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# Remediation of accidental river pollution: strategies based on the use of reservoirs

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**Abstract:** The origins of water pollution are numerous, they cause alterations due to their high load of dissolved substances, micropollutants and toxic substances. Many studies have focused on the implementation of remediation measures for these types of pollution. In this work, the case of rivers subject to accidental pollution and the use of reservoirs for its remediation is studied. Two strategies are implemented: the storage of pollutants in the reservoirs and the dilution of pollutants by injecting in the river clear water from reservoirs. Both methods are applied to a river with one reservoir, and their impacts are studied for different flow levels.

**Keywords:** Water quality management; accidental pollution, remediation, reservoirs.

## 1. INTRODUCTION

Accidental pollution is responsible for some of the pollution of groundwater and surface waters. The most frequent causes of accidental pollution are road transport and industrial activities using chemicals. Accidental pollution of rivers represents a particular challenge to the environment because of the damage it can cause and because of its uncertain nature unlike non-accidental pollution. Remediation methods include: aeration (Pimpunchat et al. (2009), Kahil and Seif (2014)), coagulation-flocculation (Ozkan (2005)) and dilution.

Dilution is the most intuitive way to remediate pollution, (Floehr et al. (2013), Paragahawewa et al. (2015), Whitehead and Lack (1982)). It reduces the concentration of pollutants by adding a quantity of solvent. Dilution occurs naturally in aquatic environments such as rivers and lakes, through the direct supply of rainwater or through the supply of rainwater from their tributaries. Because of its simplicity, dilution is widely used to solve water pollution problems, either in situ (locally) or after pumping.

Herein, because watercourses are usually equipped with multi-purpose reservoirs in which water can be stored, we study how these reservoirs can be used for the remediation of watercourses subject to accidental pollution. We thus consider not only dilution but also storage of polluted water through the use of reservoirs already existing along the watercourse. The impacts of both dilution and storage methods on the pollution reduction are evaluated in order to understand in which cases dilution or storage should be used.

## 2. STATE OF THE ART

Reservoirs have many uses, including flood protection, crop irrigation, drinking or industrial water supply, and power generation. Recently, and with the increase in the number of river pollution incidents due to industrial development and

transport systems, it is being considered to use water reservoirs as a means to address river pollution. Indeed, several scientific research projects have involved the use of reservoirs to rehabilitate rivers that are subject to pollution problems and/or to manage water quality.

Kerachian and Karamouz addressed the question on the optimal management of a river-reservoir system considering the conflict between the different actors (decision-makers, stakeholders). The objectives are the reliability of the water supply to downstream demands, reservoir water storage quantities, and the quality of the withdrawn, the stored and released water (Kerachian and Karamouz (2006), Kerachian and Karamouz (2007)). Nash's negotiation theory was used to model the conflict in issue, considering the expected value of the Nash product as an objective function of a stochastic optimization model based on genetic algorithms. The effectiveness of the model was evaluated using water quantity and quality data from the Ghomrud river-reservoir system in central Iran. The results showed that the model can reduce the salinity of the water intended for the different demands as well as its accumulation in the reservoir. The computational time of the method was reduced by using the Young conflict resolution theory without accuracy loss (Shirangi et al. (2008)).

Dhar and Datta, (2008) developed a simulation-optimization based strategy for the water quality control through operating reservoirs while minimizing deviations from a prescribed storage level. The simulation of the water flow and pollutant transport is done by using the CE-QUAL-W2 model (<https://www.cee.pdx.edu/w2/>) which is linked to an optimization algorithm based on an elitist genetic algorithm. The case of a river with an upstream reservoir and a tributary, through which a pollutant with high nitrate-nitrite concentration reach the river, is studied.

Bogobowicz (1991) formulated the improvement of water quality in a river by using the control theory. The levels of

biochemical oxygen demand, dissolved oxygen, and chloride were adjusted by the flow regulation of reservoirs.

