Application of a numerical model designed for integrated watershed management

F. Padilla[1], J.-H. Hernández[2], R. Juncosa[1] & P. R. Vellando[1]
[1]*ETS de Ingenieros de Caminos, Canales y Puertos, Universidad de A Coruña, Spain*
[2]*Ingeniería Geomática e Hidráulica, Universidad de Guanajuato, Mexico*

Abstract

The present research is concerned with the latest developments and practical application of a physically-based numerical model MELEF (Modèle d'ÉLÉments Fluides, in French) that incorporates a finite elements solution to the steady/transient problems of the joint ground/surface fresh/salt water flows in inland and coastal regulated watersheds. The proposed model considers surface and groundwater interactions to be 2-D horizontally distributed and depth-averaged through a diffusive wave approach. Infiltration rates, overland flows and evapotranspiration processes are considered by diffuse discharge from surface water, non-saturated subsoil and groundwater table. Recent developments also allow for the management of surface water flow control through the capacity of diversion on river beds, spillways and outflow operations of floodgates in weirs and dams of reservoirs. The application regards the actual hydrology of the Mero River watershed, with two important water bodies mainly concerned with the water resources management at the Cecebre Reservoir and the present flooding of a deep coal mining excavation. The model was adapted and calibrated during a period of five years (2008/2012) with the help of hydrological parameters, registered flow rates, water levels, precipitation, water uses and water management operations in surface and groundwater bodies. The results presented predict the likely evolution of the Cecebre Reservoir, the flow rates in rivers and the flooding of the Meirama open pit.
Keywords: integrated surface/subsurface flows, numerical modelling, finite elements, watershed hydrology, water resources management.

www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/WS150111

1 Introduction

Nowadays there is an increasing need for integrated surface and ground water numerical modelling. The philosophy and role of hydrological models in water resources has been widely described (Abbot and Refsgaard [1], Burnash *et al*. [2]).

Recent numerical methodologies were also developed on combined surface and ground-water applications to the whole of the water resources of a particular river basin (Ross *et al*. [3]; Sophocleous and Perkins [4]). MIKE SHE and MIKE BASIN are two examples of numerical and physically based modeling systems developed by DHI [5] for describing the major flow processes of the entire land phase of the hydrological cycle which integrates the Saint-Venant surface equation to a vertical 1-D Richards equation for unsaturated flow and a 3-D finite elements solver for saturated flow (Graham and Butts [6]); Camporese *et al*. [7], whose catchment's hydrology model couples a finite elements solver for the Richards equation describing variably saturated porous media, and a finite differences solver for the diffusive wave equation describing surface flow.

Standard features of detailed process-based numerical models for water resources management at the scales of the watershed could include: a large variety of numerical conditions and sub-models for the different hydrological components, water uses and managements. These characteristics will not be described in any case here; this research will focus instead on some new features and developments, summarized below, of an integrated surface-subsurface flow numerical model for suitable applications to practical water resources management in regulated watersheds.

In this field, a new methodology of finite element modeling has been developed (MELEF model) which considers novel modeling features of the joint surface and ground water regional flows of continental freshwater and coastal salt water intrusion from the sea by means of an immiscible fresh/salt water interface reliable for applications on different kinds of watersheds, water resources management and environmental problems (Padilla and Cruz-Sanjulián [8]; Padilla *et al*. [9]).

The model considers surface and groundwater interactions to be depth-averaged through a novel interpretation of a diffusive wave approach for surface flood routing. Infiltration rates as well as overland flows generation processes are assessed by the concerned sub-models. Evaporation and evapotranspiration processes are considered by a diffuse discharge sub-model from surface water, non-saturated subsoil and groundwater table (Hernández *et al*. [10]).

Therefore, this research deals with the numerical developments being required to consider new practical applications of this finite elements solution, in particular those concerned with water uses and management of surface water, through the water flow control of the capacity of diversion works on river beds, spillways and outflow operations of floodgates in weirs and dams of reservoirs.

