Water resources and wetlands, *Editors: Petre Gâştescu, William Lewis Jr., Petre Breţcan*
Conference Proceedings, 14-16 September 2012, Tulcea - Romania
ISBN: 978-606-605-038-8

COUPLING WETLANDS, SURFACE WATER AND GROUNDWATER THROUGH MATHEMATICAL MODELING

Valentin Zaharia
Technical University of Civil Engineering Bucharest – Faculty of Hydraulic Structures,
Apa Nova Bucuresti, Bucharest, Romania, valentin.zaharia@apanovabucuresti.ro

Abstract

Entire world corcerns more and more to improve, to maintain and to restore the wetlands. Because of the excessive urbanization and the need to have large agricultural areas, dewatering of the wetlands became inevitable in the second half of the 19th century and in the 20th century. Without awareness the environmental impact of these decisions, Romania took also the same measures. Models are simplifications of the reality, that will try to understand physical, chemical and biological processes and transpose them into mathematical relations. In the first steps, the designer of the model should establish the scale of the effort that he/she will be doing. It is necessary to take the first decisions about the future model: creating a 1D, 2D or a 3D model, the calculations will be done with analitical or numerical methods, the simulation will be done stady-state or transient. The mathematical relations between the future wetland, surface water and groundwater must be formulated. Normally, the rivers network and wetlands drain the hydrogeological basins but the exchange rate and intensity of these flows can vary in time. Infiltrations from the surface waters and the flows exchange between river and aquifer are important and influence the storage of the wetland.

Keywords: Mathematical modeling, water balance equation, wetland

1. INTRODUCTION

As a result of the intense concerns had by all countries around the world about environmental policies and sustainable development, restoration of wetlands became an important goal in this direction. First steps in the ecological engineering was made in developed countries which care a lot about the environmental protection. From this reason it is necessarly to remind some of the first projects that had as a purpose the restoration of wetlands: valley of river Nechi (U.S.A. – north of California), floodplain of river Olentangy (U.S.A. –Ohio state), Nowa Slupia (Poland), Ekeby (Sweden) (*Villa, J., Tobon, C., Modeling hydrologic dynamics of a created wetland, Colombia; Kjelin, J., Worman, A., Johansson, H., Lindahl, A., Controlling factors for water residence time and flow patterns in Ekeby treatment wetland, Sweden; Maloszewski, P., Wachniew, P., Czuprynski, P., Study of hydraulic parameters in heterogeneous gravel beds: Constructed wetland in Nowa Slupia, Poland; Zhang, L., Mitsch, W., Modeling hydrological precesses in created freshwater wetlands: an integrated system approach).* The function of these wetlands differs from one case to another: having biological - recreational functions, in this case it can be a perfect habitat for adjacent plants and animals to develop, increasing the touristical role of the area; can represent an lateral attenuation area for a flood wave; could be a wetland which have functions of a treatment plant as a result of the intense economical-industrial activities. The current state of the scientifical development allow achievement of mathematical models through which different scenarios regarding technical and ecological restoration can be simulated. This article consists an assessment of the ways through which the technical restoration of wetlands could be made and the possibility to create a tool for the proper management of the wetlands. Further, the necessary data to realize a model with a high degree of confidence will be presented and the possible technical solutions will be noticed. By coupling wetlands, surface water and groundwater through mathematical modeling, all variables in the hydrological process are considerate. This complete approach conducts to a very good quantification of the hydrologic variables. In all study cases presented before the influence of groundwater was neglected considering that it has a small precentage in the global balance. In addition the exchange rate between river/channel and aquifer wasn't considered. This fact involves a increasing in the degree of uncertainty and an incomplete perception about the hydrological processes. From this reason, the approach that is presented in this article is to integrate all the variables in the hydrological process and to couple the mathematical modeling of the wetland with surface water and groundwater. To achieve this aim it is necessary to collect all available data needed to create the model, consisting of current records and also historical records. In the case that the area was a wetland before and it had been dewatered (a case that is frequently encountered) it is important to perform field campaigns to observe properly the current situation and to understand the physical processes and the their evolving trend.

