Application of the USGS diffusion hydrodynamic model (DHM) in evaluation of estuary flow circulation

Theodore V. Hromadka II*, Chung-Cheng Yen & Patricia A. Bajak
Williamson & Schmid, 15101 Red Hill Avenue, Tustin, California 92680, USA

Many of the hydrodynamic models used for tidal flow regime and storm surge analysis are based upon use of the two-dimensional hydrodynamic equations, which are obtained from the parent three-dimensional flow equations by averaging with respect to the vertical coordinates. Various numerical techniques, such as finite difference, finite element, and the method of characteristics have been used to solve these mathematical models.

The USGS diffusion hydrodynamic model has been developed to simulate two-dimensional surface water flows, and solves the governing flow equations by neglecting the inertia terms. The DHM has previously been applied to a hypothetical bay study with results comparable to those obtained using the method of characteristics. In the current work, the DHM is applied to the Batiquitos Lagoon located in the City of Encinitas, California for the purposes of evaluation of tidal flow characteristics. The main objective is to determine local flow velocities and circulation patterns in the lagoon caused by the incoming and outgoing tide.

INTRODUCTION

Many of the hydrodynamic models used for tidal flow regime and storm surge analysis are based upon use of the two-dimensional hydrodynamic equations, which are obtained from the parent three-dimensional flow equations by averaging with respect to the vertical coordinates. Various numerical techniques, such as finite difference, finite element, and the method of characteristics have been used to solve these mathematical models. A full review of these models is given in Heaps and Nihoul & Tamant.

The USGS diffusion hydrodynamic model (Hromadka & Yen) has been developed to simulate two-dimensional water flows, and solves the governing flow equations by neglecting the inertia terms. The DHM has previously been applied to a hypothetical bay study with results comparable to those obtained using the method of characteristics (La). In the current work, the DHM is applied to the Batiquitos Lagoon located in the City of Encinitas, California (see Fig. 1) for the purposes of evaluation of tidal flow characteristics. The main objective is to determine low flow velocities and circulation patterns in the lagoon caused by the incoming and outgoing tide. This information will be useful in developing sediment and debris control and reduction measures (if necessary) for the watershed of Batiquitos lagoon, aimed at preventing further siltation of the lagoon.

DESCRIPTION OF THE DHM

Details on the theory used and verification of the DHM are contained in the USGS Water Resources Investigation Report, 87-4137 (Hromadka & Yen). Only a brief development of the DHM governing equations are provided herein.

The two-dimensional unsteady flow equations consist of one equation of continuity

\[
\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial z}{\partial t} = 0
\]  

(1)

and two equations of motion

\[
\frac{\partial Q_x}{\partial t} + \frac{\partial}{\partial x} \left( Q_y Q_x \right) + \frac{\partial}{\partial y} \left( Q_x Q_y \right) + gA \left[ S + \frac{\partial h}{\partial x} \right] = 0
\]

(2a)
\[ \frac{\partial Q_x}{\partial t} + \frac{\partial}{\partial y} \left( \frac{Q_x}{A_x} \right) + \frac{\partial}{\partial x} \left( \frac{Q_y}{A_y} \right) + gA_y \left[ S_y + \frac{\partial h}{\partial y} \right] = 0 \]  

in which \( t \) is time, \( x \) and \( y \) (and the subscripts) are the orthogonal directions in the horizontal study plane; \( q_x \) and \( q_y \) are the flow rates per unit width in the \( x \)- and \( y \)-directions; \( z \) is the depth of water; \( \bar{Q}_x \) and \( \bar{Q}_y \) are the
in which \( n \) is the Manning's roughness factor (based on a composite or weighted average); \( R_x, R_y \) are the hydraulic radii in \( x, y \)-directions, respectively; and the constant \( C = 1 \) for SI units and 1.486 for US Customary units.