Alvarez-Vázquez et al. (2009) and (2010) addressed the question of the minimum quantities to be released from tanks to bring the concentration of the pollutant below a predefined threshold. The problem was modeled as a hyperbolic optimal control problem with constraints. The partial differential equations were discretized and solved using the Nelder-Mead algorithm. The method was applied on a realistic example consisting in a 2000 m length river with 3 tributaries, 2 wastewater discharges from treatment plants, and a reservoir used as a source of clear water for dilution, showing a remediation of the pollution concentration level.

The above-mentioned works, while addressing the problem of river pollution, only consider rivers or sections of rivers that are subject to permanent pollution. Accidental pollution, on the other hand, has only been mentioned in few works.

Ciolofan et al. (2018a) and (2018b) proposed to reduce the damages caused by an accidental pollution by releasing clear water from the reservoirs of the river tributaries. Each pollution event is characterized by the time when the event occurred, its duration, its concentration and volume. For each reservoir, the optimal values for the opening date, the closing date and the volume released are computed based on a heuristic approach and on the Nelder-Mead algorithm. The multi objective optimization problem with constraints consists in minimizing both the cost of released water and economic damages. The evolution of the river flow and of its pollutant concentration, at different locations, are simulated by the numerical modeling and simulation tool MIKE11. The application of the method on the Jijia River located in Romania illustrated that the dilution produced by the water released from two reservoirs can significantly reduce the effects of the accidental pollution event.

In Farhadian et al. (2014) and Hashemi Monfared et al. (2017) the damages induced by the pollution are evaluated considering both the concentration of the pollutant and the time during which the pollution is in contact with the environment. On the basis of these criteria, the assimilation capacity of the river is defined. It can be increased by modifying the flow of the river thanks to the release of clear water from the reservoir. The optimal value of the flow required to dilute the pollution is determined using the multi objective algorithm NSGA-II (non-dominated sorting genetic algorithm). The method was applied to a hypothetical river and led to the conclusion that a too large increase in the river flow can reduce the river assimilation capacity, hence finding an optimal flow release is important.

In order to consider not only the dilution but also the storage capacities of the reservoirs, and to implement solutions suited to different cases of accidental pollution, as well as to different types of configurations, the case of a river with one reservoir is studied in the following paragraphs.

### 3. METHODOLOGY

#### 3.1 Context

We consider a river instrumented by a set of sensors distributed along its length  $X$ , providing information on flow rates  $Q(t)$  and pollution level  $C(t)$  over time. The considered river is equipped with a reservoir located nearby, and connected to it via entrance and exit gates that can be opened gradually. The reservoir, characterized by a maximum capacity  $R_{max}$ , and an initial filling  $R_{initial}$ , can be used for storage or release.

We simulate a case of an accidental pollution event occurring upstream from the river by injecting a pollutant  $P$  during the time interval  $[T_{begin}, T_{end}]$  with a constant concentration  $C_p$  and a constant flow  $Q_p$ . As soon as a pollution event is detected, managers must use the available tools to limit or even cancel the effects that may result. Depending on the filling level of the reservoir, two strategies are possible: dilution or storage. Dilution consists in injecting water from the reservoir in the river, if the quality of the water present allows it. Storage consists in storing polluted water from the river in the reservoir. In both cases, it is necessary that the river flow remains above the low water flow,  $Q_d$ , and below the overflow rate,  $Q_m$ .

The purpose of this study is to examine the contributions and limitations of each of these strategies. The strategies are implemented by operating on the entrance and exit gates of the reservoir during the time interval when the pollutant is present in front of the reservoir (referred as the exposure window); they are described in the following sections.

#### 3.2 Storage-based strategy.

Once the pollutant has been detected at the reservoir entrance, in order to store some of the pollutant, the entrance gate is opened during the time interval corresponding to the exposure window. The height setpoint is computed such that the river flow remains above  $Q_d$ , according to the algorithm 1.