2. DATA COLLECTION

It is the main concern of the modeller. The huge amount of data that he/she will collect, need to be analyzed, processed and validated. This stage takes 60-70% from the time of the study. The quantity and quality of the input data must be according to the scale of the model (regional/local model). The costs that involves this stage are the largest in such a project. For this reason, data from the archive are very important and preponderant but it is imposed to organize field campaigns to complete the lack of data. For the creation of the coupled model it is necessary to collect data for each activity. Informations about surface water must include data regarding the terrain (Digital Terrain Model or maps with elevation contour lines), bathymetry (where water surface exists), locations of the gauge stations and the records of them (if exists), informations regarding hydrotechnical structures from the area and their operating schedule (surveying plans at weirs, bridges, culverts). Data needed for groundwater are often represented by geological maps, information regarding the locations of the wells and technical data of these, discharges extracted from aquifer, informations about hydraulic conductivities. For the wetland itself, it is necessary to have hourly records for the next variables: precipitations (mm), temperature (°C), air humidity (%), atmospheric pressure (mmHg), wind speed (m/s), solar radiation (W/m^2) (Villa J., Tobon C.) and also a topographical map. A database with all of these data must be created for a easy handling and for updating it periodically.

3. MODEL DEVELOPMENT

To create a suitable coupled model with a high degree of confidence it is necessary to formulate the objectives to which it must respond. For restoration of wetlands the main challange is to maintain the water level above a desired threshold that could be variable in time as a function of the flora and wildlife expand. To achive this goal the water balance of the wetland must be calculated. Through water balance equation is established the volume of water stored in the wetland at each time step. Coupling this through a water level versus volume curve, the water surface elevation is determined. The curve could be obtained by bathymetry measurements if the water surface exists in the area or from the digital terrain model if the water surface doesn't exist. Water balance equation after Mitsch and Gosselink, 2007, could be expressed as follows:

$$\frac{\Delta V}{\Delta t} = Pn + Sin + Gin - ET - Sout - Gout$$

where: ΔV – volume of water storage in the wetland, $\frac{\Delta V}{\Delta t}$ – the rate of change in volume of water storage in the wetland per unit or time t, P_n – net precipitation, S_{in} – surface inflows , G_{in} – groundwater inflows, ET – evapotranspiration, S_{out} – surface outflows, G_{out} – groundwater outflows. To calculate the volume of water stored in the wetland at each time step it is necessary to determine each term from the continuity equation and then it must be correlated with the lag-time for each system (surface/underground flow). First, these terms must be grouped to assess them and, further, they can be determined using a hydrodynamic model for the surface water and for groundwater too. It must be noticed that groundwater flows at a time step (t) will be calculated according to the surface water levels at a previous time step (t-1) – the boundary conditions used will be time-variable Dirichlet or Cauchy according to the geology and to the connectivity between channel/river and aquifer. Net precipitation represents the volume of water fell in the area of the wetland and is determined by multiplying the area of the wetland to the rainfall depth recorded at a meteorological station located near or inside the wetland. Further, detailed assessment of each term from the water balance equation is presented.

3.1 Assessment of the flows from surface water (S_{in} and S_{out})

According to the technical solution simulated, assessment of the inflows/outflows to the wetland is different from one case to another. Then, integrating the function Q(t), the inflows/outflows respectively volume stored in the wetland are obtained. In case of recharging/discharging the wetland through a channel, flow is determined using Manning’s empirical formula to estimate water velocity:

$$v = C\sqrt{R \cdot i} = \frac{1}{n} \cdot R^{2/3} \cdot i^{1/2}$$

and

$$Q = A \cdot v = A \cdot C\sqrt{R \cdot i} = A \cdot \frac{1}{n} \cdot R^{2/3} \cdot i^{1/2}$$

where: A – cross-section area, v – water velocity, C –Chezy’s constant, R – hydraulic radius, i – hydraulic slope, n –Manning’s coefficient (after Chow, 1959, for new open channels, n = 0.016).

