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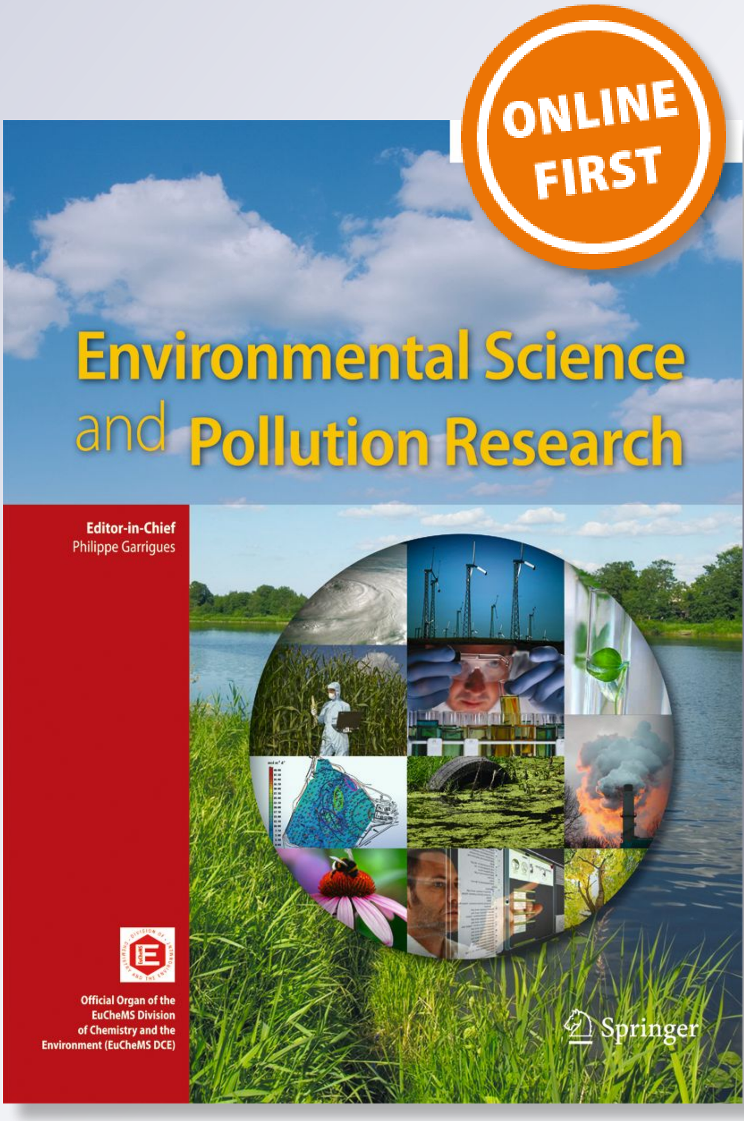

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RESEARCH ARTICLE

Decision support tool for accidental pollution management

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Abstract

Accidental river pollution can cause damage to the environment, put at risk the health of people that use the water for domestic purposes, and, not lastly, compromise dependent economic activities (e.g., agriculture). The reduction of the concentration of pollutant on any river following an accidental pollution can be achieved using dilution, by opening for certain duration the bottom gates of the reservoirs placed on the river's tributaries and releasing a significant volume of clean water in the main river. The hydraulic simulation and the pollutant transport are executed, firstly considering there is no dilution and secondly for the dilution scenario (bottom gates of the reservoirs open). A database was created, containing the results of simulations of pollutant transport for various values of the pollution characteristics in both diluted/undiluted scenarios. The database served for the implementation of a web decision support tool that presents an intuitive and easy to use GUI that allows the user to input details of the accidental pollution. Straightforward actions to be taken are presented to the end-user (e.g., "Open the bottom gates of the reservoir X at time T1 and close it at time T2") and synchronized charts show the effect of the dilution in respect to the concentration of pollutant at certain locations on the river. Using the described approach, a reduction of pollutant concentration in the river with up to 90% can be obtained.

Keywords Water pollution control · Decision support · Hydraulic modeling · Pollutant transport

Introduction

Water release from the reservoirs is intended in principle to increase the discharge in the river during low flow periods in order to provide enough water to water users, including the aquatic ecosystems. The ecological flow should be provided by adapting the monthly operation rules of the reservoirs to release into the river time variant flow water according to the specific needs of the fish community (Suen et al. 2009), or for improvement of the water quality of the river in the dry season of the year when the biochemical oxygen demand BOD(5) is high (Cha et al. 2009).

A reservoir release which increased the downstream discharge from the initial discharge of 30 to 200 m^3/s during 6 h in the Geum River (Korea) derived reservoir operation rules based on water quality changes under different flushing scenarios (Chung and Ko 2008).