If the incoming concentration,  $C_e$ , is upper than the acceptable concentration threshold,  $C_l$ , and if the reservoir is able to receive the volume of polluted water while the river flow remains above  $Q_d$ , the gate is opened. The entrance gate opening height,  $h_e$ , is computed such that the flow going out the reservoir is equal to the difference between the flow measured in the river at the reservoir inlet (i.e. the incoming flow),  $Q_e$ , and  $Q_d$ , thanks to the function  $f$ .  $f$  is a function which, depending on the type of gate (gravitational for example), determines the height of the gate according to the flow rate value.

If the reservoir is full before the end of the pollution event, the entrance gate is closed.

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**Algorithm 1:** Storage

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**Data:**

$C_e(t)$ : incoming concentration  
 $C_l$ : acceptable concentration threshold  
 $Q_e(t)$ : the flow measured in the river at the reservoir inlet  
 $Q_d(t)$ : low water flow  
 $R_{max}$ : reservoir storage capacity  
 $V_S$ : volume of reservoir stored water  
 $T_{begin}$ : begin of the pollution event  
 $T_{end}$ : end of the pollution event  
 $\Delta t$ : time step

**Output:**

$h_e$ : entrance gate opening height

**Variables:**

$V_{dis}$ : available reservoir volume

**for**  $t$  **in**  $[T_{begin}, T_{end}]$  **do**

$V_{dis} \leftarrow R_{max} - V_S$

**if**  $C_e(t) \geq C_l$  **then**

**if**  $V_{dis} \geq (Q_e(t) - Q_d(t)) * \Delta t$  **then**

$V_S \leftarrow V_S + (Q_e(t) - Q_d(t)) * \Delta t$

$h_e \leftarrow f(Q_e(t) - Q_d(t))$

**else**

$V_S \leftarrow R_{max}$

$h_e \leftarrow 0$

**end if**

**end if**

**end for**

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---

**Algorithm 2:** Dilution

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**Data:**

$C_e(t)$ : incoming concentration  
 $C_l$ : acceptable concentration threshold  
 $C_r(t)$ : reservoir concentration level  
 $Q_e(t)$ : the flow measured in the river at the reservoir inlet  
 $Q_m(t)$ : overflow rate  
 $V_S$ : volume of reservoir stored water  
 $T_{begin}$ : begin of the pollution event  
 $T_{end}$ : end of the pollution event  
 $\Delta t$ : time step

**Output:**

$h_x$ : exit gate opening height

**Variables:**

$Q_l$ : flow to release

**for**  $t$  **in**  $[T_{begin}, T_{end}]$  **do**

**if**  $C_e(t) \geq C_l$  **then**

$Q_l \leftarrow \min\left\{\frac{V_S}{\Delta t}, \frac{C_e(t) - C_l}{C_l - C_r(t)} Q_e(t) \Delta t, Q_m(t) - Q_e(t)\right\}$

$V_S \leftarrow V_S - \frac{Q_l}{\Delta t}$

$h_x \leftarrow f(Q_l)$

**end if**

**end for**

---

### 3.3 Dilution-based strategy.

Once the pollutant has been detected at the reservoir entrance, in order to release clear water from the reservoir, the exit gate is opened during the time interval corresponding to the exposure window. The height setpoint is computed such that the river flow remains under  $Q_m$ , according to the algorithm 2.

The flow to release,  $Q_l$ , is computed according to the value of the acceptable concentration level and to the value of the concentration levels of pollutant in the reservoir and in the river. If the incoming concentration,  $C_e$ , is upper than the acceptable concentration threshold,  $C_l$ ,  $Q_l$  is set to the minimum value between the flow emptying the reservoir:  $V_S/\Delta t$ , the flow corresponding to the maximum concentration level:  $Q_e \Delta t (C_e - C_l)/(C_l - C_r)$ , and the flow avoiding the river to overflow:  $Q_m - Q_e$ . Then, from the  $Q_l$  value, the exit gate opening height,  $h_x$ , is computed thanks to the function  $f$ .

