt and medium silt zones. The maximum salt content is above 1.55g/L, and above 1.3g/L in the second layer. The difference is due to the fact that this layer has a simulation time of 365d and the second layer of 78d, that is, the bottom salt has 287d more diffusion time at the third layer than the second layer.

If impoundment happens in a normal flow year, when the water level rises to 0.5m, salinity ranges from 0.3g/L to 2.8g/L on the surface; at the level of 1.5m, salinity ranges from 0.3g/L to 1.3g/L.

CONCLUSIONS

1. With impoundment in the reservoir, freshwater directly comes into contact with the bottom porous deposition, which is full of salty water, creating a complex physical and chemical process of salt migration. The model gives a good simulation of salt migration in time and space.

2. As salt migrates vertically by diffusion, besides a full consideration of salt migration at the surface, knowing the salt content at any other point is a key technical issue for the simulation work. Therefore, with the assistance of numerical analysis and computer software, we put forward the quasi-3D numerical simulation method with vertical linear interpolation, and carried out a reliability analysis. Practice has revealed that this method is reliable for the estuarine reservoirs with high vertical gradients of concentration.

3. With impoundment in a year of normal flow, the simulation selected the three layers corresponding to the storage depths of 0.5m, 1.5m and 4.5m.

ACKNOWLEDGEMENTS

This research has been financed by the National Natural Science Fund Projects (41202175) of China.

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