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Multi Objective Simulation-Optimization Approach in Pollution Spill Response Management Model in Reservoirs

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Abstract In this study, a Pollution Spill Response Management Model (PSRMM) is developed to provide an emergency response on reservoir operation during accidental injection of hazardous material to reservoirs. PSRMM consist of spatial system analyzing (SSA) model, 2D hydrodynamic and water quality simulation model (CE-QUAL-W2), and multi-objective particle swarm optimization (MOPSO) algorithm. CE-QUAL-W2 model is applied for spatial and temporal analysis of water body in simulation routine of PSRMM. Also, in an advanced modeling framework, CE-QUAL-W2 is coupled with MOPSO algorithm to obtain desirable near optimal reservoir operation strategy and/or emergency planning in selective withdrawal framework. The simulation-optimization (SO) routine of PSRMM provides pareto optimum reservoir operation strategy in selective scheme to minimize reservoir cleanup time and to reduce the magnitude and frequency of water quality standard violations. The proposed tool is applied in Ilam reservoir in Iran, as a multipurpose hydraulic project providing water for drinking, irrigation, and flood control during an accident spill of conservative hazardous material. Different scenarios are defined and tested employing the proposed PSRMM for managing accidental spill of conservative pollutant into the reservoir.

Keywords Accident pollution spill · CE-QUAL-W2 · Multi objective particle swarm optimization · Simulation-optimization

1 Introduction

Nowadays the safety and normal functionality of aquatic ecosystems and human heath are threatened by chemical pollution spill events occurring in water bodies. Pesticides,

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fertilizers, municipal wastes, sewage, and mining are common source of accident pollutions. Contamination of river, estuary, lakes, artificial water bodies, or any water borne systems as a significant political, economical, and ecological natural source of any government poses major environmental risk. The most common types of pollution accident spills are collisions, technical failures, and fires/explosions (Rogowska and Namieśnik 2010). Some examples of accident spill of pollution could be found in several places around the world.

On 1991, an accident spill of aqueous solution of the soil fumigant metam-sodium due to a car train derailed on the Cantara Curve near Mount Shasta, California led to the most ecologically damaging chemical spills in Sacramento River basin (Wang et al. 1997). An accident diesel fuel spill into a first order reach of the Cayuga Inlet, a tributary of Cayuga Lake near New York, USA had occurred in 1997. The accident spill caused the chemical containment booms, slicks of the diesel fuel were floating on the surface of Cayuga Lake 16 Km downstream within 24 h (Lytle and Peckarsky 2001). On April 25, 1998, a spill from a pyrite mine at the Los Frailes mine in southern Spain resulted in heavy metal-enriched tailings sludge and acidic mine water contaminated some 40 Km^2 of the Agrio and Guadiamar river valley (Achterberg et al. 1999; Kraus and Wiegand 2006).

Essential and important political, economic, and ecological significance of water bodies such as rivers, lakes, the artificial water constructions (reservoirs), and different water resources systems highlights the emergency planning requirements to manage intentional and accidental pollution impacts. During last decades, water infrastructures in Iran such as Gheshlagh reservoir, Amirkabir reservoir, and Zayandeh Roud reservoir experienced hazardous material spills. The accidental hazardous material spill in these reservoirs restricted their availabilities and discombobulated supplying a safe and reliable drinking water. Ever increasing events in national and international scales call for higher concern on vulnerability of water infrastructures to accident pollution spills. Therefore developing a Pollution Spill Response Management Model (PSRMM) may help in managing more efficiently the threats associated with accidental or intentional chemical releases into rivers and/or reservoirs. The PSRMM should have the ability to identify, respond, and mitigate the effects of pollution release incidents.

Modeling systems such as RiverSpill and ICWater (Samuels and Bahadur 2006), GNOME (Beegle-Krause 2001), SMIS 1.0 (Martin et al. 2004), and SMIS 2.0 (Camp et al. 2010) are among the currently available pollution spill response models. Providing enhanced modeling tools to assist decision making process requires spill responses management systems. An Incident Command Tool for Drinking Water Protection (ICWater) has been developed by implementing a set of waterborne transport tools consist of RiverSpill and PipelineNet (Samuels and Bahadur 2006). Concise summaries of current conditions and forecasts of future consequences of terrorist acts on public water supply safety have been provided by the integrated system of ICWater. GIS and simulation models are the main components of systems describe the fate and transport of pollutions in rivers and/or water distribution network system. An advanced modeling technology within a visual framework was developed by Camp et al. 2010 to improve decision-support process. The Spill Management Information System (SMIS 2.0) consisted of 3D hydrodynamic and chemical spill modeling system tool and geographic information systems (GIS) spatial environment. The predicted spill fate and transport as model responses was presented by GIS spatial environment.