If the reservoir is empty before the end of the pollution event, the exit gate is closed.

## 4. CASE STUDY

### 4.1 Description

The storage and dilution strategies were applied on a test case based on the real case of the Ebro river situated in Spain near the city of Saragossa. The river is equipped with a reservoir and sensors indicating the flow and pollutant concentration in the river. The reservoir is provided with sensors indicating its water level and pollutant concentration. A scheme representing the river system is illustrated in Fig. 1.

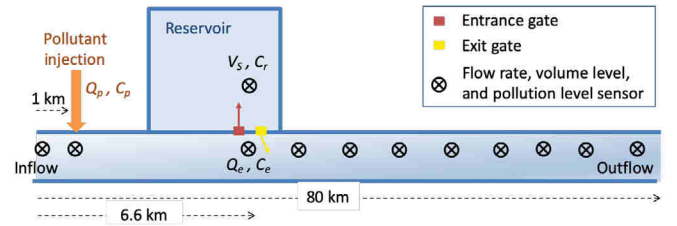


Fig. 1. Studied river with one reservoir.

In order to simulate the river and reservoirs behaviors i.e. the flow and concentration evolution, the algorithms are linked to a hydraulic simulator developed in a previous French-Spanish project entitled GECOZI, based on the coupling of 1D and 2D flow models (Morales-Hernández et al., 2013). The GECOZI project objectives were the management and control of floodplains and the developed methods were applied on the Ebro basin. This simulator was used to address the flood management problem (Romera et al., (2013), Nouasse et al. (2012), Nouasse et al. (2013)) and to control pollutants (Puig et al., 2014).

### 4.2 Results

For the experiment, see Fig. 1, the river was 80 km length with a reservoir situated 6.6 km from the upstream. The pollution

source was introduced 1 km from the upstream, with an inflow of 10 m<sup>3</sup>/s, during 5 hours (18,000 s), with  $T_{begin} = 40,000$  s. The concentration limit (acceptable concentration threshold) was  $C_l = 10$  g/m<sup>3</sup>, the base concentration in the river was 3 g/m<sup>3</sup>. The overflow rate was  $Q_m(t) = 900$  m<sup>3</sup>/s, and the low water flow was  $Q_d(t) = 300$  m<sup>3</sup>/s. The time step was  $\Delta t = 1,000$  s. Two different scenarios were done, the first one with a constant inflow in the river equals to 400 m<sup>3</sup>/s, the second one with a constant inflow in the river equals to 800 m<sup>3</sup>/s. For the first scenario, the concentration of the pollutant source was 495 g/m<sup>3</sup> and 975 g/m<sup>3</sup> for the second, such that the concentration in the river was 15 g/m<sup>3</sup> in both cases.

Three strategies were implemented: gates closed (no action) in yellow, storage in blue and dilution in green. The results are given in Fig. 2 and Fig. 4 for the first scenario and in Fig. 3 and Fig. 5 for the second scenario. The concentration at the outlet of the river is given in Fig. 2 and Fig. 3; the flow rate at the outlet of the river is given in Fig. 4 and Fig. 5.

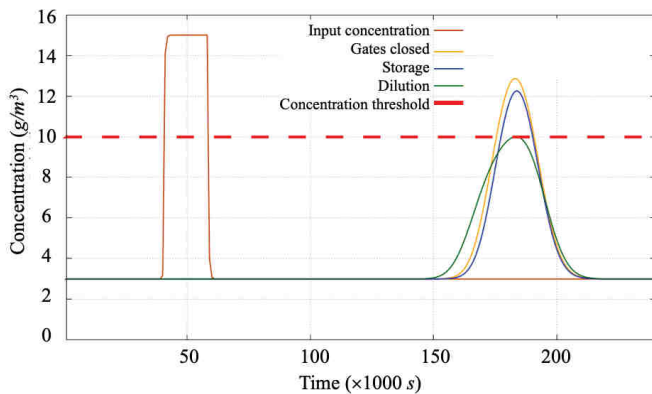


Fig. 2. Outlet concentration using the storage, the dilution and the gates closed strategies, for river inflow 400 m<sup>3</sup>/s.