In case of recharging/discharging the wetland through a rectangular weir (a case that is frequently encountered), flow is determined using the formula:

$$Q = m \cdot b \cdot \sqrt{2 \cdot g} \cdot H^{3/2}$$

where: m – flow’s coefficient of the weir, b – width of the weir, g – gravitational acceleration, H – weir head.

In case of a flood wave on the river/channel through which the recharge is done or wetland is connected to, involves another way to assess discharges from surface water and water levels. Assumption that the flow is 1D cannot be done. According to this, a 2D model for surface water flow must be created and this is the main theoretically challange. The quality of input data must be strongly better and a pre-processing is needed. Several software packages was developed to realize this 2D mathematical model. Further, it is presented the way of working of the MIKE 21 software package, developed by Danish Hydraulic Institute (DHI), for the 2D flow at surface water that solve numerically the system of equations with partial derivatives calculating the solutions for water velocities by x- and y- direction and water depths. The model is based on the solution of the three-dimensional incompressible Reynolds averaged Navier-Stokes equations, subject to the assumptions of Boussinesq and of hydrostatic pressure. The local continuity equation is written as (*from MIKE 21 FM – Scientific Documentation, 2011*):

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = Sc$$

and the two horizontal momentum equations for the x- and y- component, respectively:

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial vu}{\partial y} + \frac{\partial wu}{\partial z} = fv - g\frac{\partial \eta}{\partial x} - \frac{1}{\rho_0}\frac{\partial p_a}{\partial x} - \frac{g}{\rho_0}\int_z^{\eta}\frac{\partial \rho}{\partial x}dz + F_u + \frac{\partial}{\partial z}(\upsilon_t\frac{\partial u}{\partial z}) + u_s S_c$$

$$\frac{\partial v}{\partial t} + \frac{\partial v^2}{\partial y} + \frac{\partial uv}{\partial x} + \frac{\partial wv}{\partial z} = fu - g\frac{\partial \zeta}{\partial y} - \frac{1}{\rho_0}\frac{\partial p_a}{\partial y} - \frac{g}{\rho_0}\int_z^{\zeta}\frac{\partial \rho}{\partial y}dz + F_v + \frac{\partial}{\partial z}(v_t\frac{\partial u}{\partial z}) + v_s S_c$$

where t is the time; x,y and z are the cartesian coordinates; η is the surface elevation; d is the still water depht; h=η+d is the total water depht; u,v,w are the velocity components in the x,y,z direction, f = 2 Ω sinφ is the Coriolis parameter (Ω is the angular rate of revolution and φ the geographic latitude); g is the gravitational acceleration; ρ is the density of water, v_t is the vertical turbulent viscosity; p_a is the atmosferic pressure; ρ_0 is the reference density of water; S_C is the magnitude of the discharge due to point sources and u_s, v_s is the velocity by which the water is discharged into the ambient water. The horizontal stress terms are described using a gradient-stress relation, which is simplified to:

$$Fu = \frac{\partial}{\partial x}\left(2A\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}(A\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right))$$

$$Fv = \frac{\partial}{\partial x}(A\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)) + \frac{\partial}{\partial y}\left(2A\frac{\partial v}{\partial x}\right)$$

where A is the horizontal turbulent viscosity (*from MIKE 21 FM – Scientific Documentation, 2011*).

The terms in the Navier-Stokes flow equations that were before presented, has the next meaning (both members, from left to right): fluid acceleration, horizontal gradients in the velocity, Coriolis acceleration, acceleration from sea-surface elevation, pressure gradient term, acceleration from buoyancy effects, imbalance of horizontal Reynolds stresses, vertical stresses from the Bousinesq approximation, acceleration from discharges.