Both experimental flushes and numerical simulations of short-term water release were performed in order to investigate the effects downstream the dams (Barillier et al. 1993; Malatre and Gosse 1995; Chung and Ko 2008). The managed release from the upstream reservoirs on Seine and its major tributaries has limited impact on temperature and water quality during summer period, except the events with significant pollution (Malatre and Gosse 1995).

The longitudinal effects of three water release (experimental floods) downstream a large reservoir in the Swiss Alps put into evidence the longitudinal response of river benthos (Jakob et al. 2003). The additional water release from the reservoirs can flush aggregated algal populations downstream and thus reduce the chlorophyll A concentration (Hong et al. 2014). In other cases, higher values of the water flushes from the reservoirs lead to the dilution of the limnoplankton or to the decrease of the cyano bacterial biomass (Grabowska and Mazur-Marzec 2016).

Water release from the reservoirs can also be used to mitigate accidental pollution, which represents an important concern of water quality management. The difficulty of managing

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accidental pollution situations consists in the unpredictable nature of the event as well as in the uncertainties related to the released rate and volume of pollutant. The pollution effects are difficult to counteract because the efforts are extremely expensive and less effective. Depending on the type of pollutants, certain pollutions can be partially controlled, while in the case of others, not much can be done.

Prior to a pollution event occurred in a reservoir, simulation-optimization models can be used to provide a pro-active approach optimum operation strategy to minimize the pollution effects (Saadatpour and Afshar 2013; Amirkani et al. 2016).

Accidental pollution of the rivers can also be produced by road accidents in which trucks transporting dangerous substances are involved or by a collapse of the tailing dams (Klebercz et al. 2012). Usually, the real-time response requires neutralizing agents to react with the pollutant and to mitigate the consequences, by transforming it into a less harmful compound (Cristea 2013).

Another possibility in the case of pollution spills is the pollutant dilution by releasing water from an upstream reservoir (DeSmet 2014). The same approach is used in the present paper for diminishing the concentration of river accidental pollution below a threshold value by releasing additional clean water from the reservoirs placed on the tributaries of the polluted river. The crisis management is based on a decision system, using a pre-compiled scenario database to support the decision-making.

From an IT perspective, promoting a service-oriented architecture (SOA), the SPARROW (Booth et al. 2011) decision platform is used on South Atlantic-Gulf and Tennessee River basins, USA, for assessing regional water quality conditions and management actions. The system gets the user input (model inputs provided as an XML file) and runs a computationally intensive SPARROW model which outputs water quality maps and statistics. The geospatial database is implemented in Oracle spatial DB and the final map is rendered with Oracle's 10G MapViewer.

DSS-WMRJ (Dejian Zhang et al. 2015) is a prototype web-based decision support system for watershed management tested on the Jinjiang basin, China. It is built using the open-source web GIS GeoServer, the SWAT modeling component (Soil and Water Assessment Tool), and Apache Hadoop computational framework to parallelize model simulations. For visualization, FusionCharts library is used.

Designed around the main concepts of Cloud, SOA, and web GIS, the "Cloud Computing Framework for Hydro Information System" (Solomatine et al. 2012) was evaluated on the Zletovica basin, Macedonia. It offers a couple of web services serving various purposes such as geospatial data management (implemented with PostgreSQL and GeoServer), water resource modeling (OpenLayers library, AJAX and PHP), and water resource optimization (OpenLayers, MapInfo).

Mathematical modeling

The general method takes into consideration the following hypothesis: (a) the pollution event will take place on the main river; (b) at least one of the tributaries of the main river has a permanent reservoir (relatively close to the main river) and it has the possibility to deliberately release additional water discharges; and (c) if a tributary has more reservoirs, only the most downstream reservoir is used for dilution.

To apply this method in a real-life situation, a decision support system (DSS) in order to assist the decision-makers operating the reservoirs during the pollution event is needed. The solution provided by the DSS can be (a) computed in real time based on the specific situation and (b) elaborated prior to the event, being only retrieved or approximated based on a database (DB) which contains various scenarios and their solutions.

The first one can be more accurate and more flexible, but the solution should be found in a limited time under the pressure of the event. The second one can approximate quite well the most adequate solution; its appropriateness depends on the variety of scenarios which are contained in the DB. The system can provide the solution faster being based on a DB but requires a lot of previous computations and data storage for building pre-elaborated solutions. The application (of the second type) described in this article uses a DB to provide the solution almost instantly.