The practical application regards the actual hydrology of the Mero River watershed where there are two important water bodies. These are concerned with water resources management at the Cecebre Reservoir and the present flooding of the Meirama open pit, a deep coal mining excavation, being filled with freshwater coming from the upper Meirama sub-basin, all of it in the context of the water resources uses, management and fresh-water hydrological aspects of groundwater and surface waters at the Mero River catchment (~250 Km^2), Coruña, Spain. The model behavior is checked, during a simulation period of almost five years (2008/2012), featured by a complex geology and the particular geomorphology and hydrology of the opencast Meirama mine, being presently restored as a deep and regulated lake, as well as the Cecebre Reservoir, for the historically registered precipitation, water uses and water management operations in surface and groundwater bodies.

2 Model description

The MELEF model for continental and coastal catchment applications couples' subsurface and surface regional hydrology, by a diffusive wave approach, with a joint finite elements solver for the saturated porous media flows of fresh and saltwater through an immiscible sharp interface (Huyakorn *et al*. [11]; Padilla *et al*. [9]). Moreover, the application of the model is extended to fractured media and hydraulic anisotropy.

In this sense, this numerical approach (Figure 1) was mainly developed in order to analyze the surface and groundwater behaviour at a watershed scale, and it can also consider other water components such as the evapotranspiration process, that is a diffusive discharge from surface water and soils within the unsaturated zone by a root water uptake sub-model, as well as the overland flow by a rainfall-runoff sub-model based on an exponential method for assessing the infiltration rates (Hernández *et al*. [10]).

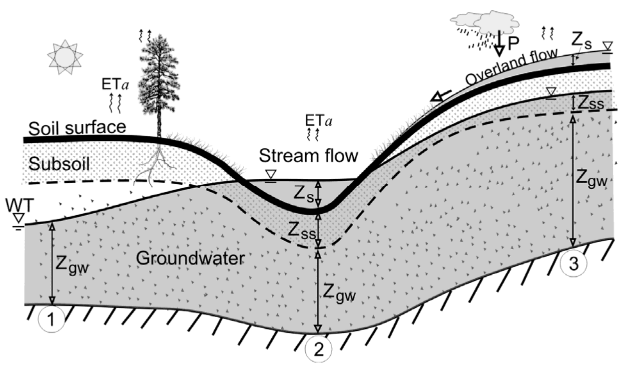

Figure 1: Surface/groundwater flows in MELEF freshwater interactions. Thicknesses of groundwater (z_{gw}), subsoil (z_{ss}) and stream/overland flow (z_s). Water table (WT). Actual evapotranspiration (ETa).

Diversion works may be considered for withdrawing water losses from a river bed due to flooding events (discontinuous ponding of soil surface) or bypassing a certain flow rate towards another place, by transferring it mainly through an impervious channel, pipeline or tunnel. The place where the water is transferred could be located in the same catchment area or in a different one. Ordinarily, it is not always possible to bypass all flows; this would depend on the required capacity of the diversion works for a particular weir.

Nowadays, the major part of water transmission is carried out through pipes, which has a considerable increase in the number of new types. Pipe spillways are often used with dams in order to regulate part of the water flow at the outlet of a surface reservoir. They have relatively low capacities, when compared to floodgates, but they carefully regulate the water stored behind the dam and reduce the peak rates of outflow. The inflow capacity of a pipe spillway at full flow can be hydraulically estimated by the flow rating curve.

Dam floodgates at the outlet of surface reservoirs are devices that usually have relatively high capacities to regulate the water outflow rates. The types of floodgates and how they operate are nowadays quite different. If we try to find an equivalence between the opening of a vertical lift gate and the water depth at a suppressed rectangular sharp-crested weir, we could easily find the required height at the vertical lift crest gate, and that in order to achieve an equivalent water outflow rate (Mays [12]).

MELEF, the current tool used in water resource modeling, is a two dimensional finite elements model for regional surface and groundwater flows through drainage basins, developed for a temporal implicit (Eulerian) centered (Crank-Nicholson) and spatially centered (Galerkin) numerical approach.

