Modeling Surface Runoff, Groundwater Flow and their Interaction with PCSWMM and MODFLOW

- for the City of Rostov the Great, Russia

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The City of Rostov the Great (Rostov) is one of the oldest cities in the Russian Federation. Many buildings need to be restored due to advanced degradation of the wooden and stone foundations. This degradation and other environmental problems are in large part caused by high groundwater levels, which are in turn directly associated with human activity over the years.

Technical analyses were completed for surface runoff and groundwater flow in order to define potential interventions to lower the groundwater levels. Surface runoff for the old part was modeled with PCSWMM, while the groundwater was analyzed with MODFLOW. The chapter describes the complex conditions that were analyzed, and different approaches to use the results from the surface runoff model as input to the groundwater model. The PCSWMM model was developed using the available information on the drainage system and limited data for calibration gathered during one spring and one summer. For MODFLOW, the model was based on historical data on groundwater regime at different wells installed since 1977 as well as other wells put in place specifically for the project in 2000 and 2002.

Different approaches to integration of the two models are discussed.

Rivard, G., R. Frenette, M. Bolgov and S. Pozgniakov. 2004. "Modeling Surface Runoff, Groundwater Flow and their Interaction with PCSWMM and MODFLOW - for the City of Rostov the Great, Russia." *Journal of Water Management Modeling* R220-04. doi: 10.14796/JWMM.R220-04.

© CHI 2004 www.chijournal.org ISSN: 2292-6062 (Formerly in Innovative Modeling of Urban Water Systems. ISBN: 0-9683681-9-0)

4.1 Introduction

The ability to model the interaction between surface water and groundwater as an integrated system is needed in many types of projects and engineering analyses. In an urban setting, it may be important to model water table variations where they influence the amount of water infiltrated into the sewer system, increasing sanitary sewer overflows (SSOs) or combined sewer overflows (CSOs). In other situations where infiltration systems are used at a large scale for stormwater management, the amount of infiltrated water could also have negative quantitative or qualitative impacts on the groundwater.

Despite the significance of these types of problems in urban drainage and the obvious interrelation between the two systems, there is not much literature on case studies of integrated analyses, relating the response of one system on the other. One of the reasons for this situation is that stormwater modeling and groundwater modeling have evolved historically as two separate fields, each developing specific software for their own more frequent types of projects. Typically, the stormwater modeler is concerned with surface or basement flooding which is mainly the result of surface runoff produced by a high intensity rainfall event. The groundwater modeler, on the other hand, is typically more interested in simulating groundwater pollution or the behavior of the water table around a well for longer periods. In recent years, however, it has been recognized that a more reliable answer to the types of problems described above has to be based on a more integrated use of models.

Although general references on the relation between the two systems can be found (Winter et al., 1998; Sophocleous, 2002; Gardner, 1999), an analysis that includes the interaction between surface water and groundwater in an urban setting is still rare, because this type of analysis is obviously complex. One of the main problems underlying the integration of surface water and groundwater processes is that the modeling must take into account the different scales of spatial and temporal variability involved. Apart from experiences using the simple groundwater routine in SWMM for some cases in Florida and with the MIKE SHE program developed by DHI (1999), it is evident from the literature review that the integration is difficult and has been attempted for only special cases. On the other hand, the unavailability of an integrated software package could also partly explain why this type of analysis is not undertaken more often. However, as more and more infiltration Best Management Practices (BMPs) are constructed, following a trend towards extended use of infiltration to control stormwater at the source, it is to be expected that global analysis tools or approaches will be needed in more projects. In the present study the interrelation

between surface water and groundwater was deemed to be very important, and should be evaluated in a global way at least, as described here.

Rostov is one of the oldest cities in the country, being first mentioned in the chronicle in 862 as a remote front post of Kiev Russia. It is located about 190 km north of Moscow, on the shore of lake Nero, the biggest lake in the Yaroslavl region. Many buildings in Rostov date back to the 16th century, and have recognized historical importance. They need to be restored due to advanced degradation of the wooden and stone foundations. This degradation and other environmental problems are in large part due to very high groundwater levels through most of the historical parts of the City, which are in turn directly associated with human activity over the years. The activities include railway embankment construction, urban infrastructure development, in-filling of drainage ditches, raising street levels and disturbed surface runoff paths.