The main assumptions for the calculation of these equations are:

- Bousinesq approximation – turbulent stresses are assumed to be proportional to the gradients in the mean velocity field: $\vartheta = v_t + \frac{\partial u}{\partial z} = \overline{u'v'}$

- Uses Smagorinsky' (1993) approach to compute viscocity as a function of the strain rate:

$$\upsilon_H = c_s^2\, l^2 \sqrt{S_{ij}\, S_{ij}}$$

By utilizing a hydrodynamic model for the surface water, the flows and the water depths at any time step are calculated if a sufficient small time step is chosen (in practice this issue doesn't exist because PC's power is enough to chose time steps at the order of seconds). The relationship between the results from the hydrodynamic model of surface water and the hydrodynamic model of groundwater must be done at predefined intervals because it is obvious that the water movement at surface is faster than in underground. So, the link between surface model and groundwater as a time-variable boundary condition must be established with a predefined regularity. The coupled model must reflect properly the exchange of flows between surface and underground systems.

3.2 Assessment of the flows from groundwater (G_{in} and G_{out})

Correct assessment of the flows coming from groundwater to the wetland and also of those discharged/infiltrated assumes to create a 2D groundwater flow mathematical model, accepting as valid Dupuit's assumption. Mathematical modeling software packages for groundwater solve numerically water movement equation in saturated medium in transient regime. The results are the piezometric heads in all of the mesh elements and implicitly of the flows transported between two neighbour elements because the hydraulic gradient i $= \frac{dH}{dl} \sim \frac{\Delta H}{\Delta l}$. The movement equation according to the conditions described before is as follows:

$$\frac{\partial}{\partial x}\int_{z1}^{z2}\left(Kx\,\frac{\partial H}{\partial x}\right)dz + \frac{\partial}{\partial y}\int_{z1}^{z2}\left(Ky\,\frac{\partial H}{\partial y}\right)dz = \frac{\partial}{\partial t}\int_{z1}^{z2} Ss\; H\;\; dz$$

where: K – hydraulic conductivity from x- and y- direction; H – piezometric head; S_s – specific storage coefficient; z_1 and z_2 – upper/lower elevation which limits the aquifer. According to Dupuit's assumption the piezometric head is constant on vertical (z); as a result, derivatives from left member $\frac{\partial H}{\partial x}$ si $\frac{\partial H}{\partial y}$, respectively piezometric head from right member could be put out in front of the integral.

To assess the flows that recharge/discharge from the underground to the wetland or viceversa, the hydrodynamic created model is used. Boundary conditions at the contact between aquifer and river are Cauchy or Fourier, used when the water flow takes place through a semi-permeable limit. As was described, the flow at any t - moment can be calculated as hydraulic head dependent flow:

$$Q = -K \cdot i \cdot A$$

where: K – hydraulic conductivity = $\begin{pmatrix} Kx & 0 \\ 0 & Ky \end{pmatrix}$, i – hydraulic gradient = $\frac{dH}{dl}$, A – cross-section area.

3.3 Assessment of Evapotranspiration (ET)

Assessment of evapotranspiration from the surface of the wetland could be made using different formulas: Penman's formula to calculate evapotranspiration from the water surface, Thornthwhite's formula or Blaney- Criddle's and Turc's formulas to calculate potential evapotranspiration, Turc's formula to calculate real evapotranspiration. Because in most cases evapotranspiration from plants can be neglected, being much smaller than evapotranspiration from water surface, further, Penman's formula will be presented. Penman proposed next formula to calculate evapotranspiration E_0 from water surface:

$$Eo = \frac{\Delta \cdot H + \gamma \cdot Ea}{\Delta + \gamma}$$

where: H – net radiation (mm/zi), γ – psychrometric constant = 0.49, Δ – slope of the saturation curve for the water vapours, E_a – evapotranspiration from water surface in the hypothetical case of an equality between water temperature and air temperature. It is determined using Dalton's equation:

$$E_a = 0.35\,(e_s - e_a)\,(0.5+0.54\cdot u)\ \text{(mm/day)}$$

where: u – wind speed (m/s), e_s – saturation vapour pressure which is determined according to air temperature, e_a – absolute pressure (effective pressure) of the water vapours which is determined through the relation: $e_a = h \cdot e_s$, where h is the relative humidity.