The inputs of freshwater are exclusively due to rainfall, however pumping and injection wells of prescribed flow rates have been also implemented, as well as irrigation and artificial recharges, which could be also prescribed inside the considered domain. Therefore, the boundary conditions of the modeled region, at the scale of the watershed, are mainly those of the outflow or discharge conditions. To this respect, prescribed water heads, outflow face and open boundary conditions are commonly used at the discharge zones of the drainage basin (Padilla and Cruz-Sanjulián [8]).

Triangular elements of three nodes are used for the analytic integration of the corresponding numerical formulation for steady and transient conditions. The preconditioned iterative algorithm GMRES (Saad and Schultz [13]) provides the solution to the system of equations by means of a reduction in the computer memory requirements and allowing for a simple processing of the numerical mesh. There is no difference in time-scales between the surface and ground water flows because they are solved together in a whole lumped and depth-averaged way. This is a clear advantage because the lumping properties allow for good numerical results in practical applications with affordable meshes as well as time scales. Hydraulic heads and gradients are the solutions. Then the model is depth-averaged solved, but the results are interpreted and approached in a multilayered way, giving solutions for water flows and mean horizontal velocities above the soil surface, runoff and overland flows, as well as under the soil surface, saturated subsurface and groundwater flows.

As part of the present surface/subsurface flow numerical approach, the model incorporates capabilities to assess the drainage layout of surface runoff and the freshwater ground levels, overland and subsurface flows, with punctual and diffuse surface and ground water recharges and discharges, thickness and velocities of surface and ground waters, as well as several types of rivers diversions, water balances and flooding of water bodies of high depth level.

3 Water management of the Mero River watershed

Since 1980, the Meirama coal mine had been exploited by Lignitos de Meirama, S.A. (LIMEISA) as part of an important activity that finished in March 2008. As part of the environmental plan of closure the opencast pit hole was to be flooded to finally create a large lake of ~1.86•10^6 m^2 up to a maximum depth level of some 200 m and a capacity of ~146•106 m^3. In this context, the forthcoming evolution is analyzed as a function of the actual strategy of flooding. The presently forming pit lake of Meirama is to lie on the drainage basin of the Barcés River, a tributary in the Mero River catchment (247 km^2) leading the flow towards the Cecebre Reservoir, north-western Spain, 20 km from the city of La Coruña (Figure 2).

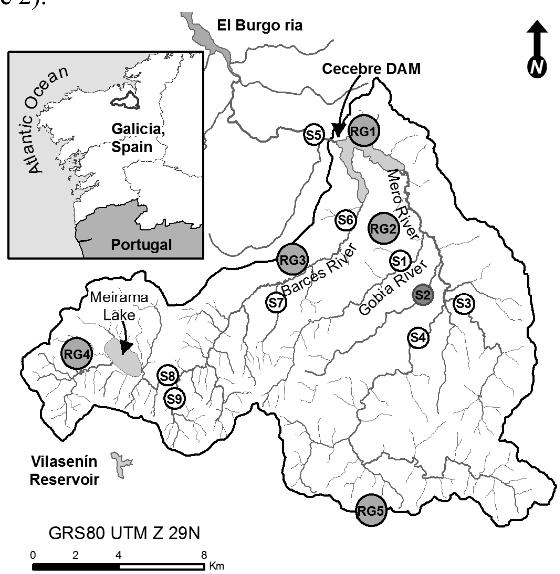

Figure 2: Mero catchment location (~ 247 km^2). North-Western Spain. S1–S9 and RG1–RG5 are the locations of measured discharge sections and rain gauging of MeteoGalicia climate stations, respectively

In order to improve the calibration of the stream flow model, continuous water depth measurements were carried out with data logger transducers on 8 of the main streams (Schlumberger Mini and CTD DIVER) at the Mero watershed (labelled with S1 to S9 in the Figure 2) from June 2011 until late September 2012. Water depth measurements were corrected by barometric pressure. Water discharge measurements by velocity area and dilution methods, for different regimes, were made on these main streams to obtain rating curves and to transform water depth measurements into water discharges.

