

Simulation of Nitrogen and Phosphorus Removal in Ecological Ditch Based on EFDC Model

S M Li^{1,2}, X L Wang², Q Y Zhou¹ and N N Han¹

¹ Department of water conservancy engineering, Tianjin Agriculture University, Tianjin 300384, China

² State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin, China

the corresponding author's e-mail address: lisongmin228@126.com

Abstract: Agricultural non-point source pollution threatens water quality and ecological system recently. To control it, the first and most important task is to control the migration and transformation of nitrogen and phosphorus in the agricultural ditches. An ecological ditch was designed, and according to the design a pilot device was built, the mechanism of N and P removal in ditches under the collaboration of aquatic organisms-hydraulic power was studied through the dynamic and static experiments, in order to find out the specific influences of different environmental factors such as influent concentration, influent flow and water level. The transport and diffusion of N and P in the ditch was simulated by a three dimensional water quality model EFDC, the simulation results and the experimental data were compared. The average relative errors of EFDC model simulated results were all less than 15%, which verified the reliability of the model.

1. Introduction

Science the 20th century, as the point source pollution control effectively enhanced, the agricultural non-point source pollution is becoming to be an important factor in water pollution. Ecological ditch is a new interception system proposed in recent years with the development of Ecological Water Conservancy, consist of water, soil, plants and microbial composition, not only has the proper irrigation and drainage ditches function, but also intercept and adsorb water pollutants, which can purify water, and has good visual effects, with great promotion prospects. Therefore, the study of migration and transformation of pollutants in the ecological ditches is of great necessary. Effective hydrodynamic model is an important means to carry out a comprehensive study of water environment system.

In recent years, research content and methods of water quality model has been continually deepen and improved, the development of mathematics and computer simulation technology provides a broad space for agricultural nitrogen and phosphorus loss assessment study, through these models, not only can simulate and predict the migration and transformation of pollutants in water, and the water quality control can be further improved and managed, which may provide a scientific basis and decision-making program.

It was widely believed that nitrogen and phosphorus in farmland are converted follow the first-order kinetics theory Since the 1970s, and quantitative research on non-point source pollution mainly based on a simple statistical model, it is single in function and structure, so the modeling and



estimation capacity is limited. Then the researches on mechanistic models rise, and it became to be the main direction of non-point source model. Up to now, research contents and methods of surface water quality model have been constantly deepening and improving (Li, 2009). Application of water pollution transport model has been studied by the scholars at home and abroad (Chau & Jiang, 2003; Salterain, 2003). Wang (2008) simulated the flow field of Jincang Lake with different designs used MIKE 21 model, and appropriate solutions were selected for the analysis and prediction of water quality changes. Pan (2009) made a visual simulation of water quality in the early water diversion used DELFT3D software, and the rationalization advice was proposed. WASP and EFDC model became to be a hot research currently, they can be used in the surface water systems, such as rivers, lakes, reservoirs, estuaries, oceans and wetlands. Pilar (1997) simulated various kinds of environmental factors in reservoirs used WASP model. EFDC model is a three-dimensional mathematical model of water quality, it can be used to simulate the concentration changes of 21 kinds of water quality indicators, including COD, ammonia nitrogen, total nitrogen, total phosphorus etc., can quickly coupled hydrodynamic, sediment and water quality modules, the process of different model interface program can be omitted, at the same time, it has a complete preprocessing and post-processing software (EFDC-Explorer) (Hamrick, 1997). Currently, EFDC model has become one of the most respected models in US EPA, and is widely used in various universities, government agencies and environmental enquiry agencies. Ji & Mortonb (2001) simulated the dry and wet grid of shallow water estuarine in Morro Bay area, California based on the EFDC hydrodynamic model, in the previous studies, the most common problem is the lack of detailed experimental data of the calibration model and the wet and dry mesh design verification, it will be enhanced in the application of EFDC. Chen (2005) described the main programming principles and data structures of EFDC. Water quality of Dianchi Lake was simulated take advantage of load and observation data in the year of 1988 and 1989, the simulation results are in good agreement with the monitoring results.