In the DHM, the local and convective acceleration terms in the flow equation (i.e. the first three terms of eqn (2)) are neglected (Akan & Yen). Thus, eqn (2) is simplified as

\[
S_x = -\frac{\partial h}{\partial x} \tag{4a}
\]

and

\[
S_y = -\frac{\partial h}{\partial y} \tag{4b}
\]

Combining eqns (3) and (4) yields

\[
Q_x = \frac{C}{n} A_x R_x^{2/3} \left( -\frac{\partial h}{\partial x} \right) \left( \frac{\partial h}{\partial x} \right)^{1/2} \tag{5a}
\]

\[
Q_y = \frac{C}{n} A_y R_y^{2/3} \left( -\frac{\partial h}{\partial y} \right) \left( \frac{\partial h}{\partial y} \right)^{1/2} \tag{5b}
\]

which accounts for flows in both positive and negative \( x \)- and \( y \)-coordinate directions. The flow rates per unit width in the \( x \)- and \( y \)-directions can be obtained from eqn (5) as

\[
g_x = \frac{C}{n} z R_x^{2/3} \left( -\frac{\partial h}{\partial x} \right) \left( \frac{\partial h}{\partial x} \right)^{1/2} \tag{6a}
\]

\[
g_y = \frac{C}{n} z R_y^{2/3} \left( -\frac{\partial h}{\partial y} \right) \left( \frac{\partial h}{\partial y} \right)^{1/2} \tag{6b}
\]

Substituting eqn (6) into eqn (1), gives

\[
\frac{\partial}{\partial x} \left[ \frac{C}{n} z R_x^{2/3} \left( -\frac{\partial h}{\partial x} \right) \left( \frac{\partial h}{\partial x} \right)^{1/2} \right] + \frac{\partial}{\partial y} \left[ \frac{C}{n} z R_y^{2/3} \left( -\frac{\partial h}{\partial y} \right) \left( \frac{\partial h}{\partial y} \right)^{1/2} \right] + \frac{\partial h}{\partial t} = 0
\]

or

\[
\frac{\partial}{\partial x} \left[ K_x \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K_y \frac{\partial h}{\partial y} \right] = \frac{\partial h}{\partial t} \tag{7}
\]

where

\[
K_x = \frac{C}{n} z R_x^{2/3} \left| \frac{\partial h}{\partial x} \right|^{1/2}
\]

and

\[
K_y = \frac{C}{n} z R_y^{2/3} \left| \frac{\partial h}{\partial y} \right|^{1/2}
\]
Fig. 4. (a) Results of deep lagoon (Case 2) simulation (cont.); (b) results of shallow lagoon (Case 1) simulation (cont.); (c) results of shallow lagoon (Case 1) simulation (cont.).

\[ K_r = \frac{C}{n} \left( \frac{z R}{v} \right)^{\frac{2}{3}} \left( \frac{\partial h}{\partial y} \right)^{\frac{1}{2}} \]

The numerical algorithms used for solving eqn (7) are fully discussed in the USGS Water Resources Investigation Report, 87-4137 (Hromadka & Yen). The data preparation needs for a floodplain analysis is also discussed in the USGS Water Resources Investigation Report.
DESCRIPTION OF THE BATIQUITOS LAGOON

Batiqitos Lagoon (see Fig. 1) is located at the northwestern part of the City of Encinitas, California. The lagoon is approximately 2.3 miles long and 0.25 miles wide and is constricted by three bridges. The front portion of the lagoon is between the Pacific Coast Highway (PCH) and the Atchison Topeka and Santa Fe (AT&SF) railroad. The AT&SF railroad and the San Diego freeway (I-5) form the middle portion. The upstream portion extends from I-5 to the mouth of the San Marcos Creek and comprises 70% of the entire lagoon.