As part of a project funded by the Council of Europe and the Canadian International Development Agency (CIDA) for the rehabilitation of the ancient City of Rostov, some technical analyses were completed for surface runoff and groundwater flow in order to define, at least globally as a preliminary step, some potential interventions to lower the groundwater levels.

Surface runoff for the old part was modeled with PCSWMM, while the groundwater was analyzed using MODFLOW. The chapter describes the PCSWMM and MODFLOW model development and the global approach that has been used to evaluate the interrelation between the two systems. Different approaches that could be used to integrate the two models are discussed, highlighting the problems to be resolved in order to properly simulate the global water system and evaluate appropriate remedial measures.

4.2 Rostov and the Hydrotechnical Problems to be Addressed

Water problems associated with the lack of proper surface drainage and the rising levels of groundwater in the Old City of Rostov have developed since the beginning of the 20th century. Russian experts who have studied the problems in the past are unanimous in confirming that the causes of these problems are numerous and directly linked to human actions, such as the construction of the railway, closure of the moat surrounding the kremlin (ancient walled part of the City), the raised level of the streets and the lack of maintenance of surface drainage systems. Many unsuccessful action programs have been put forward since the 1930s.

Rostov has been built close to Lake Nero, which is the largest natural water body in the Yaroslavl Volga region. Its area, depending on the water level, varies from 39 to 58 km² with a mean value of 51.7 km² (length of 12.5 km and width of 8 km); the maximum depth in the lake is about 5 m, with more than 80% of its area being about 1 m deep. The water level of the lake is regulated and varies during the year with maximum elevation in May (95.2-96.5 m) and minimum in September (94.6-95.2 m). The drainage basin of Lake Nero, shown on Figure 4.1, is 1314 km². The main water management problem for the water body is the selection of optimal lake water level for every season. For the present analyses, the water level in the lake was important as it influence the draining capacity of creeks and sewer pipes as well as groundwater movement in Rostov.

Figure 4.1 Location of Rostov and watershed for Lake Nero.

Figure 4.2 Urban development for the old city in Rostov and location of artificial ponding areas.

The Nero Lake basin is located in a zone of temperate continental climate, with cold winters and temperate warm summers. In winter, snow cover is observed on the average during 150 days and average water equivalent of the snow pack is 87 mm with a depth of snow cover of 32 cm. Average annual precipitation amounts to 520 mm (liquid and solid).

Figure 4.2 presents the configuration of the Old City in Rostov, built with a kremlin in a semi-circular form, and the urban area that developed around the kremlin walls. The hydrographical network within the limits of the historical part of Rostov includes several artificial ponds, ephemeral streams, water-logged areas and a large ditch (ancient moat surrounding the kremlin) named the Piga River, where runoff is observed mainly during spring flood periods. During low-flow periods, the sanitary and ecological condition of the ditch is catastrophically degraded, being literally transformed into an open sewer.

The drainage network in Rostov has some specific elements that have historically contributed to an inefficient surface drainage, which in turn have induced an artificial recharge of the groundwater. First, as can be seen in Figure 4.2, the railway, built about 50 years ago just north of the old part of the City, has to some extent cut off the pre-existing natural drainage pathways, thereby creating a wetland area just north of the railway. Secondly, 27 ponds can be found in the old part of the City alone, and many of these artificial ponds have no outlet (Figure 4.2); about 11 % of all the sub-basins in this area (255 ha out of 2,050 ha) drain toward these ponds. Some of these ponds are permanent water bodies with quite clear water but but most ponds are polluted, like the one in Figure 4.3, where the water is deep opaque green.

Figure 4.3 Typical artificial pond with no outlet.

