AN INTEGRATED APPROUACH TO GROUNDWATER RISING PROBLEM USING MODELING AND GIS

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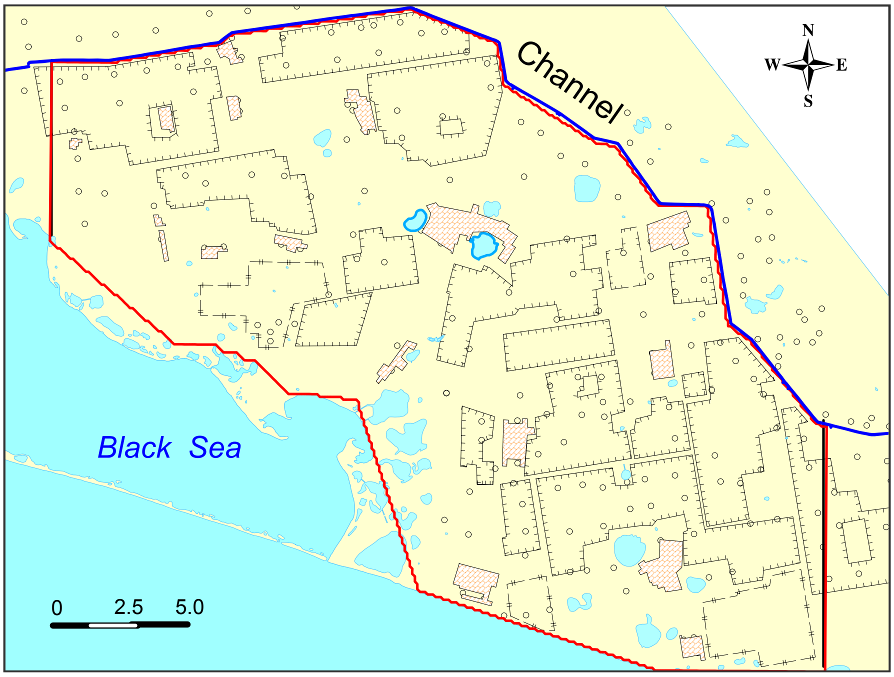
Abstract
This research is aimed at development a map-based groundwater flow model with three model-components (governing equations, maps, databases) integrated. The model is applied to a problem of groundwater rising on a territory of a Krasnoznamensk irrigation system. The system, located in a southern part of Ukraine, is one of the largest in the world, while a study area occupies a territory of about 460 sq. km between the irrigation channel and the Black sea coastline. Results of a plane model developed are used as a basis for optimization of an existing drainage system. GIS and databases related are used as a model's pre-processor and post-processor.

Introduction
Irrigation water filtration, increasing irrigation rate and malfunction of a worn drainage system are among main reasons of groundwater rising on a territory of the Krasnoznamensk irrigation system. Besides, a large drainage effluent to the Black Sea with increasing rate of saltiness and mineralization (up to 13.8 million of cubic meters for the year 2000) leads to water quality deterioration. To protect settlements from groundwater rising, reconstruction and optimization of the existing drainage system is necessary. In turn, to fulfil these tasks, the short and long term forecasting of groundwater dynamics according to irrigated area and irrigation rate is necessary. A 2D mathematical model of flow in plane is developed. A large study area, variety of hydrogeological conditions and large amount of cartographic input data (monitoring data, medium characteristics, irrigation system description) demand using of databases and GISs (1).

Methods
The Krasnoznamensk irrigation system is located in a southern part of Ukraine. Its western part with an area of about 460 sq. km was selected as a study area for the next reasons: it is representative of agricultural and irrigation practice of southern Ukraine and it has clearly defined hydrogeological boundaries, namely the Krasnoznamensk irrigation channel (North, North-East) and the Black Sea coastline (South) (Fig. 1).