The main hydrologic parameters (hydraulic conductivity, porosity, infiltration rate, soil thickness, capillary fringe,…) have been adjusted during the simulation period (going from January 2008 to September 2012) mainly based, on one hand, on the field measured parameters and on the tectonics and geological features of the region, as well as, on the other hand, on the measurements of the surface water flows, the free surface levels at the Cecebre Reservoir and at the pit lake of Meirama, as well as on the known groundwater phreatic levels and the water balances inside an area delimited around the pit (Figure 3).

Otherwise, it is quite a challenge to reproduce the outflow regulation operations of Cecebre Reservoir dam at its outlet, through the particular and changing openings of its five floodgates and its three submerged pipe spillways (one near the middle, and two deep). In respect of this, the flow rating curves of the pipe spillways were calibrated, on one hand, to the actual flow rating curves of the middle pipe, and on the other hand, to the two deeper pipes being considered together. Therefore, the diameters of the pipes were calibrated for the different openings of the valves installed at the pipes and the corresponding discharge coefficients, and this according to the flow rating curves provided by the operator, (Figures 3 and 4-Up right).

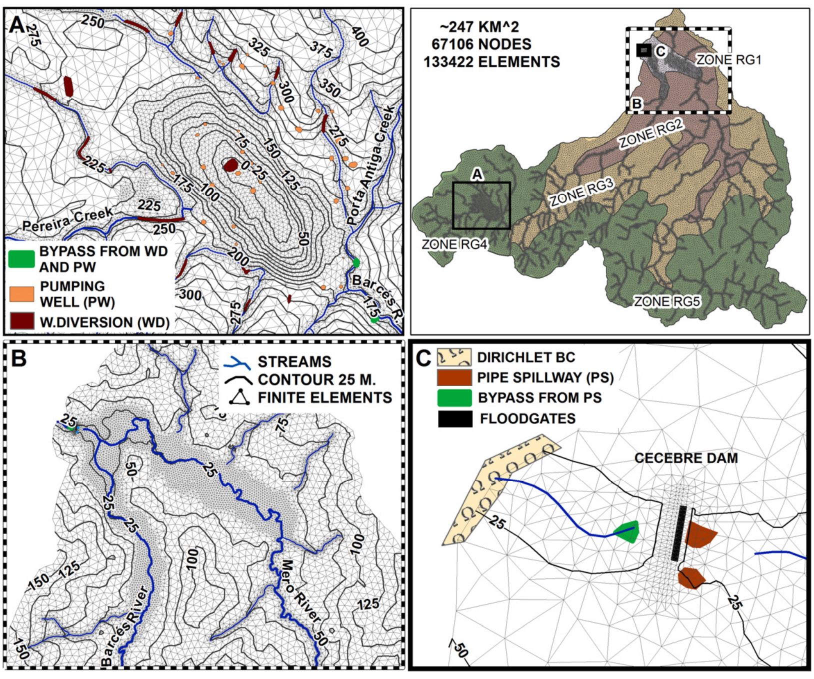

Figure 3: Finite elements mesh model and rainfall zones in the Mero River catchment area. Water management and boundary conditions at the Meirama open pit (A) and the Cecebre Reservoir (B, C).

With respect to the five sluice gates (vertical lift floodgates), they were placed together in the numerical model, as if they were just one bigger floodgate (with lumped position, shape and openings), during the almost five years of operation, and that in order to try to reproduce their hydraulic behavior from the point of view of the surface discharges as well as the surface and groundwater levels in the reservoir and its surrounding area (Figure 4-Up right).

In order to properly achieve this issue, the initial groundwater and surface water levels of the simulation period in the whole watershed need to be a steady-state solution, because those simulated water levels required to be quite similar to the actual ones. This is the most important reason why the simulation period starts on 1 January 2008, which was a short period of actual severe drought in the region, where the groundwater levels and surface water discharges were very low (with a quite dried Meirama open pit, still exploiting the coal, and the Cecebre Reservoir having very low free water levels), quite close to a steady-state numerical solution for those particular hydrological conditions.