The modeling activities, both for surface water and groundwater, had therefore as a principal objective to provide technical background in order to define possible interventions to lower the groundwater levels in the Old City and to enable, at least globally, a preliminary evaluation of the beneficial effects.

4.3 Surface Runoff Modeling

This technical activity had as a main objective to provide a tool to evaluate water balance for surface runoff in the whole City of Rostov, using the model to determine the existing amounts of surface runoff, of infiltration and evaporation following precipitation in different seasons and, also and more importantly, to evaluate the same parameters after specific interventions. These interventions had to be defined in order to increase surface runoff and thereby reduce the amount of infiltrated water contributing to groundwater level increase. Infiltration is a main source of inflow to groundwater and it is therefore essential to limit surface infiltration.

PCSWMM was used to obtain the overall hydrologic response for the Old part of the City. Using local flow measurements obtained during summer 2001, the first step was to calibrate the model with a significant rainfall event that occurred on July 29th, when about 55 mm of rainfall was recorded. The model, for which a plan view is shown on Figure 4.4, could then be used to evaluate the water balance for different conditions.

As discussed previously, a total of 255.4 ha of drainage areas ultimately drained toward areas where the only outlet for the accumulated water is either by infiltration or evaporation. This represents about 11% of the entire drainage area in the urbanized part of the City modeled with SWMM, which is significant. This quantity of water adds to the water infiltrating elsewhere in the City in pervious areas (2049.87 ha), even if drained by adequate ditches or culverts.

To investigate the water balance for surface runoff, the model was then run for different conditions corresponding to runoff produced by snowmelt or rainfall. The different conditions simulated were:

- snowmelt (springtime),
- short summer rainfall events (duration 1 h), and
- long fall rainfall events (duration 24 h).

For the snowmelt conditions and to define a typical spring runoff event, an average snow water equivalent of 87 mm was assumed for Rostov (based on available data), distributed over a 15 d period with intensities varying from 2 to 12 mm/h. This maximum intensity of 12 mm/h lasted only a few hours for

Figure 4.4 PCSWMM model configuration for the old city in Rostov.

the peak period and corresponds to an event of rain on snow. The remaining part of the snowmelt period (15 d) consisted mainly of snowmelt intensities of 2-3 mm/h, with a total of 87 mm for these 15 days. The infiltration parameters for the Horton equation were reduced in the model from 10 to 2 mm/h (maximum infiltration rate) and from 1 to 0.5 mm/h (minimum infiltration rate), to take into account the partly frozen soils. Evaporation was set at 3 mm/d and the simulation was carried out for 15 days.

For short summer rainfall events (duration 1 h), the total quantities were 14.4 mm, 18.8 mm and 26.1 mm for return periods of 0.5 y, 2 y and 5 y respectively, as based on available data at a meteorological station in Rostov. Simulations were completed for total durations of 3 h, 25 h and 49 h. For long fall rainfall events (duration 24 h), the quantity was 40 mm for a return period of 2 y; simulations in this case were completed for total duration of 360 h and 540 h.

Table 4.1 Typical results from PCSWMM simulations.

Conditions simulated	Duration of event (h)	Duration of simulation (h)	Parameter	% of total precipitation
SCS (Type II) mass curve Rainfall 1/2 year	24	25	Total infiltration	48.8
			Evaporation	0.3
	49	49	Runoff	14.6
			Water remaining	36.3
			Total infiltration	83.5
			Evaporation	0.4
			Runoff	15.1
			Water remaining	1.0

The results (see Table 4.1 for a typical example) indicate that the amount of snowmelt or rainfall transformed into runoff is quite low for the City of Rostov, ranging from 7.6% for low intensity summer rainfall to about 15% for long duration rainfall during fall. By contrast, this value should be close to 30% in a typical residential area well drained by adequate ditches and conduits. For areas with higher imperviousness, like the area close to the kremlin, the percentage of runoff as compared with precipitation should be closer to 40 to 50%.