A pollution scenario represents a possible event, characterized by the input time and the duration of the pollution event, the concentration of the pollutant, and the volume of the pollutant which reaches the river. The first phase of each scenario consists in extracting the result for a simulation in which no dilution took place. In the following phase, only the reservoir situated on the first tributary downstream the location of the pollution event is active and participates to the dilution. The optimal period for additional water discharge from this reservoir as well as the water quantities to be released is calculated.

Next, the most downstream reservoirs located on the first two tributaries downstream the location of the pollution event are active, and so on, until all the reservoirs release additional water for dilution of the pollutant concentration in the main river. Thus, for each pollution scenario, there are $m + 1$ solutions, where m is the number of reservoirs. The period during which any new reservoir releases additional water is calculated based on the previous scenario, when the reservoirs situated on the upstream tributaries are active. This approach is necessary because increasing the discharges in the upstream stretch of the main river causes a faster transport of the pollutant. From the simulation results, only relevant information representing the best operation solution will be kept.

The hydraulic model based on Saint-Venant partial differential equation system requires a large volume of data consisting in detailed information about riverbed and flood plain geometry including bridges and break lines, as well as roughness coefficients both for the riverbed and for the floodplain.

Based on the river network of the analyzed catchment, sub-basins and inter-basins are defined, which provide their input in the hydraulic model. Using the resulted topological model, the hydraulic simulations using the Mike 11 software by DHI were run.

The upstream boundary conditions of the hydraulic model are represented by the discharge hydrograph of the main river upstream the location of the pollution event as well as by the hydrological input of the tributaries. The downstream boundary condition in the flow model usually is the rating curve. Besides the HD (Hydraulic) and SO (Structural Operation) modules, which were used for the flow modeling (hydrodynamic processes) and reservoir operation, the AD (Advection-Dispersion) module of the Mike 11 software is solving the advection-dispersion differential equation for pollutant transport modeling. The boundary conditions introduced in the AD module are (a) the pollutant discharge as upstream boundary condition and (b) at the most downstream section of the Jijia River, a condition of type "Open, Concentration."

The module used for simulating the processes of advection-dispersion is based on the 1D Eq. (1) of dissolved or suspended mass conservation (DHI-Reference manual 2012):

$$\frac{\partial AC}{\partial t}+\frac{\partial QC}{\partial x}-\frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right)=-AKC+C_2q \tag{1}$$

where C is concentration, D is dispersion coefficient, A is the area of the cross section, K is the linear decay coefficient, C_2 is the concentration of the lateral inflow, q is the lateral flux, x is coordinate, and t is the time.

The dispersion coefficient is described as a function (2) of the mean flow velocity, v:

$$D=av^b, \tag{2}$$

where a is the dispersion factor and b is the dispersion exponent.

The main parameter of the transport module is the longitudinal dispersion, considered as a unique value for the whole stretch of the modeled river (lumped model) or variable for the different sectors of the river (semi-distributed model). These parameters can be obtained based on tracer tests and processing the evolution of the concentration in different sections along the river. In the absence of such measurements, in the present study, the empiric formula (2) for longitudinal dispersion was used, where the value of dispersion factor is set to $a = 15$ and the value for dispersion exponent is $b = 2$ (Popa 1998).

Obviously, this approach raises issues related to the uncertainty of the obtained value for the dispersivity coefficient. The solution in such cases is to establish a domain of values and a statistical distribution for the parameter (for instance beta distribution) and to generate a set of possible values of it. An ensemble of pollution curves will be obtained along the river. However, in the present study, a deterministic approach was adopted, considering a unique value for the longitudinal dispersion. The same approach was used for the hydraulic parameters, due to the fact that the hydraulic model was calibrated and validated based on previous measurements of water levels and discharges along the river.

Although the simulations are run based on 1D modeling, due to the complexity of the specific mathematical model, the duration time for one complete simulation could reach 10–15 min. Hundreds of scenarios of pollution events are investigated and put together in a DB to offer quick solutions to decision-makers via a web platform. The purpose of the simulations is to (a) analyze the pollutant transport in various scenarios of the polluted river, (b) compare the effect of dilution on the pollutant concentration, and, the most important, (c) provide suggestions to decision-makers regarding the operation of the reservoirs.

The pollution scenarios were designed considering the variation of the four variables that are the most important in describing a pollutant event: (1) flow regime in the analyzed period, corresponding to a low flow regime; (2) location of accidental pollution; (3) the volume of pollutant solution that was discharged into the river; and (4) the pollutant concentration of the harming substance present in the discharged solution.

From each simulation, only the relevant information from gauge stations (time series of water discharge and pollutant concentration) and the recommended timestamps of opening and closing the bottom gates for each reservoir is kept.