Figure 1: Model domain with irrigation fields and drainage wells



The model uses the finite difference method for the two-dimensional flow equation in a region Ξ variables x_1, x_2 with an exterior boundary $\partial\Xi$ and inner boundaries $\partial\Xi_k$, $k=\overline{1,n}$. Regions confined with boundaries $\partial\Xi_k$ are surface reservoirs and are designated with Ξ_k, $k=\overline{1,n}$. For the inner boundary the following conditions are imposed

$h(x_1,x_2)=g_k(t),\ x=(x_1,x_2)\in\partial\Xi_k,\quad k=\overline{1,n}$,

where $g_k(t)$ - water height in an according reservoir; $h(x_1,x_2)$ is a hydraulic head, which obeys the next equation:

$$S\frac{\partial h}{\partial t}=\sum_{i=1}^{2}\frac{\partial}{\partial x_i}\left(T\frac{\partial h}{\partial x_i}\right)-\sum_{m=1}^{p}q_m(t)\delta(x-r_m)-\sigma(h-h_1)+W,$$

where $T(x_1,x_2)$ is an aquifer transmissivity; $S(x_1,x_2)$ is an aquifer storage coefficient; $x=r_m$, $m=\overline{1,p}$, are drainage wells locations; $q_m(t)$ is a water withdraw at the mth well; $\delta(x-r_m)$ is a Dirac delta function at r_m; $h_1(x_1,x_2)$ is a hydraulic head in the lower aquifer; σ is a leakage factor; $W(x_1,x_2)$ is a function, characterizing a total water input on the water table.

Solution with the fictitious domains method leads to the equation (2):

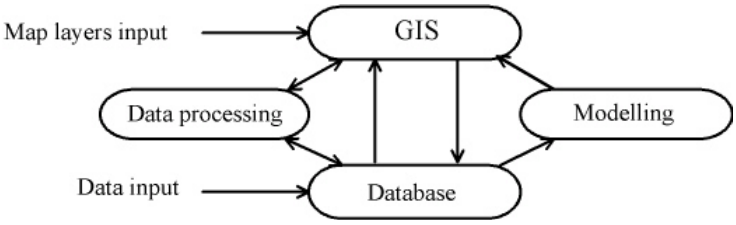
$$S\frac{\partial h_\varepsilon}{\partial t}=\sum_{i=1}^{2}\frac{\partial}{\partial x_i}\left(T\frac{\partial h_\varepsilon}{\partial x_i}\right)-\sum_{k=1}^{n}c_k(h_\varepsilon-g_k(t))-\sum_{m=1}^{p}q_m(t)\delta(x-r_m)-\sigma(h_\varepsilon-h_1)+W$$

$$x\in\Omega,\ \Omega=\Xi\cup(\sum_{k=1}^{n}\overline{\Xi}_k),$$

$$c_k=\begin{cases}0, & x\in\Xi,\\ \varepsilon^{-2}, & x\in\overline{\Xi}_k,\ \mathrm{k}=\overline{1,\mathrm{n}},\ \varepsilon\ \text{is a small.}\end{cases}$$

A prescribed head is given on the boundary $\partial\Omega$.
The mathematical model is coupled to GIS, used for the model referring to the study area. In the GIS and databases related input data as well as model parameters are stored, prepared and updated. The main difficulty in the model adaptation is matching and input of large amount of tabular and of cartographic information. Data nature and their structure determined the general structure of the model coupled to GIS as shown in Figure 2. Previous experience gained at modeling of environmental impact from tailing ponds of the Poltava open pit iron ore mine was used as well (3).