It can therefore be seen that an increase in surface runoff, for example just by draining ponding areas that have no outlet, could significantly help reduce the amount of direct infiltration to groundwater. Implementing an adequate

system of conduits and pipes to drain surface runoff is another way to decrease the amount of infiltrated water.

4.4 Groundwater Modeling

4.4.1 Description of the Specific Hydrogeological Features for the Study Area

The drainage basin close to Lake Nero is characterized by a very flat topography; there is no noticeable ground slope inside Rostov, except very close to the lake shore. High groundwater tables in the region are endemic and have been reported in many documents. However, available data indicate that since the beginning of the 20th century this problem has been aggravated by human actions such as construction of the railway north of the city (without appropriate drainage installations), closure of the moat around the Kremlin, raising the level of the streets and the lack of maintenance of surface drainage systems. As a result, the historical monuments of the Old City have experienced accelerated decay and the sanitary conditions in the city have worsened.

Figure 4.5 Location of Rostov City and piezometers. Dashed line is boundary of regional flow model.

The goal of the groundwater model was to assist, for the area shown on Figure 4.5, in understanding and solving the following problems:

- quantitative assessment of the hydrogeological conditions under the City;
- impacts of the existing natural and urban factors on groundwater regime;
- impacts of the proposed solutions on groundwater regime; and
- optimization and development of a groundwater monitoring network

4.4.2 Available Data and Groundwater Regime

The City is built on a series of geological layers characterized by different periods of sedimentation. According to available data (Figure 4.6) provided by the local firm Intergeo (2002), the upper geological layer (t IV) is man-made ground. This material is highly heterogeneous, discontinuous, and thus makes the hydrogeological analysis particularly difficult in the kremlin (left of Figure 4.6). The bottom of Lake Nero is characterized by a layer (l IV) of lacustrine deposits called Sapropel (thickness up to 4.9 m) having very low hydraulic conductivity. The first continuous geological layer (p IIIvd₃ or Upper Valday) is made of a water-bearing brown-gray loam ($K_H \approx 0.4 \text{ m/d}$ or $4.6 \times 10^{-6} \text{ m/s}$). The next geological layer (l IIIvd₁₋₂ or Lower and Middle Valday) is mainly composed of gray muddy loam ($K_H \approx 0.2 \text{ m/d}$ or $2.3 \times 10^{-6} \text{ m/s}$). The two layers p IIIvd₃ and l IIIvd₁₋₂ form what is generally considered to be the top unconfined aquifer, although the values of hydraulic conductivity are relatively low. The underlying layer (l IIImik, Mikulinsk period) comprises black and heavy dark gray clay and constitutes an aquitard ($T \approx 0.001 \text{ m}^2/\text{d}$ or $1.2 \times 10^{-8} \text{ m}^2/\text{s}$ for an average thickness of 4-5 m) between the previously mentioned unconfined aquifer and the upper confined aquifer. It is suspected that this aquitard possesses small zones of lithological windows through which some vertical exchange is possible between the two aquifers. The upper confined aquifer resides in layer fgIIms (Moscovite period) formed of gray hard unequal granular sand ($T \approx 10 \text{ m}^2/\text{s}$ or $1.16 \times 10^{-3} \text{ m}^2/\text{s}$ for an average thickness of 4 m). The underlying aquitard (layer lgIIms or Moskovite period) is made of red-brown bandy clay, moraine loam that is considered to be impermeable. There exists another lower confined aquifer under the latter aquitard, but it is suspected that no interaction occurs between the two aforementioned aquifers so this aspect was thus neglected.

Figure 4.6 Geological and hydrogeological features of Rostov.

Prior to the study, the elevation of the water table had been measured each time a geological investigation was required in the city. Overall, more than 600 localized measurements of the water table elevation were made over the period 1966-2000. This data, summarized in Figure 4.7, provides some information about the range of the water table fluctuations in the city. Nevertheless, no continuous and systematic hydrogeological measurements have been performed. When this project started in 1999, a line of piezometers (visible in Figure 4.5) was therefore installed perpendicular to the shoreline, across the historical sector of the City, and up North to the new part of the city. Spanning the period 1999- 2002, this continuous monitoring of the water table in the City gave not only an insight into the temporal fluctuation over the whole year, but also and for the first time instantaneous pictures of the water table situation at a given time. Following these successful observations, an additional series of piezometers were installed in Summer 2002 in order to give a two-dimensional (horizontal) picture of the groundwater table distribution.

