GIS-BASED MODELLING FOR THE ENVIRONMENTAL ASSESSMENT OF SMALL URBANIZED CATCHMENTS

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Abstract

Much of regional water flow is formed within urbanized catchments, nevertheless since the diversity and number of pollution outlets in the cities can be enormous, it is difficult to evaluate the scope of human-caused environmental damage. Thereby, we are aiming at the GIS-based modelling the fluxes of pollutants within small urban catchments. A GIS is required because the urban systems have different geographically defined information. The case study from the city of Mogilev, a major industrial centre in Belarus, has been drawn upon. Chosen catchments of Dubrouna and Dzebra feature divers land-use, and many of city's industrial productions. Sets of maps and databases on city topography and planning, relief, local hydrography, soil cover and its contamination, quality of surface water, pollutant emissions, storm sewage have been compiled. 3D analysis (making triangulated irregular network models for relief and soil pollution), spatial analysis (creating grid-themes on environmental pollution), buffer analysis (locating buffer zones along the streams), "overlay" analysis (checking correlations among different spatial objects) have been applied to the data from catchments. Next, "what if" scenarios were applied to simulating issues of location, condition, and trends, i.e. system dynamics behavioural patterns of environmental pollution and possible natural- and human-caused accidents were explored.

Introduction

Mahiliou's municipality is one of the largest in Belarus (over 370 thousand people as of 2002). It serves as an important regional centre and location of large-scale chemical and machine-building industrial productions. The latter is resulted in the dramatic air pollution, also associated with rapidly expanding private car's ownership, mainly comprised of second-hand cars. Thus, Mahiliou takes leadership as the most polluted city in Belarus (UNDP, 1997). Besides the air pollution, heavy chemical contamination of surface waters occurs at the large-scale. The most attention of environmental stakeholders is customary given to the pollution of the Dnepr, as five big industrial productions and the municipal water treatment plant discharge the sewage waters to the river (Ministry of Environment, 2003). However, small rivers draining Mahiliou's commune are obviously much more affected by human impacts, since their ecosystems are more vulnerable, their catchments are totally urbanized, and most of the channels have been changed and subsequently lost their self-purification capacity. In brief, the major effects of urbanization resulted in the environmental pollution of the small rivers are as follows:

- Concentrated surface runoff of pollutants: from the outlets of storm water drainage systems and industrial sewage.
- Diffused surface runoff: underground flow from leaky underground sewer lines; runoff contaminated by the air-born particles, which are coming to watersheds with rainfall.
- Direct surface runoff: flows of temporary steams from uncaptured storm and melted snow waters.

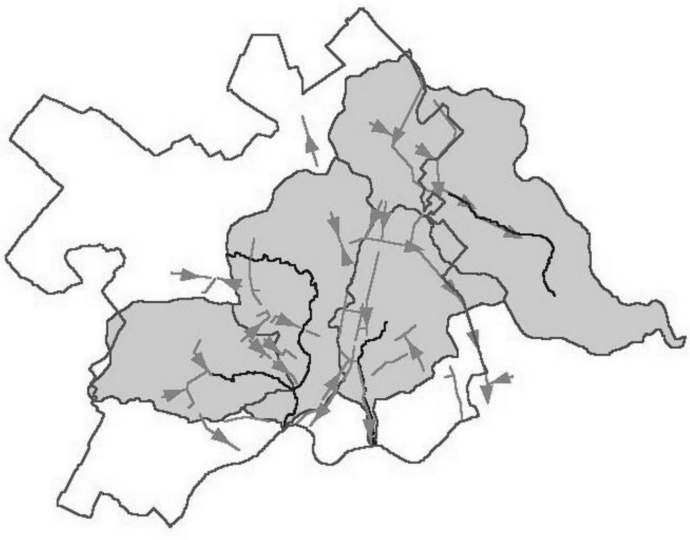
Such a wide diversity of the ways of environmental pollution of the small streams might have challenged the municipal environmental stakeholders to acquire managing tools predicting environmental consequences of the human impacts on the short- and long-term to improve the city-planning and management practices. However, so far such a tool has not been required. Moreover, when taking city-planning decisions, relatively small attention is paid to the issues of the ecology of small watersheds because, as we have noticed, environmental problems of the city small streams are usually underrated or even neglected. Probably this happens because they are not considered as important sources of municipal and industrial water supply, and they active role in the contamination of the Dnepr River is barely taken into account.