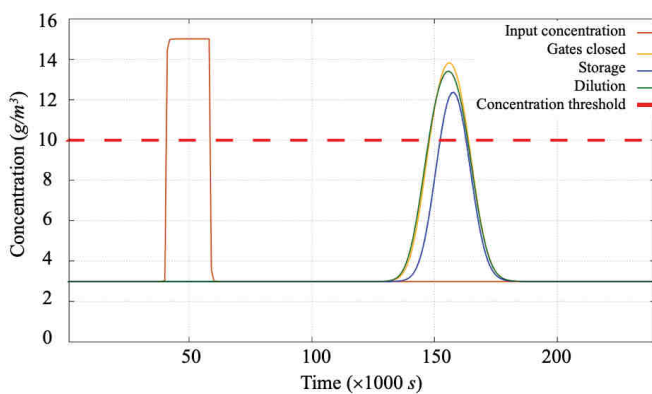


Fig. 3. Outlet concentration using the storage, the dilution and the gates closed strategies, for river inflow 800 m<sup>3</sup>/s.

The difference between the maximal concentration and the concentration threshold,  $C_l = 10$  g/m<sup>3</sup>, was computed as well as the difference between the maximum mass and the mass threshold, 4,000 g/s for the first scenario (400 m<sup>3</sup>/s) and 8,000 g/s for the second scenario (800 m<sup>3</sup>/s). In order to characterize the impacts of the three strategies, the evolution of these differences, depending on the distance from the

upstream, is given in Fig. 6 for the concentration and in Fig. 7 for the mass. The duration during which the concentration exceeded the concentration threshold, as well as the value of the corresponding area, were calculated and reported in Table 1 for the first scenario (400 m<sup>3</sup>/s) and in Table 2 for the second scenario (800 m<sup>3</sup>/s).

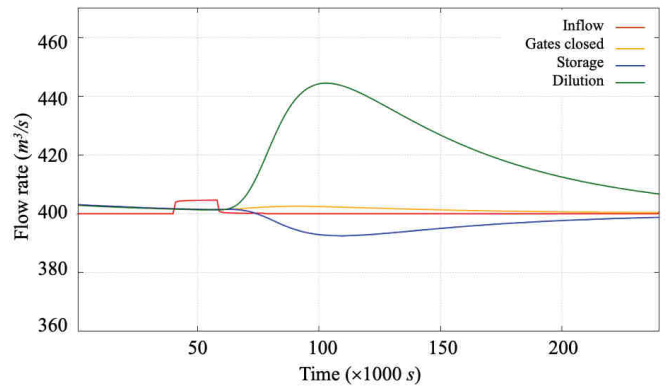


Fig. 4. Outlet flow rate using the storage, the dilution and the gates closed strategies, for river inflow 400 m<sup>3</sup>/s.

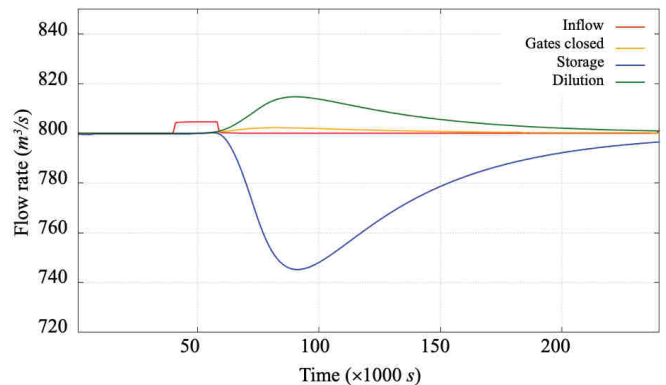


Fig. 5. Outlet flow rate using the storage, the dilution and the gates closed strategies, for river inflow 800 m<sup>3</sup>/s.