Figure 2. General structure of the model



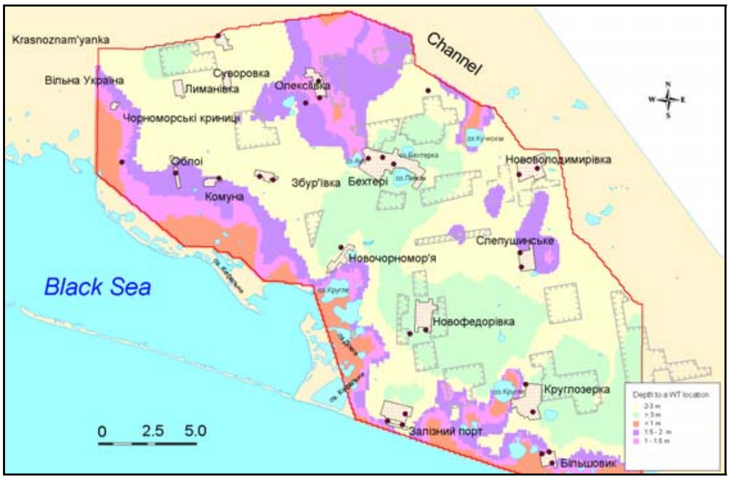
Two main ways of data representations (cartographic and tabular) determined technique of their input into the model:
1. Data input by means of map digitizing.
In turn, vector information stored in the GIS can be divided as:
- Map layers with settlements, communications, topography, the Black Sea coastline, the study area boundary, which are used for visualization of the area and of the modeling results, for current condition estimation and for decision making support;
- Map layers with monitoring system wells, drainage system wells, irrigated fields contours, surface reservoirs and canals, which also are used for mapping of different attributive data such as results of regular observation on a ground water regime, pumping rates for drainage wells, irrigation rates and regimes, water height in reservoirs. Contours of the irrigated fields can vary with time and is used in the model as source functions. Thereby opportunity to write down of objects co-ordinates from a digital map to ASCII files and their further storage in the databases is provided;
- Map layers with contours of different levels for transmissivity and water storage;
- Map layer with computing grid nodes, which is created dynamically and is used for mapping of the results in a numerical representation.

2. Tabular data input to the databases is performed by means of user interface developed. Monitoring results, tabular parameters, grid nodes co-ordinates, the study area boundary etc. are stored in the databases. Data stored in the databases are transferred to the model for modeling and to the GIS for mapping on a query.

Results
An implicit difference scheme (4) with an uniform 100 m x 100 m grid (total amount of nodes was 46525) was adopted for the boundary problem solving. Cell dimensions were chose on the basis of a spatial scale of data available. A time step of 0.5 day was used in modeling. Spatial and temporal distribution of irrigation for different farms as well as pumping rates and regimes of the drainage wells were given. Soil parameters were recovered as two dimensional functions from contour maps for transmissivity and storage coefficient. For functions interpolation at grid

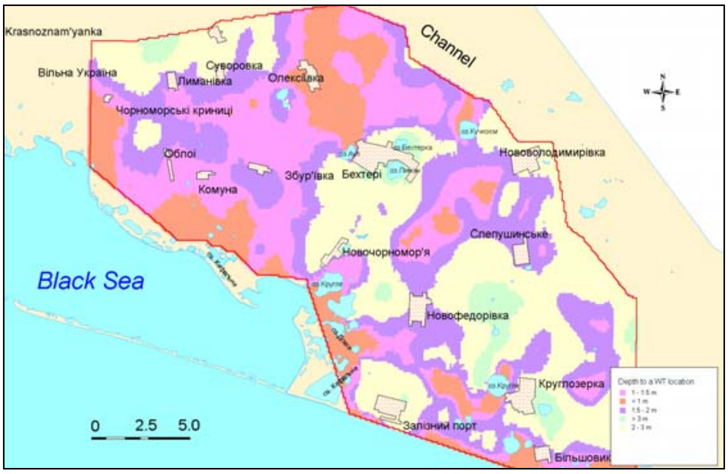
nodes a Delaunay triangulation was applied. For calibration of the model monitoring data beginning from the year 2000, when only 28 of 280 drainage wells were operable have been used. The study area with a thematic map on a water table depth for the year 2000 obtained as a result of modeling is given in Figure 3.

Figure 3: Result of modeling for the year 2000



As it is seen, this amount of drainage wells cannot protect the territory from groundwater rising. Results of modeling of a groundwater rising development under total malfunctioning of the drainage network are given in Figure 4.

Figure 4: Groundwater rising under the drainage network malfunctioning



Conclusions

The fulfilled study demonstrated a good applicability of mathematical modeling integrated with GIS and databases for forecasting of 2D groundwater flow in a large area such as an irrigation system. Using of GIS and databases allowed to input hydrogeological conditions with necessary accuracy. On the other hand, it revealed inaccuracy in the data available. The model is to be passed to the Kherson Regional Water Management Administration for further exploitation and verification.

The results obtained allow to hope for successful application of the developed technique to another irrigation systems in Ukraine.

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