DESCRIPTION OF BATIQUITOS LAGOON MODEL

The lagoon was discretized into 130 grid finite-elements, of dimension 400-feet, as shown in Fig. 2. A longitudinal gradient of 1-5 feet/mile was assumed for the lagoon bottom along the east-west direction and 0.75 feet/mile was assumed for the north-south direction. An effective flow path of 100 feet was assumed for the restrictions under the PCH, the AT&SF railroad, and also the I-5 freeway. A Manning’s roughness factor of 0.035 was assumed for the entire lagoon. To model the flow-depth variation, with respect to time, due to tidal fluctuations, the sinusoidal equation is used to model the tidal depth \( Z(t) \) as shown in Fig. 3 as follows:

\[
Z(t) = A \sin \left( \frac{2\pi(t + \xi)}{T} \right) + M
\]

where \( A = \) amplitude (feet), \( \xi = \) phase lag (hour), \( M = \) mean water surface elevation (feet), \( t = \) time (hour), \( T = \) tidal period (hour). Due to only minor freshwater inflow from the tributary San Marcos Creek, the DHM model further assumes that the circulation of the lagoon is driven by the fluctuations of the assumed tide hydrograph.

Shallow and deep-water depths were used to investigate the flow circulations for existing and dredge conditions, respectively.

Case 1 — Shallow lagoon analysis

An initial water surface elevation of 3 feet above mean sea level was assumed for the lagoon. The tide hydrograph was specified to have a period of 12 hours, an amplitude of 3 feet, and to coincide with the standard sine curve (i.e. phase lag is zero). Because of the long and narrow shape of the lagoon, negligible flow circulation inside the lagoon is predicted from the DHM model. Figure 4 depicts the water surface profiles for the shallow lagoon during a 24-hour simulation.

Figure 4 indicates that the flow direction in the lagoon is either inward or outward depending upon the rising or the recession of the assumed tide hydrograph, respectively. Figure 5 illustrates the averaged water surface elevations for the downstream, central, and upstream portions of the lagoon corresponding to the specified tide hydrograph. The DHM results indicate that the two crests of the tide hydrograph (between hour 0-6 and hour 12-18) have the major effects on the front and middle portions of the lagoon and negligible impact on the upstream portion of the lagoon. The averaged flow velocity of the lagoon was predicted to be less than 2 ft/sec during the entire 24-hour simulation. Therefore, deposition of sediment may occur under the assumed shallow lagoon conditions.

Case 2 — Deep lagoon analysis

In Case 2, the lagoon was assumed 7 feet deeper than in the Case 1 analysis, to simulate a dredged lagoon. The same initial and boundary conditions as used in Case 1 were also used to investigate the flow conditions for the dredged lagoon. Figure 6 illustrates the averaged water surface profiles for a 24-hour simulation within the deep lagoon. Average flow velocities of 5-5 ft/sec and 4.6 ft/sec were estimated for the central and upstream portions of the lagoon. This indicates that the area between the AT&SF railroad bridge and the breakwater has sufficient flow velocity characteristics to transport the sediment from San Marcos Creek to the front portion of the lagoon. The average velocity in the front portion of the lagoon was estimated to be 2.8 ft/sec during the low tide period. Thus, the sediment may accumulate on the downstream portion of the lagoon. Figure 7 depicts the average water surface elevations corresponding to the tide hydrograph. Figure 7 suggests that the tide hydrograph has more hydrodynamic influence on the assumed deep-water lagoon configuration than on the shallow lagoon.

TOPOGRAPHIC MODEL

A short version of the topographic routing component of the DHM is presented herein in FORTRAN. The FORTRAN listing is provided in Appendix A, with User’s Instructions given in Appendix B.
Fig. 6. (a) Results of deep lagoon (Case 2) simulation; (b) results of deep lagoon (Case 2) simulation (cont.), (c) results of deep lagoon (Case 2) simulation (cont.).
CONCLUSIONS

The DHM has been primarily used for floodplain analysis. In this study, the DHM is used to evaluate the flow characteristics within a narrow estuary. Application of the DHM to Bataquitos Lagoon provides the average water surface profiles and flood velocities within the lagoon. These computed results indicate that the subject lagoon has negligible capability to transport sediment under existing shallow-water conditions. Modeling an assumed dredged lagoon does indicate some sediment transport capability but more detailed sedimentation and estuary analysis are needed to ensure an optimum condition for the lagoon.