In all cases, the outlet flow rate remained under the overflow rate,  $Q_m(t) = 900$  m<sup>3</sup>/s, and over the low water flow,  $Q_d(t) = 300$  m<sup>3</sup>/s, see Fig. 4 and Fig. 5.

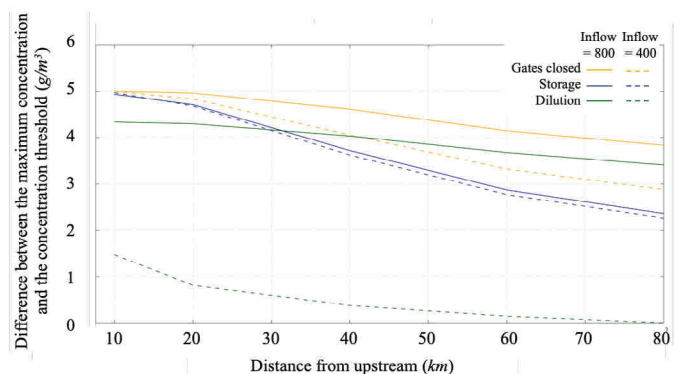


Fig. 6. Difference between the maximum concentration and the concentration threshold using the storage, the dilution and the gates closed strategies.

In the low flow scenario (400 m<sup>3</sup>/s), the maximum concentration is minimum in the case of the dilution strategy (green), and is under the limit (see Fig. 2 and Fig. 6). At the distance of 40 km from the upstream the exceeding concentration duration time is 8,000 s and 1,000 s at the river end which, compared to the gates closed case, corresponds to a reduction from 50% to 93% respectively; the area of the exceeding curve is 7,118.59 s.g/m<sup>3</sup> at the distance of 10 km from the upstream and 0.24 s.g/m<sup>3</sup> at the river end which, compared to the gates closed case, also corresponds to a reduction from 89% to 100% (see Table 1).

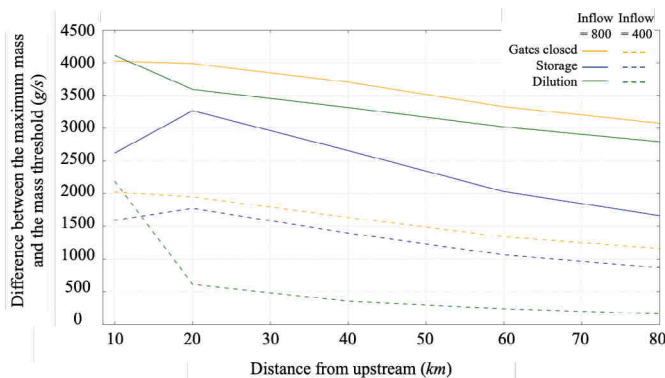


Fig. 7. Difference between the maximum mass and the mass threshold using the storage, the dilution and the gates closed strategies.

**Table 1. Area curve value and duration of the exceeding concentration with flow rate 400 m<sup>3</sup>/s.**

| Distance from upstream (m) | Exceeding concentration area (s.g/m <sup>3</sup> ) |           |          | Duration of exceeding concentration (x 1,000s) |         |          |
|----------------------------|--|-----------|----------|--|---------|----------|
|                            | Gates closed                                       | Storage   | Dilution | Gates closed                                   | Storage | Dilution |
| 10000                      | 67,208.38  | 62,693.59 | 7,118.59 | 17   | 16      | 11       |
| 20000                      | 56,745.97  | 47,725.43 | 5,003.79 | 17   | 15      | 11       |
| 40000                      | 42,927.91  | 33,279.98 | 2,091.50 | 16   | 14      | 8        |
| 60000                      | 33,932.64  | 24,119.54 | 537.88   | 16   | 13      | 6        |
| 80000                      | 28,618.51  | 18,998.59 | 0.24     | 15   | 13      | 1        |