Nevertheless, we are arguing that the expert system devoted to the ecology of small watersheds ecology should be created and run as an essential section of the municipal environmental management system (EMS). In this paper, we explore the use of GIS techniques to build a spatial multi-actor model that simulates direction and intensity of contaminated runoff, thus locating the areas of the more dramatic environmental conflicts and offering alternative locations for objects to be built. Our main focus is to integrate the variety of environmental data from the watersheds and riverbeds into the single system, thereby grounding environmental impact assessment (EIA) system on the links between the vulnerability of channel ecosystems and environmental performance of urbanized catchments.

Study area

Study area includes watersheds of the rivers of Dzebra, Dubravenka (downstream the Lake of Piachersk), Strushnia, and Mikalajeuskaja, as it is shown at figure (1). All watersheds are chiefly underlain by Riss moraine clay. Their close location also assumes that they receive the same rainfall rates – 650-680 mm/year, and mean temperature, varying from -7.6°C in January to +18.0 °C in July (Sivikovkiy et al, 1982).

Figure 1: Watersheds under the study (gray areas): Strushnia, Dubravenka, Dzebra, Mikalajeuskaja respectively from west to east; lines with arrows mark storm sewers



In the area of the case study river's runoff is mainly generated as a mixture of melted snow water stored in deeper hill-slope groundwater and, during spring-early summer also in shallow soil layer. The annual surface runoff for Mahiliou neighborhood mounts to 6.0-5.5 $dm^3/sec/km^2$ (Academy of Science, 1984). In the rivers studied there is a substantial component of direct street runoff, especially evident for the valleys of Dzebra and downstream Dubravenka, edging the downtown. As far as watersheds of Dzebra, Strushnia and downstream Dubravenka are totally build up with multistoried residential blocks and industrial productions, much of their stream flow is generated by waters, releasing from the outlets of storm pipe system; Dzebra's runoff is also generated by sewage waters from a steel production and big municipal heat plant. Waters from storm sewer lines also contribute a lot to the runoff of Dubravenka and Mikalajeuskaja, though drainage basin of the latter stream is located mainly in non-urban settings (figure 1).

An important feature of Dubravenka, Dzebra, and Strushnia basins, less typical for Mikalajeuskaja basin, is that they are underlain by separated systems of transport pipes with storm overflow and sewage from industrial and residential areas, as it is shown at figure 1. On average, 276.2 m^3/day of sewage is conveyed through the system. A total 459.6 km of sewage and storm water pipe underlies the city of Mahiliou. The industrial/municipal waste is pumped to treatment facilities of the city of Mahiliou; storm water is for the most part discharged to the small rivers. It is a common occurrence for this storm pipes to overflow and discharge sewage through manholes during storm events, thus contributing to direct street runoff, as it was repeatedly noticed even in the very inner city. It is also reasonable to pose that these storm drains as well as transport pipes of municipal sewage system leak underground, thereby entering groundwater and impacting flow chemistry of urban streams.

Proposed method

To illustrate the integration of riverbed ecological indexes with watershed hydrology, we propose a simulation model that allocates stream transects that belong to the certain catchments patches. This allocation is based upon the analysis of watershed surface, and includes the routing of flow curve from the patch to channel, thereby allowing the estimation of changes in the flow intensity and water chemistry that depend on the parameters of underlain surface. Contribution of the estimated inflow can be compared with the existing footprint on the ecosystem of the target channel transect, also simulated by the model. Thus, we provide a reference point for environmental assessment of the intended impact.