As above, the simulation and control of nitrogen and phosphorus transport and transformation are mostly focused on hydrodynamic and one or two-dimensional, a certain amount simplification and assumptions was made in the simulation of the actual three-dimensional flow, which can not accurately reflect the evolution of the water flow. Therefore, how to simulate nitrogen and phosphorus pollutants transporting in ditches using three-dimensional mathematical model needs further investigated.

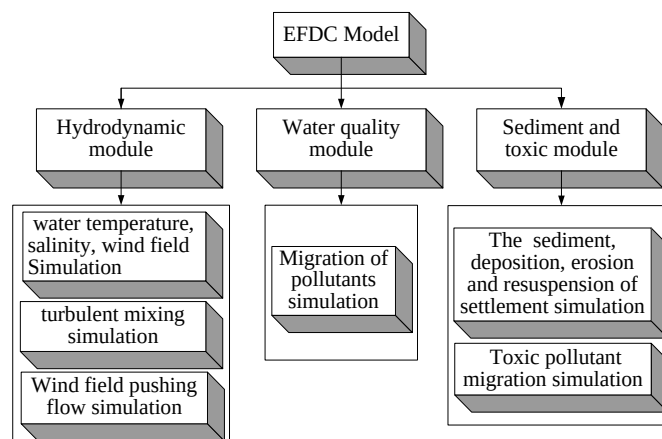


Figure 1. Structure of EFDC model

2. Theory of EFDC Model

EFDC model can realize the simulation of hydrodynamic and water quality of rivers, lakes, reservoirs, wetlands systems, estuaries, oceans and other water bodies, which can simulate the concentration Change of 21 kinds of water quality indicators, including COD, ammonia nitrogen, and total phosphorus and so on, the diffusion and degradation of pollutants can be reflected. It includes hydrodynamics, water quality and sediment modules, the structure is shown in Figure.1, you can

control the input file to simulate different modules, one-dimensional, two-dimensional and three-dimensional calculation can be done respectively as needed.

2.1 Hydrodynamic module

The EFDC model's hydrodynamic component is based on the three-dimensional hydrostatic equations formulated in curvilinear-orthogonal horizontal coordinates and a sigma or stretched vertical coordinate. The momentum equations are:

$$\begin{aligned} & \partial_t(m_x m_y H u) + \partial_x(m_y H u u) + \partial_y(m_x H v u) + \partial_z(m_x m_y w u) - f_e m_x m_y H v \\ & = -m_y H \partial_x(p + p_{atm} + \phi) + m_y (\partial_x z_b^* + z \partial_x H) \partial_z p + \partial_z \left(m_x m_y \frac{A_v}{H} \partial_z u \right) + \partial_x \left(\frac{m_y}{m_x} H A_H \partial_x u \right) + \partial_y \left(\frac{m_x}{m_y} H A_H \partial_y u \right) - m_x m_y c_p D_p (u^2 + v^2)^{1/2} u \end{aligned} \quad (1)$$

$$\begin{aligned} & \partial_t(m_x m_y H v) + \partial_x(m_y H u v) + \partial_y(m_x H v v) + \partial_z(m_x m_y w v) - f_e m_x m_y H u \\ & = -m_x H \partial_y(p + p_{atm} + \phi) + m_x (\partial_y z_b^* + z \partial_y H) \partial_z p + \partial_z \left(m_x m_y \frac{A_v}{H} \partial_z v \right) + \partial_x \left(\frac{m_y}{m_x} H A_H \partial_x v \right) + \partial_y \left(\frac{m_x}{m_y} H A_H \partial_y v \right) - m_x m_y c_p D_p (u^2 + v^2)^{1/2} v \end{aligned} \quad (2)$$

$$m_x m_y f_e = m_x m_y f - u \partial_y m_x + v \partial_x m_y \quad (3)$$

Where u and v are the horizontal velocity components in the dimensionless curvilinear orthogonal horizontal coordinates x and y , respectively. The scale factors of the horizontal coordinates are m_x and m_y . The vertical velocity in the stretched vertical coordinate z is w . The physical vertical coordinates of the bottom bed is z_b^* . The total water column depth is H and ϕ is the free surface potential. The effective Coriolis acceleration f_e incorporates the curvature acceleration terms, with the Coriolis parameter, f , according to (3). The Q terms in (1) and (2) represents optional horizontal momentum diffusion terms. The vertical turbulent viscosity A_v relates the shear stresses to the vertical shear of the horizontal velocity components.