REFERENCES


APPENDIX A: PROGRAM LISTING

```
APPENDIX: A

PROGRAM NAME: TOPOGRAPHIC MODEL
CHARACTERISTICS: 4000, 6000, 2000, 10, 10, 10
DESCRIPTION: 1-D, 1-D, 1-D, 1-D, 1-D, 1-D
SIMULATION TYPE: (SIMPLE, SIMPLER, SIMPLER, SIMPLER, SIMPLER, SIMPLER)
SIMULATION MODE: (SIMPLE, SIMPLE, SIMPLE, SIMPLE, SIMPLE, SIMPLE)
INSTRUCTIONS:

FLOODPLAIN FORMULA:

EQUATION (1.1): EQUATION (1.2): EQUATION (1.3): EQUATION (1.4): EQUATION (1.5):

SIMULATION TIME (HOURS)

--- AVERAGED WATER SURFACE ELEVATION ON FRONT PORTION OF THE LAGOON ---
--- AVERAGED WATER SURFACE ELEVATION ON THE MIDDLE PORTION OF THE LAGOON ---
--- AVERAGED WATER SURFACE ELEVATION ON THE REAR PORTION OF THE LAGOON ---

Fig. 7. Summary of deep lagoon (Case 2) results.
```
Short communication

...
APPENDIX B – USER'S INSTRUCTIONS ON INPUT FILE

The DHM topographic model calls for the following data entries:

Variables

\[
\begin{align*}
DTMIN, & \text{ DTMAX, } DTI, DTD, \text{ SIMUL, TOUT, KODE, KMODEL} \\
NNOD, & \text{ SIDE, TOL, DTOL, DTOLP, XAREA, XGN} \\
FP(1,J), & \text{ J = 1,7} \\
\text{IF(FP(1,5).EQ.2.)FP(1,J), } J = 1,9 \\
& I = 1, \text{ NNOD} \\
NERI & \\
(R(I,J), & \text{ J = 1,2), I = 1, NERI} \\
NFP1, & \text{ NFPF1} \\
(KINP(I), & \text{ HIP(I,J,1), HIP(I,J,2), J = 1, NFPF1), I = 1, NFP1} \\
NRAT, & \text{ NPRAT} \\
(NRATN(I,1), & \text{ NRATN(I,2),} \\
RCURV(I,J,1), & \text{ RCURV(I,J,2),} \\
RCURV(I,J,3), & \text{ J = 1, NPRAT),} \\
& I = 1, \text{ NRAT} \\
NDC & \\
NODDC1(I), & \text{ I = 1, NDC} \\
NFLUX, & \text{ NFOUT} \\
NODFX(I), & \text{ I = 1, NFLUX} \\
\end{align*}
\]

where

\[
\begin{align*}
\text{DTMIN} & \text{ is the minimum allowable timestep in second, (R)} \\
\text{DTMAX} & \text{ is the maximum allowable timestep in second, (R)} \\
\text{DTI} & \text{ is the increment of timestep in second, (R)} \\
\text{DTD} & \text{ is the decrement of timestep in second, (R)} \\
\text{SIMUL} & \text{ is the total simulation time in hour, (R)} \\
\text{TOUT} & \text{ is the output period in hour, (R)} \\
\text{MODE} & \begin{cases} 0, \text{ suppress the efflux} \\
1, \text{ output the efflux} \end{cases} \begin{cases} \text{velocities} \quad \text{(I)} \\
\text{velocities} \end{cases}
\end{align*}
\]