Then, the aim is to reproduce the actual regional hydrology of the Mero River catchment, during these almost five years of water management (2008–2012), focusing on the actual evolution of the present flooding of the Meirama open pit, and on the estimated surface water discharges at the main streams, as well as on the evolution of the free water levels at the Cecebre Reservoir.

The results of the application of the model to the whole of the water resources at the Mero River catchment, during a total period of almost five years, that includes the recent hydrological history of the destination of surface and ground waters, related to the Cecebre Reservoir and the flooding of the Meirama open pit, provide a good variety of hydrological data based on the precipitation, the water usages, the calibrated parameters and the geology of the region.

In this respect, a trial and error method was employed to estimate the hydrological parameters, on a 6 hour time step system resolution, and it was emphasized at those materials closer to the surface of the soil, where the regional hydrogeology is considered more relevant.

The flooding of the open pit began on 18 March 2008 with groundwater flow only. Meanwhile, the surface water drained by the Meirama basin was diverted to the Barcés River. After 3 October 2008, the mine is being flooded with water diverted from some of their drainage streams, including the Porta Antiga and the Pereira streams (Figure 3), and this was done until 11 June 2011, when the diversion is shared with the Barcés River in order to better satisfy its environmental flow. The evolution of the flooding, illustrated in Figure 4-Up left, is depicted from the point of view of the comparison between the registered and the assessed water levels during the simulation period (it includes calibration and validation stages), as well as that of the evolution of the relative errors for the maximum water depth (about 150 meters). Although the general behaviour of the flooding is quite acceptable, some of the differences are understood as a consequence of the variability of the surface and ground water hydrology, focused on the upper basin of the Barcés River, where the flooding of the open pit mine of Meirama takes place.

It is also of great interest in this study to analyze the regulation capacities of the outlet works installed in the dam of the Cecebre Reservoir, although it could bring to unavoidable cumulative errors in the reservoir water storage. The behavior of the floodgates is supported, firstly, onto the average openings of the five gates (transformed on the equivalent transient heights of the corresponding overflow gates), secondly, onto the coarse numerical approximation for the dam and the five gates shape (as if they were only one) and, thirdly, onto the continuously computed water heads, hopefully appropriated anytime around the dam gates. On this regard, some calibrations have been required in order to properly assess the discharging curves of the concerned sluice floodgates.

After the calibration of the behaviour of the reservoir outlet works was considered satisfactory, for the estimated discharge flow rates at the dam, the comparison was made between the registered water levels reached in the reservoir, as provided by the water supply company of La Coruña (EMALCSA), and the simulated water levels, at two points of the reservoir, one downstream and the other upstream (Figure 4 Down).