DSS design and implementation

The decision support application offers two main types of functionalities: setting of the pollution scenario and displaying the simulation results. The first use case is composed of six included sub-use cases, selecting a value for the following parameters: main river and tributary discharge (m^3/s), accident location (km), pollutant volume accidentally released in the river (m^3), pollutant concentration (mg/l), date/time of the accident, and a selected location on the river for which the results are displayed.

The simulation will produce the results for discharge $Q(t)$ and concentration of pollutant $C(t)$ for the selected location both in undiluted and diluted scenarios. The second use case refers to visualization of pollutant propagation simulation and offers the user the possibility to visualize graphics, to print them, to export in a PNG, JPEG, PDF, or SVG format, to zoom in/out, to view details on each point on the graphic, and to obtain the decision recommendation. Another important feature of the tool refers to recommendations regarding the timestamps when the reservoirs should be open/closed. It also displayed the volume of water that is introduced in the river as a result of the reservoir operation. The recommendations have the following format: "Open bottom gates of Reservoir xon dd/mm/year at hh:mm and close them on dd/mm/year at hh:mm (Released y cubic meters of water)."

To calculate the timestamps for opening/closing the reservoirs, two approaches have been tested: a heuristic one and an optimization method. In the first one, it is determined the moment t_1 when the pollutant concentration exceeds a predefined threshold value c^*, respectively, and the moment t_2 when concentration decreases below this threshold. To these timestamps is added an error margin Δt to make sure that the measure is effective. Also, it is necessary to consider the time T needed by the river's flow to travel from the reservoir placed on the tributary to the main river. The assumption was made that the bottom gates of the reservoir can be either entirely opened or completely closed. Thus, the opening/closing times of the reservoir can be expressed as shown below (Fig. 1):

$$t_{open} = t_1 - T - \Delta t \quad (3)$$

$$t_{close} = t_2 - T + \Delta t \quad (4)$$

Considering the fact that the reservoir water has a specific cost per cubic meter, the heuristic approach is not optimal because it can lead to the release of more water than necessary (too high cost). Also, in reality, the bottom gates can be opened partially, having a level of opening that variates from 0% (completely closed) to 100% (entirely opened). In the optimized approach, the main idea is to minimize both the cost of released water used for dilution (C_1) and the economic damages induced by the accidental pollution (C_2). The Nelder-Mead algorithm (Nelder and Mead 1965) is used to solve this multi-objective optimization problem with constraints. Considering m reservoirs, the cost function f depends

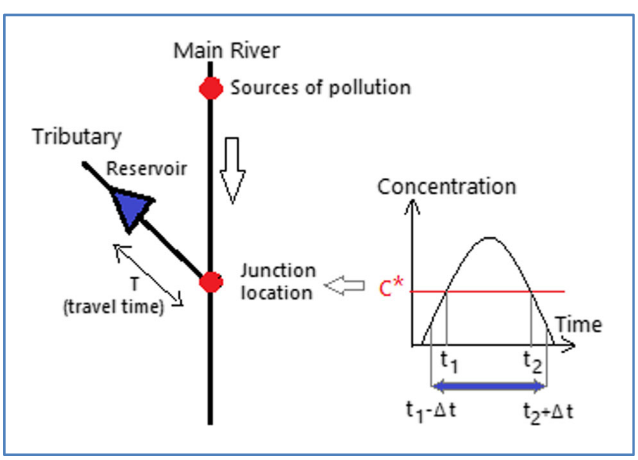

Fig. 1 Timing scheme

on the timestamps for opening/closing the gates and the level of opening, for each of the reservoirs:

$$f\left(t_{open}[1], t_{close}[1], level[1], \ldots, t_{open}[m], t_{close}[m], level[m]\right) = w_1 C_1 + w_2 C_2 \quad (5)$$

The cost C_1 of the released water can be formulated as a sum of the costs of the water volumes released from each reservoir:

$$C_1 = U_p \sum_{i=1}^{m} \left(\int_{t_0}^{t_1} Q_i^{diluted}(t)dt - \int_{t_0}^{t_1} Q_i^{undiluted}(t)dt \right) \quad (6)$$

where U_p represents the cost of 1 m^3 of water. As stated in the literature (XiaoLi Zhang 2015), the economic damages caused by water pollution are modeled using a sigmoid function. To compute the cost C_2, the following function was used:

$$C_2 = \frac{S_{max}}{1 + e^{-\alpha\left(\frac{2c' - c_M}{c_M}\right)}} \quad (7)$$

where S_{max} is the maximum value of the damages that are produced when the pollutant concentration is c_M, α is a tuning parameter that is chosen depending on the desired precision of the calculus, and c' represents the maximum concentration of pollutant in the stretch of the river where dilution takes place. Both approaches were tested on the case study described in section 4 (Jijia River); for the optimized method, a total cost 5.86 times smaller than in the heuristic approach was obtained.