Net radiation H is determined using next equation: $H=R_l - R_B$, where R_l – short wave radiation, R_B – long wave radiation .

Short wave radiation R_l is determined using thte relation:

$$R_l = R_A\,(1- r)\,(0.2 + 0.48\,\frac{n}{D})$$

where R_A – short wave radiation at the upper limit of the atmosphere, as a function of latitude and time, $\frac{n}{D}$ – relative period of the sunshine, where n represents effective duration of sunshine and D represents maximum possible duration, r = 0.06 – water albedo.

Short wave radiation R_B is calculated using emprical relation:

$$R_B = \sigma \cdot T_a^4\,(0.47-0.077 \cdot \sqrt{e_a})\,(0.20+0.80\,\frac{n}{D})$$

where: T_a – absolute temperature at the terrain surface (°K), σ –Stefan-Boltzman's constant = $117.4 \cdot 10^{-9}$ (cal/cm^2· day·°K).

Slope of the saturation curve for the water Δ is determined surrounding the temperature between two neighbour values t' si t'' to which corespond saturation vapour pressure e' and e''. As a result:

$$\Delta = \frac{e' - e''}{t' - t''}$$

Using all these considerations, through Penman's formula the evapotranspiration from water surface is obtained (*from Drobot, R, Serban, P, 1999, Aplicatii de hidrologie si gospodarirea apelor*).

4. CONCLUSIONS

Starting from the functions that the wetland will have, we can chose from the simulated scenarios in the coupled model which is the best restoration solution. Also, a cost-benefit analysis can be done with support of the technical solusions proposed. Using this approach, we don't have further the issue that the variables that we cannot control will represent a barrier in management of the wetland. Also, such an approach could represent a tool for water autorities to properly manage flood waves or flash floods. One of the great advantages offered by a coupled model of the wetland, surface water and groundwater is that we can estimate correctly all the variables of the hydrologic process. In contrast with previous approaches made with same purpose where the contribution from groundwater was neglected, considered with some orders of magnitude less than the contribution from surface water, current approach is comprehensive from this point of view because all flows from/to the wetland are considered. Applications of this approach could be more precisely than the other to analyze extreme periods such as: prolonged drought (when the contribution of the groundwater in the total balance could be significant); high precipitation events when the flow is not 1D and the flows from surface water is not determined correctly by a 1D model. The presented approach will be used in few study cases in the PhD thesis of the autor.

REFERENCES

Drobot, R, Serban, P, 1999, Aplicatii de hidrologie si gospodarirea apelor

Freeze, R.A., Cherry, J.A., 1979, Groundwater

Villa, J., Tobon, C., Modeling hydrologic dynamics of a created wetland, Colombia

Kjelin, J., Worman, A., Johansson, H., Lindahl, A., Controlling factors for water residence time and flow patterns in Ekeby treatment wetland, Sweden

Maloszewski, P., Wachniew, P., Czuprynski, P., Study of hydraulic parameters in heterogeneous gravel beds: Constructed wetland in Nowa Slupia, Poland

Zhang, L., Mitsch, W., Modeling hydrological precesses in created freshwater wetlands: an integrated system approach

MIKE 21 FM, 2011 Scientific Documentation

Zaharia, V., Ioan, V., Aspecte privind realizarea hartilor de hazard in cadrul proiectelor PPPDEI