**Table 2. Surface curve value and duration of the exceeding concentration with flow rate 800 m<sup>3</sup>/s.**

| Distance from upstream (m) | Exceeding concentration surface (s.g/m <sup>3</sup> ) |           |           | Duration of exceeding concentration (x 1,000s) |         |          |
|----------------------------|---|-----------|-----------|--|---------|----------|
|                            | Gates closed  | Storage   | Dilution  | Gates closed                                   | Storage | Dilution |
| 10000                      | 70,542.93   | 59,809.10 | 60,846.28 | 18   | 15      | 18       |
| 20000                      | 62,171.07   | 39,952.22 | 55,520.35 | 17   | 13      | 17       |
| 40000                      | 51,188.22   | 27,895.61 | 45,908.58 | 16   | 11      | 16       |
| 60000                      | 43,940.01   | 20,523.91 | 39,336.85 | 16   | 11      | 16       |
| 80000                      | 39,561.08   | 16,303.65 | 35,682.56 | 15   | 10      | 15       |

The effects of the dilution strategy (green) are less significant in the second scenario (800 m<sup>3</sup>/s) because the overflow rate limit does not allow to release enough clear water (see Fig. 6).

At the river end, the exceeding concentration duration time is 1500 s and thus is not reduced compared to the gates closed case; however, the area of the exceeding curve is 35,682.56 s.g/m<sup>3</sup> and corresponds to a reduction of 10% compared to the gates closed case (see Table 2).

Even if, in the storage strategy (blue), the concentration does not reduce significantly and is of same order for both scenarios, it is less than when the gates are closed (yellow), see Fig. 6. At the river end, the exceeding duration time is 1,3000 s for the 400 m<sup>3</sup>/s scenario and 1,000 s for the 800 m<sup>3</sup>/s scenario, thus, compared to the gates closed case, the duration time is 13% reduced and 33% respectively the area of the exceeding curve is 18,998.59 s.g/m<sup>3</sup> for the 400 m<sup>3</sup>/s scenario and 16,303.65 s.g/m<sup>3</sup> for the 800 m<sup>3</sup>/s scenario, which, compared to the gates closed case, corresponds to a reduction from 34% and 59% respectively (see Table 1 and Table 2).

In fact, when the storage strategy (blue) is used, the flow in the river is reduced, however the water concentration is not modified even if, due to the flow movements a weak dilution operates; only the volume of pollutant is modified thus the mass decreases (see Fig. 7) and the concentration is almost the same (see Fig. 6).

Depending on the filling level of the reservoirs, it is possible that the duration of storage (storage strategy – blue) or release (dilution strategy – green) may be shorter than the duration of the pollution event, a strategy consisting in choosing to reduce the height of the gates opening in order to distribute the storage or dilution over the entire interval can be implemented. Moreover, reservoirs can be prepared to be released, respectively filled, so that the storage, respectively the dilution, strategy can be more efficient.

The storage strategy, although it does not allow the direct reduction of the pollutant concentration, makes it possible to provide a solution to pollution during high flows. In addition, if there are downstream reservoirs, it becomes therefore possible to use them for dilution because the flow will have been reduced. The dilution strategy is well adapted and efficient in the case of low flows in the river.

## 5. CONCLUSION

Two strategies for the remediation of an accidental pollution event occurrence in a river using reservoirs were proposed: storage and dilution. The effects of the strategies on a river equipped with one reservoir were given. Dilution allows to reduce the pollutant concentration in the case of low flows. Storage strategy allows to reduce the mass of pollutant and the river flow. Based on these results, it is possible to implement strategies adapted to different cases of accidental pollution, as well as to different types of configurations. The flow level in the river, the concentration of pollutant and its mass must be included in a criterion allowing to decide which strategy or combination of strategy should be used. Future works will focus on the implementation of such an approach in a graph-based optimization framework.

## ACKNOWLEDGEMENTS

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