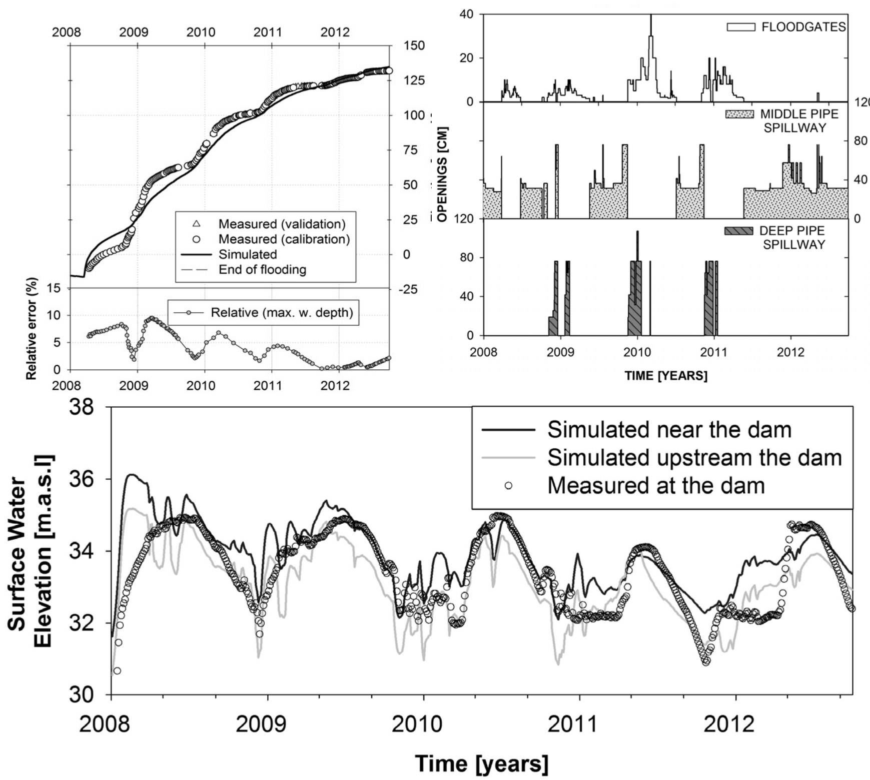

Figure 4: Up: (left) Observed and simulated flooding evolution and (right) Openings of pipe spillways and floodgates at the dam of Cecebre Reservoir. Down: Observed and simulated water levels evolution at the Cecebre Reservoir.

In other respects, the results in the surface domain are compared with some of the measured discharges at different sub-catchments and superficial drainage sections at the Mero River (Figures 2 and 5). Although the discharges were not measured continuously throughout the period of simulation, the analysis of the comparison of surface runoff results shows in general a quite good behavior. Although, it is also interesting to note the evolution of surface flow rates in Section 8 (S8) far upstream in the Barcés River, where a quite good behavior was obtained after calibrating the diversion capacity of the weir installed at the Pereira stream. Since 15 June 2011, this weir splits up the diverted flow into the flooding of the Meirama Lake and the environmental flow supplied downstream through a tunnel to the Barcés River. This former flow was calibrated for a diversion capacity, in terms of a flow rate being diverted per unit area of a flooded surface.

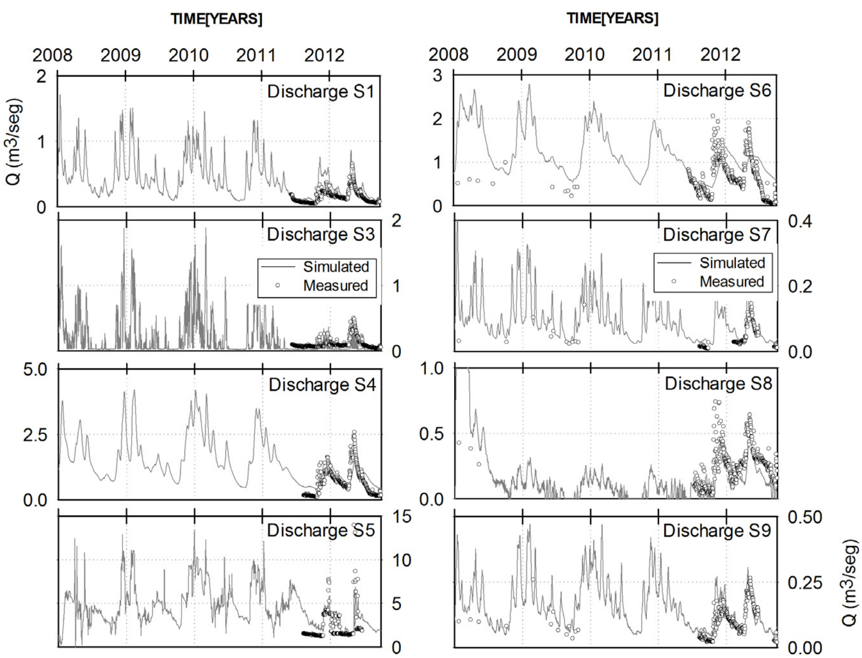

Figure 5: Some of the surface flow discharge sections measured and assessed during the simulation period.