From an implementation perspective, the architectural design of the Java EE web application was realized according to the model-view-controller pattern (MVC), which highly promotes the software design principles of separation of concerns, modularity, and reusability. In our specific implementation, the model is the DB and the controller is a servlet that gets the user input from the GUI and then reads the corresponding data from the model, processes, and sends them to the view (JSP pages) for display. The slider and calendar controls are realized with the JQuery Easy UI. Highcharts, a Javascript-based library, was used to implement the synchronized graphics. The data is sent/received to/from the server asynchronously, this way highly enhancing the user experience. To host the client-server application, Apache Tomcat 8.0 was chosen as a servlet container.

Case study: Jijia River

As an experimental validation of the general method described earlier, the upper Jijia River (a tributary of Prut River, located in NE Romania) was considered. The Jijia River has two main tributaries: Sitna River and Miletin River (Fig. 2). The

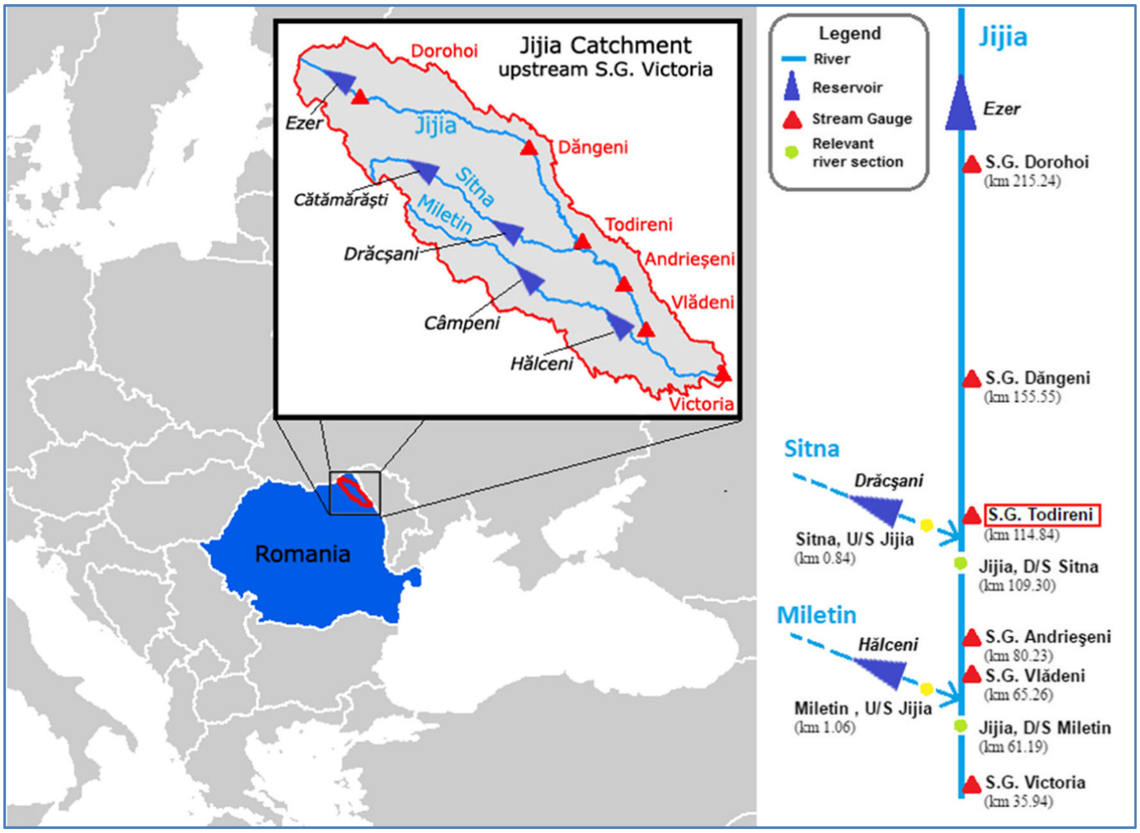

Fig. 2 Hydraulic scheme of the Jijia River

catchment area at Victoria gauge station upstream the confluence with the Bahlui River is 3643 km^2. A number of five reservoirs are located in the basin: Ezer reservoir on the Jijia River, Cătămărăşti and Drăcşani reservoirs on the Sitna River, and Câmpeni and Hălceni reservoirs on the Miletin River.