2.2 Water quality module

The generic transport equation for a dissolved or suspended material having a mass per unit volume concentration C , is

$$\partial_t(m_x m_y H C) + \partial_x(m_y H u C) + \partial_y(m_x H v C) + \partial_z(m_x m_y w C) - \partial_z(m_x m_y w_{sc} C) = \partial_x \left(\frac{m_y}{m_x} H K_H \partial_x C \right) + \partial_y \left(\frac{m_x}{m_y} H K_H \partial_y C \right) + \partial_z \left(m_x m_y \frac{K_v}{H} \partial_z C \right) + Q_c \quad (4)$$

Where K_v and K_H are the vertical and horizontal turbulent diffusion coefficients, respectively, and Q_c represents external sources and sinks and reactive internal sources and sinks.

3. Modelling of EFDC

3.1 Grid subdivision

Grid subdivision is a very important step in the modeling process. The part of ditch in the model device is selected to be the calculation area, because the ditch model unit was designed with a regular size, a rectangular net was used in this simulation, the computational domain was divided into 360 equidistant meshes, with the mesh size $0.1\text{m} \times 0.1\text{m}$.

According to the actual situation in Yixing experimental area, according to Froude's law, the ditch device was built with length 6m, width 0.8m, water and sediment depth 0.7m, which cross-section is trapezoidal, top width 0.5m, bottom width 0.2m, depth 0.5m. A distribution tank was set in front of the ditch, and the end was equipped with an outlet located close to the bottom, to ensure drain empty. The water was pumped from tank into ditch.

3.2 sources of data

A series of initial conditions and boundary conditions are required in Hydrodynamic and water quality simulation based on EFDC model. The concentrations of water quality measured on July 29th, 2014

were set as the initial conditions of model, the temperature was 27.2°C, and the boundary conditions were convection boundary controlled by measured flow and concentrations.

Parameters involved in the model were primarily determined through relevant experimental data, references and model calibration, etc. The model described in detail microbial nitrification and denitrification rate, different forms of nitrogen and phosphorus amounts generated under metabolic conditions as well as nitrogen and phosphorus hydrolysis rate.

4. Water Quality Simulations and Verification

In this research, the simulation time period is from July 29th to August 3rd, 2014, a total of 144h. According to the measured value on July 29th, the import boundary of the model was set with ammonia nitrogen concentration 27.21mg/L, nitrate concentration 28.74mg/L, and total phosphorus concentration 1.14mg/L, timing start at zero o'clock on July 29th, at the beginning 12h, the water drained with a 200L/h flow through the ditch, then stopped pumping and discharging, the water in ditch was keeping in a static state.

4.1 TN transport simulation

Take zero o'clock on July 29th 2014 as beginning, 0h (the initial moment), 5h, 12h of the inflow under dynamic conditions and 72h, 144h (the final moment) under the static conditions were selected, to study the variation of TN under the dynamic and static conditions along the ditch. Vertical view of the concentration distributions at the selected moments were shown in Figure 2. The nitrogen pollutants gradually migrate towards the end of the ditch during the first 12h with continuous flow, and the flow disturbances result in the isoconcentration gradient line of TN was more complicated. From 12h to 144h, water in the ditch has been in stationary state, as time prolonged, TN concentration in the ditch decreased, and TN diffused and migrated from high to low concentration area, at last, the isoconcentration line of TN became to be structured.