Figure 4.7 Groundwater level measurements in Rostov (1966-2000).

4.4.3 Development of the Regional Groundwater Flow Model and Calibration

The horizontal limits of the models are shown in Figure 4.5. To the South, the boundary extends about 650 m into the lake, in order to simulate the discharge of the two aquifers into the lake through the Sapropel layer. The RIVER package

was used for the lake itself, with a hydraulic conductance calculated from Sapropel hydraulic conductivity and thickness of layer. To the West, the channel of an intermittent river was chosen. To the North, the model limit was the lowest point of the water table (inline with piezometer c-26p in Figure 4.5), considering that this low point could be represented by a symmetry condition. To the East, no physical feature could be found, so a distance arbitrarily far from the center was chosen.

The geological formations described in the previous section were translated into four numerical layers in MODFLOW. The first two numerical layers are used to describe the unconfined aquifer (layers p IIIvd₃ and l IIIvd_{1,2}), the third numerical layer describes the aquitard (layer l IIImik) and the fourth numerical layer describes the upper confined aquifer (layer fgIIms). The bottom of this last layer constitutes the lower limit of the numerical simulation. All available geological data and topography have been geo-referenced and mapped in the model. The hydrogeological parameters (hydraulic conductivity, transmissivity) were estimated from the mean values of material described in each layer. They were later calibrated against available data. Recharge was estimated using the nature of the surface (asphalt, grass, bare soil), the amount of yearly precipitation and the nature of the soil. The yearly-averaged values vary between 0.4 and 0.65 mm/d. Evapotranspiration was also calibrated against local hydrological conditions and type of coverage. The yearly-averaged values vary between 0.35 and 0.7 mm/d. The so-called extinction depth (depth beyond which no evapotranspiration can occur) was estimated to be 4 m.

4.4.4 Results

Geological formations of Rostov are characterized by very low hydraulic conductivities and very flat topography. As a result and because of the high water table in the region, the hydro-geological regime consists mainly of a vertical exchange between the recharge and the evapotranspiration. Indeed, the water balance analysis shows that almost 75% of the recharge goes to evapotranspiration. In contrast, the horizontal transit of the water is very slow and limited (25%). Another impact of this feature is that any local intervention has only a localized impact on the regional water table elevation.

Both measured data and simulations show a clear hydro-geological mound just under the old part of the city. This mound is interpreted as being the result of the intensive infiltration generated by the multiple ponds that accumulate water in the old City, combined with a deficient drainage system. The fact that the dome is absent in the new part of the City confirms this analysis since there

are no ponds in this area and the drainage system is more recent. The three-dimensional numerical modeling shows clearly this mound (Figure 4.8), which is also visible from the data collected since the beginning of this project. The data available in Figure 4.6 also show the presence of this hydrogeological dome under the old city of Rostov.

Figure 4.8 Steady-state groundwater flow simulation: averaged water levels in the city of Rostov.

4.5 Integration of Models

Due to time and budget limitations, the first step of the project described here was to develop the two models separately and to investigate globally how a change in the surface runoff would affect groundwater behavior. A real coupling of the two models would however be more interesting and some avenues were explored for future steps, yet to be completed.

The GROUND subroutine already available in SWMM (James et al., 2002) was first investigated for these tasks. In this simple subroutine, groundwater flow is modeled in both the unsaturated and saturated zones. The groundwater component is a lumped model for both zones and is based on individual water balances. Some of the major limitations (James et al., 2002) are that the moisture

content of the unsaturated zone is taken as an average over the entire zone and that non-uniform infiltration over the catchment can not be simulated. Although these limitations could be neglected in very flat areas such as South Florida (for which essentially the subroutine was developed), the use of this option was not appropriate for Rostov.