The main objective of the hydraulic developments on the Jijia River is the water supply and flood management. However, the water stored in the reservoirs can be used for flushing during the accidental spills in order to improve by dilution of the water quality. In the present research, the accidental pollution event was supposed to occur only on the Jijia River in different possible locations. The Ezer reservoir is very upstream on the Jijia River, and except the case when the accidental pollution is in the near proximity, the dilution by water release from this reservoir is not effective due to river length (more than 100 km until the confluence with the Sitna River). Consequently, the water for dilution will be released from the most downstream reservoirs located on Sitna and Miletin rivers: Drăcşani and/or Hălceni water accumulations.

The bottom gates of the two dams have limited discharge capacities (17.4…26.3 m^3/s by Drăcşani bottom gates and 29.7…36.7 m^3/s by Hălceni bottom gates depending on the water level in the reservoir), but which are still sufficient to provide enough volume of water for dilution on the Jijia River.

After analyzing the Jijia catchment and the hydrographic network upstream the confluence with the Bahlui River, a number of 50 sub-basins and inter-basins have been defined.

A number of 600 scenarios were designed considering (1) dozens of combinations of low flow regime on the main river and on 50 tributaries, which were aggregated into a unique value represented by Jijia discharge at the downstream section Vlădeni; the considered values of the discharge at Vlădeni are 5, 15, 25, and 35 [m^3/s]; (2) location of accidental pollution. The chainage of the accident has the following values: 120, 140…200 [km] on the Jijia River, meaning that all accidents occurred upstream the Sitna tributary; (3) the volume of pollutant solution that was discharged into the river. This can be 5, 10…30 [m^3]; and (4) the pollutant concentration which can take one of the following values: 200, 400…1000 [mg/l].

In the case of the Jijia River, there are only two reservoirs that can be used for dilution: Drăcşani on the Sitna River and Hălceni on the Miletin River.

To demonstrate the benefits of the proposed decision support tool based on dilution, a hypothetical scenario in which an accident was produced by a cistern falling down the Jijia River on the 14th of November 2016 at 14:28 was considered. The cistern was transporting 15,000 l of pollutant with a concentration of 400 mg/l. The accident happened between stations Dangeni and Todireni at 140 km. The discharge at the Vlădeni station is 5 m^3/s.

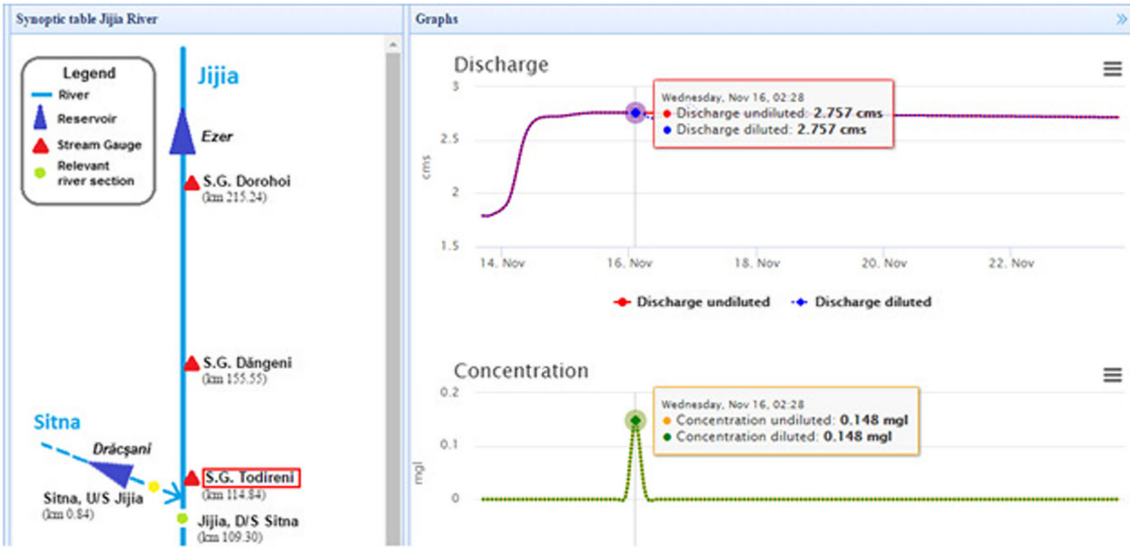

Fig. 3 Discharge and concentration for S.G Todireni

To visualize the effect of pollution on the river, the Todireni station is selected in the application, as depicted in Fig. 3.

Because the Todireni station is upstream the confluence of the main tributaries with the Jijia River, there is no dilution (Fig. 3). The discharge is constant approx. 2.75m^3/s and corresponds to a maximum concentration of 0.148 mg/l.