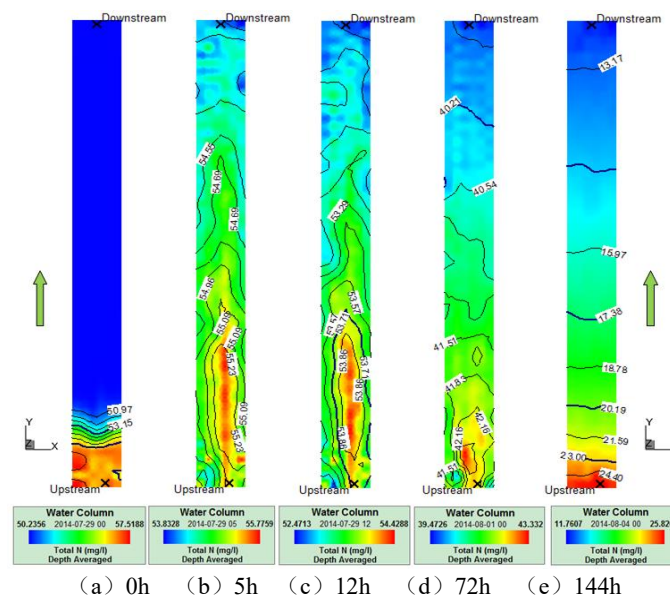


Figure 2. Vertical view of the concentration distributions of TN in different time

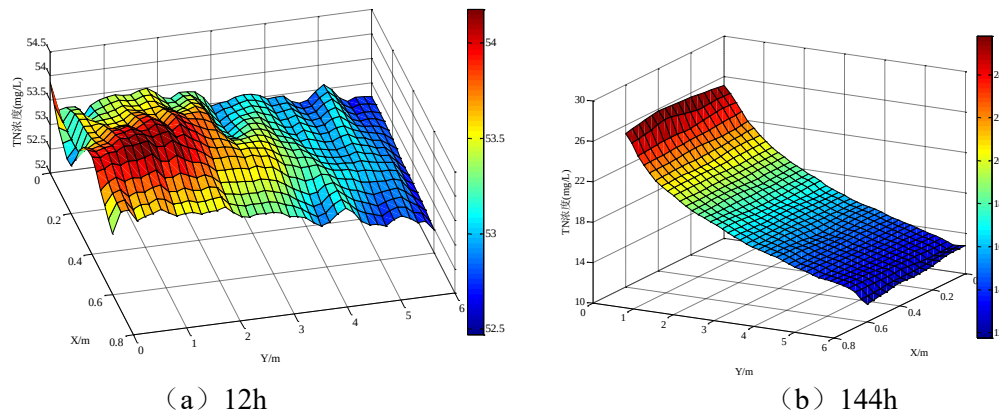


Figure 3. Surface plot of TN concentration distribution at typical moments

Depending on the concentration distribution of TN in the ditch at different times, just stop water time (12h) and the final time (144h) were focused on, as shown in Figure 3. X direction refers to width direction of the ditch, and y direction refers to longitudinal direction. Continued pumping water for 12h, the maximum TN concentration in the ditch was 54.2 mg/L, the minimum value was 52.6 mg/L, compared with the inlet concentration at initial time (57.0 mg/L), TN is slightly reduced, and TN concentrations significantly fluctuated in different sections (Figure 3 (a)). When the water keeps a static state, TN concentrations decreased along the ditch, TN at the entrance was 24.5 mg/L, and at the outlet TN was 12 mg/L, there was small fluctuation among the concentrations in different locations (Figure 3 (b)), this probably because there was small disturbance.

4.2 TP transport simulation

As the TN analysis, the variation of TP under the dynamic and static conditions along the ditch was also studied. Vertical view of the concentration distributions were shown in Figure 4. TP concentration along the ditch was similar to TN, phosphorus contaminants gradually migrate towards the end of the ditch during the first 12h with continuous flow, and the flow disturbances result in the isoconcentration gradient line of TP was complicated. From 12h to 144h, water in the ditch has been in stationary state, as time prolonged, TP concentration in the ditch decreased, and TP diffused and migrated from high to low concentration area, at last, the isoconcentration line of TP also became to be structured.