Construction of the model goes through four steps. Firstly, assessment of the carrying capacity of channel ecosystem should be done. This includes summarizing and integrating the information on the following components that form channel's resistance to external impacts: mean runoff, type of channel sedimentation (fluvial processing), bedrocks, dominant channel vegetation (macrophytes), stream velocity, and characteristics of riparian ecosystems. The assessment is resulted in the set of integrative environmental indexes, describing purification capacity of different riverbed ecosystems. The second step involves constructing and analyzing watershed databases and maps that allow the simulating of runoff generating and further transformation in the intensity and water chemistry: underlain bedrocks, slope, local erosion network, groundwater table, infiltrating capacity of underlain surface, paved and built-up surfaces, surface runoff, design and pattern of storm sewers. The third step includes delineating watershed patches that belong to the channel transects featuring particular environmental indexes. These spatial entities are equipped with the behavior that is needed to establish and maintain the environmental interactions between watersheds and channel ecosystems. At the fourth step the links between watershed patches and appropriate channel transects are established, mimicked and approved on the indicators of stream ecology, such as hydrochemistry and stream communities.

Urbanized area is a scene of the dramatic environmental changes that also affect watersheds and stream ecosystems. Therefore, current update of the working databases is essential to get relevant model outputs. For instance, if a new network of storm drains with appropriate water-treatment equipment would be constructed, this would lead to the increase in the watershed's environmental carrying capacity, since the less impact on the affected stream ecosystem is imposed and it gains better environmental performance. Pretty similar, if a stream transect is getting canalized, i.e. pool-riffle system, macrophytes, and riparian ecosystems are blown out, than watershed belonging to this stream transect also looses in the environmental carrying capacity, because the stream ecosystem becomes more vulnerable to the human impacts coming from the watershed.

Pilot application

We have implemented the model using a combination of GIS and mathematical modeling software. Stream ecosystems have been developed in polyline themes. Given the frequently occurring dramatic changes of urban streams, we have linked channel databases to transects of 10-15 m each. This length is sufficiently small to depict spatial heterogeneity of stream ecosystems and their changes in the scale chosen for the GIS being developed (1:10,000). Each transect stores the table that includes such fields, as transect ID, runoff (m^3/sec), stream macrophytes, fluvial processing (after Kondrat'yev, Popov & Snischenko, 1982), channel morphometry (width and depth (m)), riparian ecosystem (width and vegetation), bedrocks, typical human impacts, unit of ecological classification (includes and summarizes all the above data). Any of the databases fields can be viewed in the map.

The surface runoff consists of the indexes of infiltration and slope. The infiltration map has been mapped after the recommendations of The State Hydrological Institute (Kupriyanov, 1976), as is shown at figure (2) for Dzebra. To compute the surface runoff we intersected the polygonal theme resulted from digitized contours of slopes with the infiltration polygonal theme. Time the surface runoff needs to reach the stream (stream reaching time) has been calculated by merging the type of underlain surface, slopes (figure 3), and distance from the main stream.

Since much of urbanized runoff is captured by storm drains, we have derived micro-catchments that belong to the sewers. It is common occurrence when the drains capture storm runoff hydrographically belonging to another basin. Thereby, storm drainage system change watershed's hydrological model.

When delineating micro-watersheds belonging to the stream transects with particular environmental capacity, we have employed Hydro extension. First, elevation grid model has been made. Next, we have allocated the very downstream point of the transect. Than, all the grid cells belonging to upstream watershed were selected and used to create polygonal micro-watershed theme.

The GIS outputs have been used in mathematical modeling of the micro-watersheds. We have made separate models for winter, spring, and summer hydrological seasons. Modeling outputs have been compared with stream chemistry databases and hydrobiological indicators.