The decision-maker accesses the web application and sets the pollution parameters. The system provides the following recommendation: to open the Drăcşani reservoir the following day at 21:28 and to close it on the 16th of November at 15:28, releasing 921,840 m^3 of water, and to open the Hălceni reservoir on the 17th of November at 04:28 and close it at 11:28, releasing a volume of 3,463,438 m^3 of water in the river. To put into evidence the effect of opening the Drăcşani reservoir, the user should select the green circle from the topological map corresponding to Jijia, downstream the confluence with Sitna (Fig. 4).

If no action is taken, the maximum concentration of 0.096 mg/l on the Jijia River downstream the confluence with the Sitna River (Fig. 4) is reached on the16th of November at 10:28 (orange continuous line corresponding to a discharge red line of 3.96 mc/s).

Due to the release from the Drăcşani reservoir, the pollution is reduced in this section to 0.013 mg/l (corresponding to an increase of discharge to 15.7 mc/s).

In the absence of release from the Drăcşani reservoir, the situation would be critical at S.G Andrieseni, S.G Vlădeni, and downstream the confluence with the Miletin River, where the maximum pollutant concentration would be about 0.05 mg/l. Due to the release from the Drăcşani Reservoir

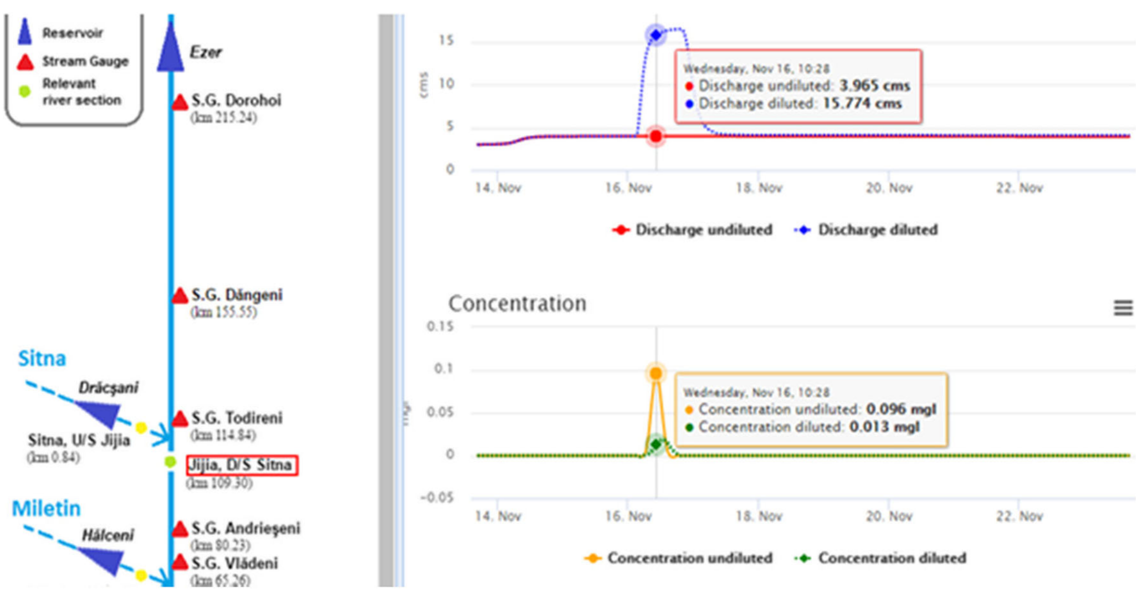

Fig. 4 Discharge and concentration for Jijia D/S Sitna

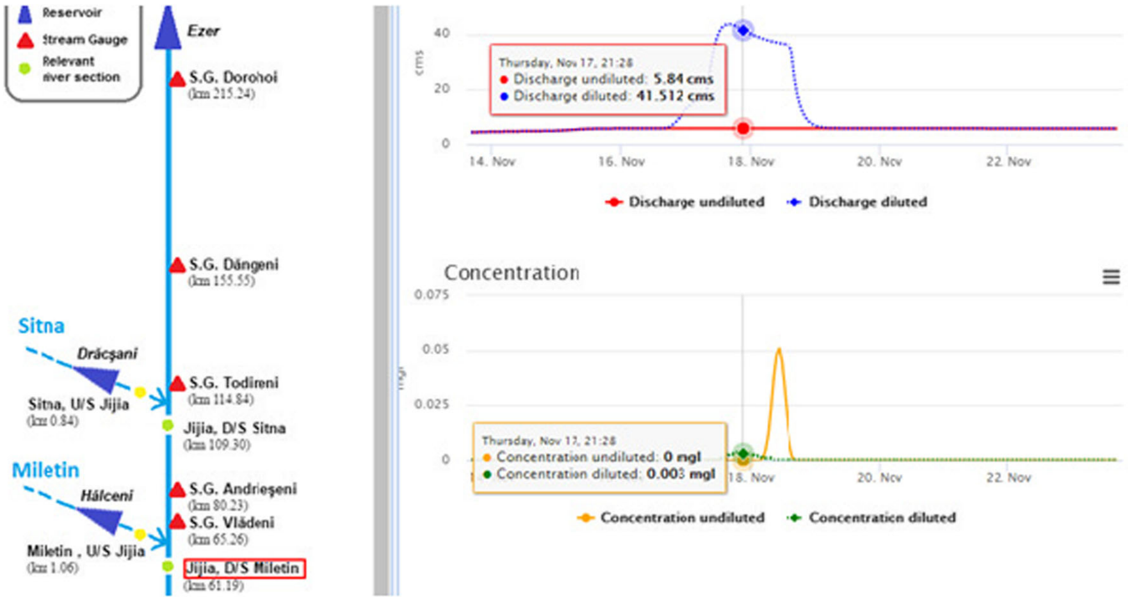

Fig. 5 Discharge and concentration for Jijia D/S Miletin

and an additional volume of water released from the Hălceni Reservoir, the discharge increases to about 40 m^3/s and concentration decreases to 0.003 mg/l (Fig. 5). Thus, opening the reservoirs at the timestamps and for the duration recommended by the system, a reduction to up to 16 times of the pollutant concentration is achieved compared with the situation in which the reservoirs are not operated.

Conclusions

In this paper, a web-based decision support tool for reducing the concentration of pollutant in case of accidental pollution is presented. The central idea is to dilute the polluted water of the river by adding clean water. The general method applicable to any river was tested and validated on the Jijia River (located in the eastern part of Romania), on 180 km stretch. The actions recommended by the system to the decision-makers are to open the bottom gates of the Drăcşani reservoir (located on the downstream reach of the Sitna tributary) as well as to open the bottom gates of the Hălceni reservoir (placed on the downstream reach of the Miletin tributary) for a specified duration and to release a supplementary volume of water into the Jijia River. By performing these actions, the discharge on Jijia River is increased; dilution takes place, thus having an immediate effect on the decrease of pollutant concentration below the critical threshold that would