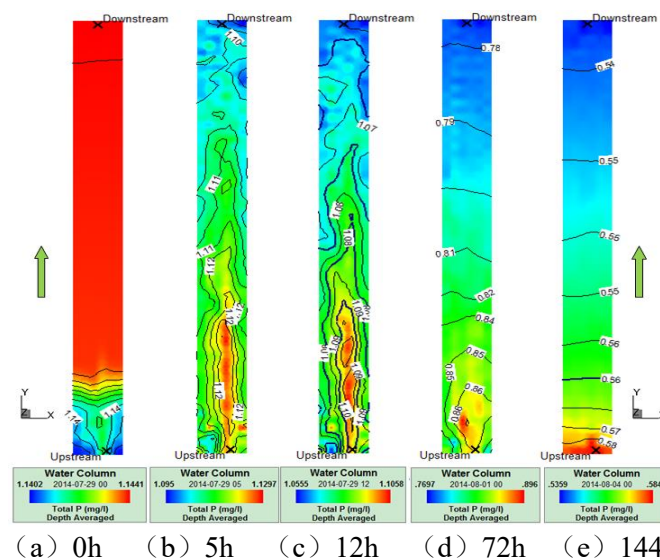


Figure 4. Vertical view of the concentration distributions of TP in different time

The concentration distribution of TP at just stop water time (12h) and the final time (144h) were focused on to analyze the TP distribution, as shown in Figure 5. Continued pumping water for 12h, the maximum concentration of TP was 1.1 mg/L, and the minimum value was 1.06 mg/L, compared with the inlet concentration at initial time (1.14 mg/L), TP is slightly reduced, and the concentrations significantly fluctuated in different sections (Figure 5 (a)). When the water keeps a static state, TP concentrations decreased along the ditch, at the entrance TP was 0.58 mg/L, and at the outlet it was 0.54 mg/L, there was small fluctuation among the concentrations in different locations (Figure 5 (b)).

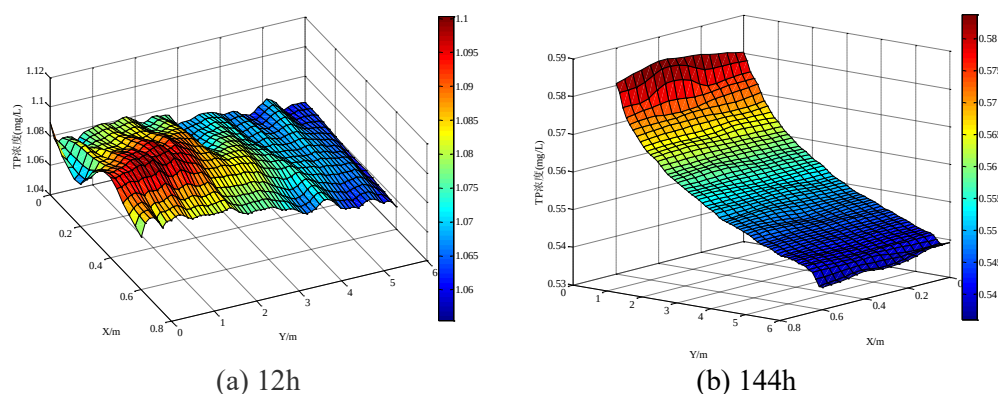


Figure 5. Surface plot of TP concentration distribution at typical moments

Water in farmland ditches stays in stationary state in most times, except for the rainfall, irrigation and drainage events. Based on the above analysis of the simulation results, ecological ditch has certain intercept and removal efficiency for TN, TP under both dynamic and static conditions, and the removal effect would be better when the water keeping stationary for a longer time. When the water flowed continuously for 12h, through the model simulation, removal rate of TN, TP were 6.32% and 5.59% respectively. Then the water start to keep Stationary until 144h, at the final moment TN removal was 65.82% and TP removal rate was 48.15%.

4.3 Model verification

Take the section at 1/4 length of ditch as example, simulated data by EFDC and the test data of TN, TP, concentrations were compared, the results were shown in Figure 6. Through the comparison between the curve and the spot, the simulated and test values of TP agreed well.