Despite how tough the calibration process of the parameters was for the involved devices, which were operating during almost five years (January 2008 to September 2012), it looks like the comparisons are, in general, in quite acceptable agreement.

Finally, a past scenario of the surface and groundwater layouts which have been simulated is depicted in Figure 6, where the high level of interaction and variability of the hydrology of surface and groundwater flows in the Mero River watershed is clearly shown during a specific hydrological event of the close to five years simulation period. Among these results, we would like to underline, for instance, the drainage layout of surface runoff and the freshwater hydraulic heads around the Meirama open pit, and the Cecebre Reservoir.

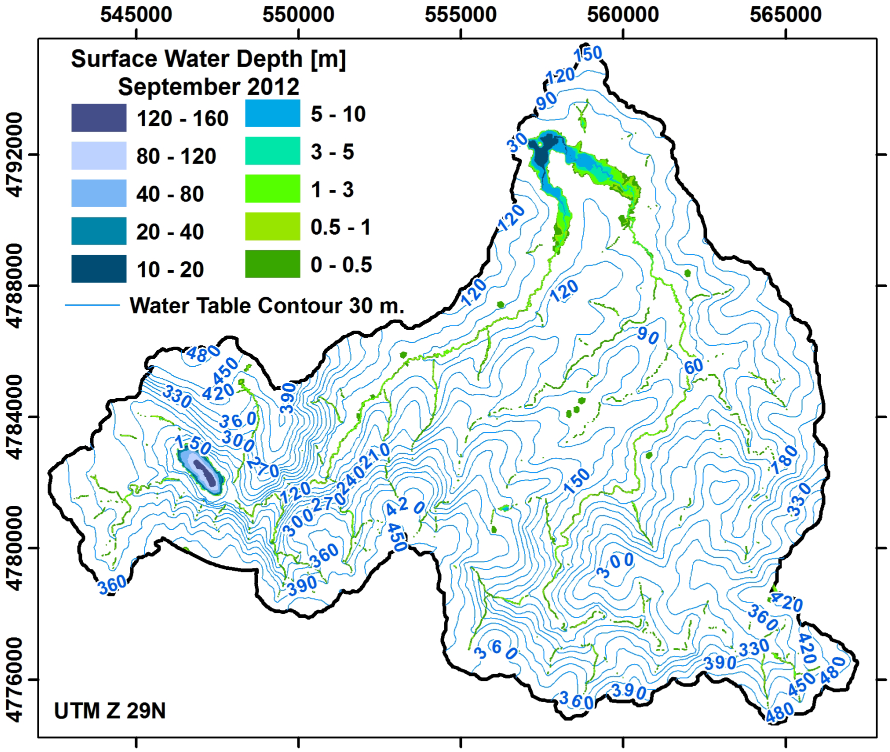

Figure 6: Simulated surface and groundwater levels in September 2012 at the Mero River catchment.

4 Conclusions

Some new developments have been performed on a process-based integrated hydrological model of 2-D saturated subsurface and surface flows (MELEF). This numerical model for continental and coastal catchment applications couples surface and subsurface regional hydrology through a finite element resolution of the saturated flows of fresh and saltwater. Hydrological properties, simulated conditions and numerical results are managed by GIS.

Recent numerical developments are presented in order to extend this finite element solution to new practical applications dealing with flooding events and water uses and management of surface water in widely regulated watersheds. This comprises the management of surface water flow control through the capacity of diversion on river beds and flooding areas, as well as spillways and outflow operations of floodgates in weirs and reservoir dams.

The application is concerned with the freshwater management in the Mero River catchment (La Coruña, Spain), during a period of almost five hydrological years. The results of the simulation presented illustrate a high variety of interactions between surface and subsurface water, where regional hydrology allows, among others, the water management and flooding of a deep surface water body (Meirama pit lake), as well as the regulation operations at the dam of the Cecebre Reservoir through its pipe spillways and floodgates.

The comparison of observed and simulated runoffs, surface water levels in rivers, lakes and reservoirs seem quite appropriate with respect to the observed regulation capacities, the environmental flow rates and the flooding evolutions.