KMODEL

\[
\begin{align*}
1, \text{ kinematic routing} \\
\text{technique} \quad \text{(I)} \\
otherwise, \text{ diffusion} \\
\text{hydrodynamic model}
\end{align*}
\]

NNOD is the total number of nodal points for flood plain, (I)

SIDE is the length of the uniform grid size in feet, (R)

TOL is the specified surface detention in feet, (R)

DTOL is the maximum change of water depth in feet for each timestep, (R)

DTOLP is defined as

\[
\text{DTOLP} = \frac{\text{change of water depth}}{\text{ pervious water depth}} \times 100\% \ (R)
\]

XAREA is the global effective area factor, (R)

XGN is the global Manning's factor, (R)

FP(1,1) is the northern nodal point of node 1, (R)

FP(1,2) is the eastern nodal point of node 1, (R)

FP(1,3) is the southern nodal point of node 1, (R)

FP(1,4) is the western nodal point of node 1, (R)

FP(1,5) is the flag for global/local element, (R)

FP(1,5) \begin{cases} 1, \text{ — global element used} \\
2, \text{ — local element used} \end{cases}

FP(1,6) is the averaged ground surface elevation for node 1 in feet, (R)

FP(1,7) is the initial water depth for node 1 in feet, (R)

FP(1,11) is the northern effective flow-path, factory of node 1, (R)

FP(1,12) is the eastern effective flow-path, factor of node 1, (R)

FP(1,13) is the southern effective flow-path, factor of node 1, (R)

FP(1,14) is the western effective flow-path, factor of node 1, (R)
Short Communication

FPA(1,5) is the northern Manning's factor of node 1, (R)
FPA(1,6) is the eastern Manning's factor of node 1, (R)
FPA(1,7) is the southern Manning's factor of node 1, (R)
FPA(1,8) is the western Manning's factor of node 1, (R)
FPA(1,9) is the effective area factor of node 1.
NERI is the number of data pairs for uniform effective rainfall rate, (I)
R(I,1) is the time (hour) corresponding to the effective rainfall rate, (R)
R(I,2) is the effective rainfall intensity (in/hr) ordinate for effective rainfall rate, (R)
NFPI is the number of input nodal points for the flood plain, (I)
NPFP1 is the number of pair of inflow hydrograph rate entries, (I)
KINP(I) is the array that stores the inflow boundary condition nodal points (I)
HP(I,1) is the time (hour) corresponding to the inflow hydrograph, (R)
HP(I,2) is the inflow rate (cfs) ordinate for the inflow hydrograph, (R)
NRAT is the number of the rating curves, (I)
NPRA1T is the pair of rating curve entries, (I)
NRATN(I,1) is the upstream node number of rating curve 1, (I)
RATN(I,2) is the downstream node number of rating curve 1, (I)
RCURV(I,J,1) is the array which stores the depths of rating curve 1, (R)
RCURV(I,J,2) is the array which stores the multipliers of rating curve 1, (R)
RCURV(I,J,3) is the array which stores the exponent factors of rating curve 1, (R)
NDC is the number of critical-depth outflow nodal points, (I)
NODDC(I) is the array which stores the critical-depth outflow nodal points, (I)
NFLUX is the number of nodal points where outflow hydrographs are being printed, (I)
TFOUT is the output interval (hour) for outflow hydrograph, (R)
NODFX(I) is the array which stores the nodal points where outflow hydrographs are being printed, (I)

Notes:
1. If any value of NERI, NFPI, NDC, NRAT, NFLUX and NODC is equal to zero, then the values for the corresponding array need not be entered in the input file.
   For an example, if NERI = 0 then R(I,1) needs not be included in the input file.
2. If FP(I,5) equals to two, then the local element information (FPA(I,1) = 1.9) need be entered in the next line immediately after FP(I,5), I = 1,7.
3. (R) denotes real number and (I) denotes integer number.