Although few research articles have been published which tackle spill response management on water bodies (Samuels and Bahadur 2006; Beegle-Krause 2001; Martin et al. 2004; Camp et al. 2010), almost no structured research on scenario analysis and mitigation management on accidental or intentional reservoir contamination is available. Ever increasing probability of accidental and/or intentional reservoir contamination encouraged the authors to develop an enhanced PSRMM using an efficient simulation-optimization (SO) approach. The simulation model addresses the fate and transport of pollutions in responses to various boundary conditions. The optimization model develops the most desirable operating strategy to maintain the best water quality management scheme. The SO routine of PSRMM derives the mitigation management strategy to decrease the pollution damages and/or increase the pollutant degradation in the reservoir in pollution spill events.

This research focuses on the controlling of reservoir releases that influence the fate and transport process of conservative pollution. The reservoir operation strategy determines the release from the reservoir in a given management period. The applied simulation model, CE-QUAL-W2 (Cole and Wells 2008) is capable to incorporate various physicochemical processes. A Multi Objective Particle Swarm Optimization (MOPSO) technique is applied to generate Pareto optimal solutions to derive optimum operational strategy in selective scheme in Ilam reservoir as a drinking source of Ilam city. The SO routine of PSRMM considers the advantage of the close relationships existing between quality and quantity variables with regard to effectively maximize the benefits for water utilization while simultaneously enhancing its quality (Loftis et al. 1985; Hayes et al. 1998; Chaves et al. 2003; Chaves and Kojiri 2007; Kerachian and Karamouz 2007; Shirangi et al. 2008). In fact, the jointly water quality and quantity issues is implemented in PSRMM for integrated water resources management.

2 Pollution Spill Response Management Model (PSRMM)

The developed Pollution Spill Response Management Model (PSRMM) in this research combines Spatial Systems Analyzing (SSA) model with two-dimensional (2-D) surface water quality and hydrodynamic model, CE-QUAL-W2 Version 3.5, for surface water quality modeling and Multi Objective Particle Swarm Optimization (MOPSO) model for enhanced spill response support. The model input data, executions, and results representation have been implemented through programming in Intel Visual Fortran and Matlab environment. The Spatial Systems Analyzing (SSA) model is programmed in Intel Visual Fortran and Matlab environment to map the pollution spill location in spatial segmentation of hydrodynamic and water quality model. Developed programming scheme enables the users to input and view the fate and transport of pollution spill, temporally and spatially. In this research, SSA model provides an interface between the PSRMM and its users, linking inputs, outputs, and managing the temporal and spatial databases.

In simulation routine of PSRMM, the numerical simulation model (CE-QUAL-W2) is implemented into scenario analyzing, evaluation various scenarios, estimating the fate and transport of pollution in reservoir, track the pollution plume, and identifying the threat zones. This water quality model is linked to the MOPSO in SO routine of PSRMM to obtaining the optimal reservoir operation in selective withdraw framework to achieve the defined goals by decision makers and/or incident commanders. The various boundary conditions defined by MOPSO algorithm affect the transport process of pollution in stratified reservoir. The natural process of thermal and vertical variation of pollution in the reservoir is modeled by CE-QUAL-W2 model. The coupled simulation-optimization model provides the optimum pareto reservoir operational strategies in selective withdraw scheme. This integrated tool provides the decision makers and reservoir operators with a wide range of potentially useful information including incident information and diagrams, contaminant transport model outputs, chemical response data, and emergency mitigation strategy in various hydrological scenarios.

The time series hydrological, metrological and quality information are provided by the stream and metrological gauging program of Iran Water Resources Management Company (IWRMC) and Iran Metrological Organization (IMO). Low, average, and high flow conditions in each day are considered as the defined hydrological scenarios to assess the water body responses in accident pollution spill events. The component of the proposed PSRMM is illustrated in Fig. 1.

If the concentration of the pollutant at Ilam reservoir inflow gauging stations is above a specified level of concern, then the associated table of gauge record is colored red to indicate a warning.

In this case, the various statistical (low, average, and high) hydrological and metrological conditions according to the specified days of year, the pollutant information, and the origin of the spill events are defined as the input data for PSRMM. The components of PSRMM are described in the below sections.