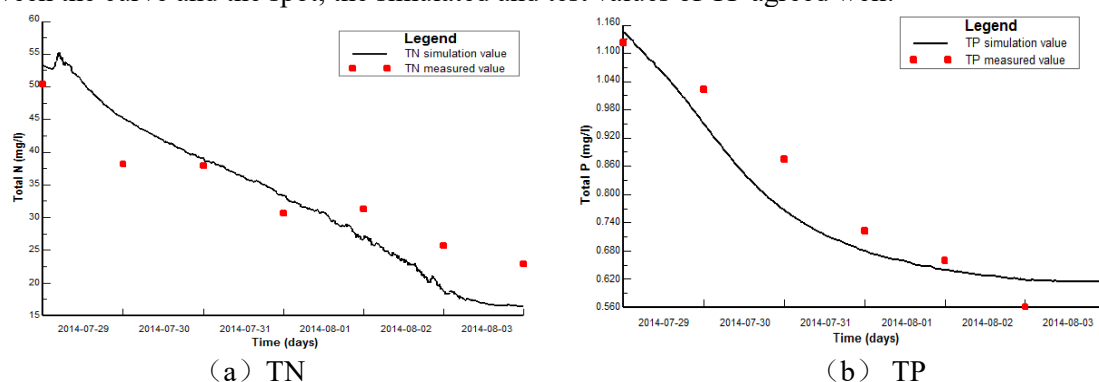


Figure 6. Water quality simulation verification at 1/4 length section

The model simulated results fit well with the test data, with the accuracy less than 15%, the reliability of model is high. The simulated and measured values of TP fit best, simulation error was less than 10%, and the average relative error was only 3.95%. The average relative error of TN was 14.82%. Simulation results of nitrogen indicators are hardly ideal. This may due to the relatively ideal

state simplified by the EFDC model. In fact, with the increase of flooded time, organic matters in the ditch reduced, microbial activity weakened, and the sediment gradually reached adsorption equilibrium, these resulted in the higher concentration at the later period of experiment.

5 Conclusions

At present, there were many studies on the model of nitrogen and phosphorus migration and transformation, they mostly based on one-dimensional simulation. Thus the three-dimensional water quality mathematical model (EFDC) was used in the research, and an ecological ditch model build has been built in laboratory, based on the test data, the model was applied to simulate the water quality variation in the ditch.

In the simulation of water quality change process through EFDC model, many factors were taken into account, such as the sediment adsorption, microbial nitrification and denitrification, etc. the simulation results and error analysis shows that: the ecological ditch have certain effect in TN, TP removal both under dynamic and static conditions, it would be better for a longer standing time. The simulation results fit well with the measured data, the error of all the water quality indicators are less than 15%, showed a high reliability.

ACKNOWLEDGEMENTS

This research was supported by the Chinese National Natural Science Fund (51609170), the Major Science and Technology Program for Water Pollution Control and Management (2012ZX07101-008) and the Natural Science Fund of Tianjin City (16JCYBJC23100).

References

- [1] Chen Y. H. 2005. Water Quality Simulation of Dianchi Lake Based on EFDC Model. *Yunnan Environmental Science* 24(4): 18-30.
- [2] CHAU K W, JIANG Y W. 2003. Simulation of transboundary pollutant transport action in the Pearl River delta. *Chemosphere* (9):1615-1621.
- [3] Hamrick J M, Wu T S. 1997. Computational design and optimization of the EFDC/HEM3D surface water hydrodynamic and eutrophication model//Delich G, Wheeler M F. Next generation environmental models and computational methods. Philadelphia: *Society for Industrial and Applied Mathematics*, 143-161.
- [4] Ji Z. G. Mortonb M R, Hamrick J M. 2001. Wetting and drying simulation of estuarine processes. *Estuarine, Coastal and Shelf Science* 53(5), 683-700.
- [5] Li X. 2009. Modelling of Eutrophic Contaminants Distribution and Degradation Processes in Lake Wuliangsu, Huhhot: College of Water Resources and Civil Engineering, Inner Mongolia Agricultural University.
- [6] Pilar Hernandez, Ambrose Jr, Robert B. 1997. Modeling Eutrophication Kinetics in Reservoir Microcosms. *Water Research*, 31: 2511-2519.
- [7] Pan X.D., Tang J.S, Tian Z.J. 2009. Research on the Numerical Simulation of Water Quality in Huadao Reservoir. *Journal of Anhui Agri. Sci.* 37(21): 10104- 10106, 10108
- [8] SALTERAIN A. 2003. Development and verification of a new simulation tool for water quality prediction in the Ebro river progress in water resources. *Water Pollution VII: Modeling, Measuring and Prediction*, (9):13-22.
- [9] Wang Z. Liu L., Song L. L. 2008. Application of Mike 21 in Ecological Design of Artificial Lake. *Water Resources and Power* 26(5):124-127.