It can be concluded that the numerical model MELEF, developed for the present joint surface and subsurface regional flows, can provide useful and quite precise results concerning all the freshwater resources management of relatively large and regulated watersheds, where regional hydrology allows flooding events and the practical water regulation in weirs of river beds and common reservoir outlet works as pipe spillways and floodgates.

Acknowledgements

The work reported in this paper has been funded by the Spanish Ministry of Education and Science CICyT (CGL2009-11258), the Xunta de Galicia (Maria Barbeito Program), the companies DRAGADOS, LIMEISA and EMALCSA, as well as the European Science Foundation.

References

[1] Abbot, M.B. and Refsgaard, J.C. *Distributed Hydrological Modelling*. Water Science and Technology Library 22. Kluwer Academic Publishers, Dordrecht, 1996.

[2] Burnash, R.J.C., Ferral, R.L., McGuire, R.A. and McGuire, R.A. *A generalized stream flow simulation system*. Conceptual modeling for digital computer. Joint developed by Federal-State River Forecast Center and Nacional Weather Service. Dep. Water Resources (California), 1973.

[3] Ross, M., Said, A., Torut, A., Tara, K. and Geurink, J. A new discretization scheme for integrated surface and groundwater modelling. In: Hromadka, T.V. (Ed.), Integrated Water Resour. *Management. American Institute of Hydrology*, Las Vegas, Nevada, pp. 143-156, 2005.

[4] Sophocleous, M. and Perkins, S.P. Methodology and application of combined watershed and ground-water models in Kansas. *J. Hydrology*, 236(3-4): 185-201, 2000. DOI: 10.1016/s0022-1694(00)00293-6.

[5] DHI. MIKE BASIN. A tool river planning and management. Report, Danish Hydr. Inst., Horsholm, Denmark, 1997.

[6] Graham, D.N. and Butts, M.B. Flexible, integrated watershed modelling with MIKE SHE. In: Singh, V.P., Frevert, D.K. (Eds.), *Watershed Models*. CRC Press, Boca Raton, Fla., pp. 245-272, 2005.

[7] Camporese, M., Paniconi, C., Putti, M. and Orlandini, S. Surface-subsurface flow modeling with path-based runoff routing, boundary condition-based coupling, and assimilation of multisource observation data. *Water Resour. Res*., 46(2): W02512, 2010. DOI: 10.1029/2008wr007536.

[8] Padilla, F. and Cruz-Sanjulián, J. Modeling seawater intrusion with open boundary conditions. *Ground Water*, 35(4): 702-712, 1997.

[9] Padilla, F., Méndez, A., Fernández, R. and Vellando, P. Numerical modelling of surface water/groundwater flows for freshwater/saltwater hydrology: the case of the alluvial coastal aquifer of the Low Guadalhorce River, Malaga, Spain. *Environmental Geology*, 55(1): 215-226, 2008. DOI: 10.1007/s00254-007-0977-2.

[10] Hernández, J.H., Padilla, F., Juncosa, R., R-Vellando, P. and Fernández, A. A numerical solution to integrated water flows: Application to the flooding of an open pit mine at the Barcés River catchment – La Coruña, Spain. *J. Hydrology*, 472-473: 328-339, 2012. DOI: 10.1016/j.jhydrol.2012.09.040.

[11] Huyakorn, P.S., Wu, Y.S. and Park, N.S. Multiphase Approach to the Numerical Solution of a Sharp Interface Saltwater Intrusion Problem. *Water Resour. Res*., 32(1): 93-102, 1996. DOI: 10.1029/95wr02919.

[12] Mays, L.W. *Water Resources Engineering*. John Wiley & Sons, Inc., 2011.

[13] Saad, Y. and Schultz, M.H. GMRES: A Generalized Minimal Residual Algorithm for Solving Nonsymmetric Linear Systems. SIAM *Journal on Scientific and Statistical Computing*, 7(3): 856-869, 1986. DOI: 10.1137/0907058.