represent a danger for population and environment. The recommended action is immediately presented by the system instead of launching real-time MIKE11 simulations that would take, for the modeled river, at least 10 min each one to complete. The system uses a database of the expected transport of pollutant considering 1200 scenarios (600 for both diluted and undiluted cases). To create the database, the MIKE11 software was previously run, introducing for each scenario discrete values for the four sets of variables of the model: low flow discharges on the main river and tributaries (aggregated as discharge at the Vlădeni hydrologic station), the accident location, pollutant volume that is accidentally released, and pollutant concentration. Also, the user can input the time when the accident happened. The results of the simulations make up the database that provides the required data for the visualization application that was implemented in J2EE. The GUI was realized using the jQuery EasyUI framework, while the Highcharts library provided the support for rendering interactive zoomable synchronized charts. The synchronized charts of discharge and pollutant concentration allow the user to better understand the impact of increasing discharge in relation to the decrease of concentration. The user can compare the level of concentration in the future if the dilution takes place in comparison with the level of concentration if no action is taken.

The recommended actions are presented in an easy to understand format (e.g., "OPEN the bottom gates of Drăcşani Reservoir at 09/28/2016 14:18 AND CLOSE them at 09/29/2016 08:18"), so even people with no background on the hydrodynamic phenomena are able to act in a timely effective manner. By using dilution, the concentration of pollutant was reduced below the threshold value; generally, the concentration is decreased with up to 90%.

For future improvements, the extension of the database by realizing a higher number of simulations in MIKE11 and thus broadening the range of the pollution variables is considered. Another future improvement is related to dealing with uncertainties in the hydrological parameters. Using an ensemble Kalman filter (Zhang and Meng 2017) is possible to alleviate the errors introduced by the uncertainties in mean flow velocity and longitudinal dispersion coefficient.

The contribution presented in this paper is represented by a pre-compiled scenario database to support the decision-making process of reservoir operation during pollution events, in order to reduce the water pollution below the critical threshold, and a decision support tool that significantly improves the user experience by providing to non-expert users, with zero latency, all necessary information required to immediately mitigate the effects of the accidental pollution and avoid severe consequences.

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