Figure 2: Map of infiltration coefficients for Dzebra's catchment; darker areas indicate more impermeable surfaces

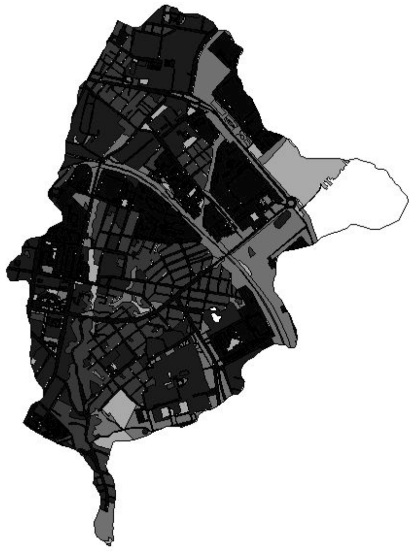
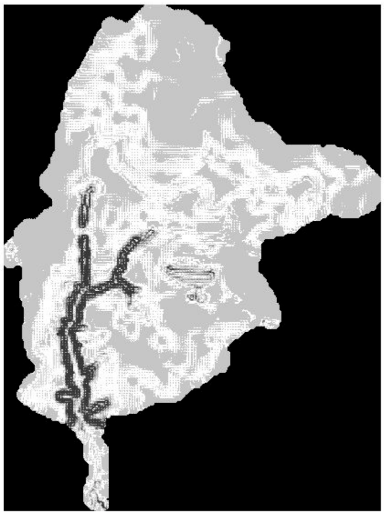
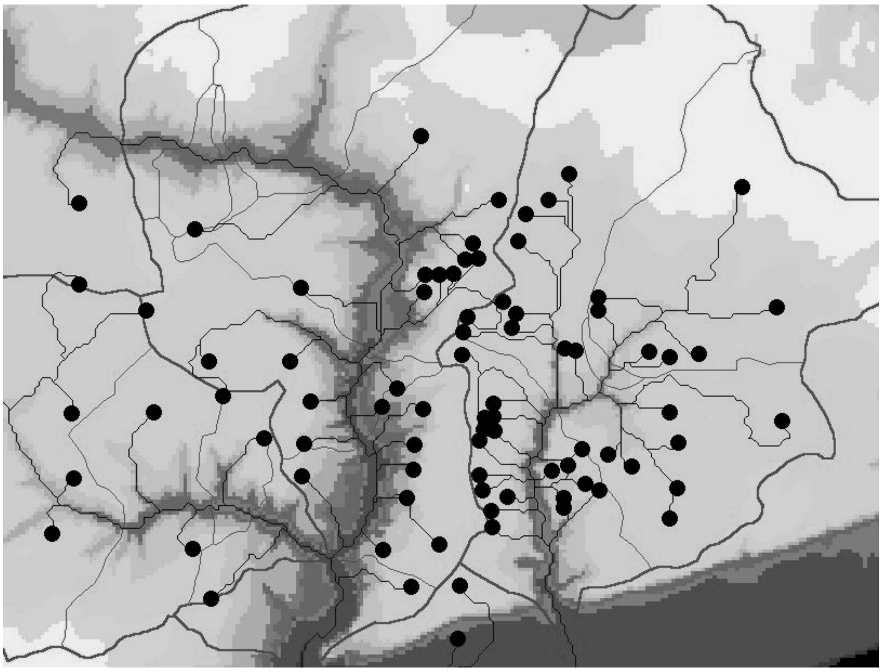


Figure 3: Slopes for Dzebra's catchment; darker areas indicate the steeper slopes



Two kinds of tasks can be solved in the environment of the model created, namely predicting and setting of alternative locations. For instance, we can allocate buffer zones, flow tracks from linear and point contamination sources (figure 4).

Figure 4: Selecting flow tracks from point sources of environmental pollution (marked respectively thin lines and heavy dots) to the targeted transect of channels; done for watersheds of Dubravenka and Dzebra



Conclusions

In this paper, the use GIS for modeling small river watersheds is proposed and illustrated. It clearly shows interesting features for the hydrological modeling.

In the first, it provides a platform where various techniques already used in spatial planning and hydrological modeling can be integrated. In the pilot study, GIS-based allocation procedure and mathematical modeling were combined.

Secondly, it provides for the construction of dynamic models that combine stream ecology indexes and watershed land-use/cover, hydrology and environmental performance.

An important question (not touched in this research) is how social/economic dynamic impacts stream-watershed ecology, and how hydrological section can be integrated into the municipal environmental management system (EMS). However, our study proves that it is reasonable to build municipal EMS upon GIS combined with mathematical models, as we have done with for watersheds.

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