Another capability of PCSWMM that could be put to use in this context is the new option available in version 4.4H of SWMM, which enables the user to direct runoff from one overland plane to another. In older versions, runoff from an impervious or pervious surface had to be directed to a node. With this new option, it is possible to obtain the infiltrated water from each sub-basin, to lump as necessary the amount of water from different sub-basins and to then direct this water to MODFLOW, where further analysis can be carried out. For the groundwater component, it was concluded for the project that the use of MODFLOW, which is a fairly comprehensive and widely used program for groundwater analysis, was the preferable modeling tool. To extract the information from the SWMM output file and to re-format it as input to MODFLOW, therefore appears to be the most cost-effective alternative option to be investigated in the next phase.

The models will then be used to produce a month by month water balance for the surface and groundwater systems, based on a typical overall hydrological balance (Novotny and Olem, 1994):

$$P = Q + ET + \Delta S_s + \Delta S_g \quad (4.1)$$

where:

- P = precipitation,
- Q = runoff,
- ET = evapotranspiration,
- ΔS_s = change in surface storage, and
- ΔS_g = change in groundwater storage.

If the balance is averaged over a period of several years, then $\Delta S_s = 0$ and in the recharge area

$$P = Q_s + R + ET \quad (4.2)$$

where

- R = recharge rate (infiltration), and
- Q_s = surface runoff only because base flow is not discharging.

And at the outlet in the discharge area

$$Q = Q_s + D - ET + P \quad (4.3)$$

where:

D = discharge rate (exfiltration).

These equations are useful for defining the problem at a macroscopic level. For example, comparing Equations 4.2 and 4.3 with the overall balance expressed in Equation 4.1, it follows that:

$$\Delta S_g = R - D.$$

In the case of Rostov, due to hydrogeological layers of low transmissivity, D should be relatively low and slow (drainage towards the lake Nero). As the available storage is not very important (high water table), it follows that an increase of the amount of runoff could have a significant impact on the potential overall change in groundwater storage. The simulation results presented in Figure 4.9 indeed indicate that reducing infiltration (by increasing the surface runoff) will contribute to a lowering of the water table in the area of concern.

Figure 4.9 Groundwater table lowering (in m) due to 30% reduction of additional infiltration in the study area.

Detailed simulations with associated water balance considerations are however to be finalized before recommending specific interventions; in the case of Rostov, a lowering of the water table levels too much could be detrimental to old timber foundations and it is therefore essential to correctly assess the impact of decreased groundwater levels. A phased approach, with adequate monitoring after a given local intervention, was therefore deemed appropriate before a full scale program for the entire area could be implemented.

In a sense, the existing conditions prevailing today in Rostov might well be a case of looking “back from the future” if we consider the current trend of accentuating stormwater infiltration as a means of runoff control. Although the infiltration BMPs that are being recommended more and more appear to be a sensible and cost-effective option, we should be cautious about using these approaches at a large scale without a proper analysis of the possible impacts on groundwater regime. Although recent references do present detailed design information for infiltration BMPs (Guo, 2001; Ferguson, 1994)), this aspect is however not routinely studied in a typical stormwater management project as an appropriate software package to address it conveniently is yet to be developed.

4.6 Conclusion

The global modeling presented here using PCSWMM for surface runoff and MODFLOW for the groundwater has provided a technical base to analyze complex conditions in Rostov and investigate, at least in a preliminary fashion, potential remedial measures. Many types of projects in urban drainage are characterized by this interaction of surface water and groundwater systems, where changes in one system have a significant influence on the other. Examples of very practical importance for stormwater management are the influence of groundwater levels on the amount of infiltration in sewer networks (which could impact on SSOs and CSOs) and the effect of large-scale infiltration BMPs on the groundwater regime. A truly integrated modeling software with these two public domain programs would therefore be a welcome addition for the modeling community.

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