2.1 Simulation Model

CE-QUAL-W2 model as a two dimensional laterally averaged hydrodynamic and water quality model supported by the U. S. Army Engineering Waterways Experiment Station. The temporal and spatial variation of water movement, temperature, and constituents are predicted by CE-QUAL-W2 model. Application this model is based on minor lateral variation assumption. The model is applicable to lakes, rivers, and estuaries that do not exhibit significant lateral variability in water quality conditions. It allows application to multiple branches for geometrically complex waterbodies with variable grid spacing, time variable boundary conditions, and multiple inflows and outflows from point/nonpoint sources and

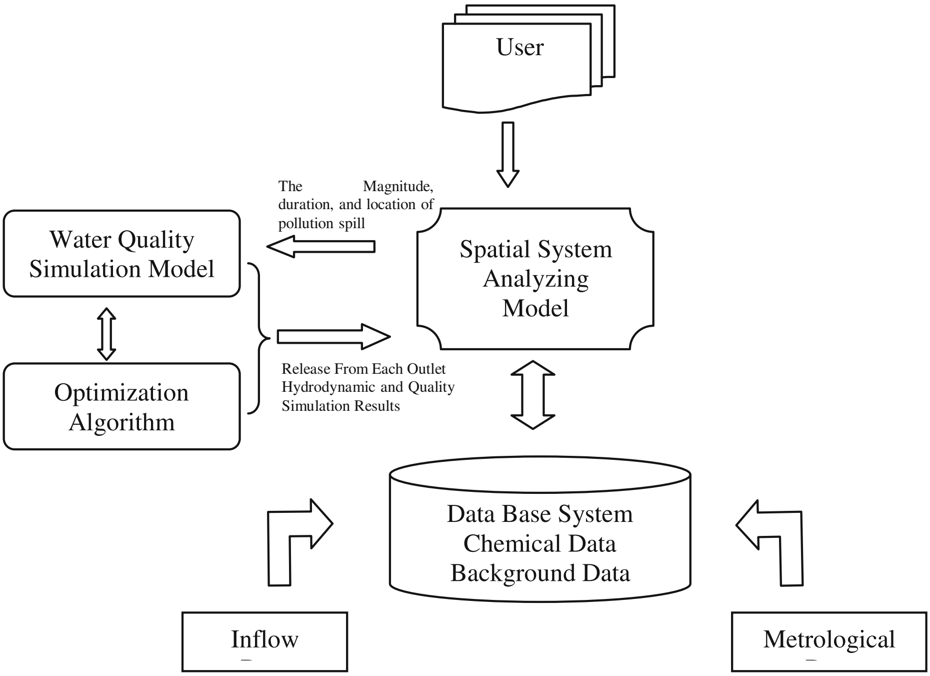

Fig. 1 System flowchart

precipitation (Steg 2007; Cole and Wells 2008). Advantages to choosing CE-QUAL-W2 model as simulation section of PSRMM includes addressing the concern contaminations, providing the output from upstream to downstream in the reservoir and at depth, providing adequate detail of analysis, and opportunity for advanced researchers to modify the code according the desired requests.

The water quality module of CE-QAL-W2 simulates 21 constituent. User would be able to select a subset of interrelated constituents in the simulation. The reservoir bathymetry data, meteorological data, initial conditions, inflow quantity and quality, outflow quantity, and outlet description are the required input to model description. The time series of inflow rates and water quality, meteorological data, outflow rate, and appropriate kinetic rate coefficients are required for executable model during simulation periods. In this research, conservative tracer is considered as a state variable of pollution spill response management model.

2.2 Optimization Model

A multi objective optimization problem has a number of objective functions which are to be minimized and/or maximized. The multi objective problem is defined as Eq. (1) (Deb 2001):

$$\begin{array}{lll} Maximize/Minimize & f_m(x) & m = 1,2,\ldots,M \\ Subject\ to: & & \\ g_j(x) \geq 0 & j = 1,2,\ldots,j & \\ h_k = 0 & k = 1,2,\ldots,K & \\ x_i^L \leq x_i \leq x_i^M & i = 1,2,\ldots,n & \end{array} \tag{1}$$

The optimization problem is to find the vector $x^* = \left(x_1^*, x_2^*, \ldots, x_n^*\right)$ which solves the above equations.

Non-dominated Solutions: Among a set of solutions P, the non dominated set of solution P' are those that are not dominated by any member of the set P (Deb 2001).

Global Pareto-optimal Set: The non-dominated set of the entire feasible search space is the Global Pareto- optimal set (Deb 2001).

2.3 Single Objective PSO

Particle swarm optimization (PSO) is a decade old concept in global optimization domain. Since PSO is based on population, it shares many similarities with evolutionary algorithm for solving real-world optimization problems. In PSO, the particle flies randomly in D dimension search space, the position and velocity of i th particle is represented as $Xi = (x_{i,1}, x_{i,2}, x_{i,3}, \cdots, x_{i,D})$ and $V_i = (v_{i,1}, v_{i,2}, v_{i,3}, \cdots, v_{i,D})$, respectively. With increased iteration, the swarm will move towards the global best position (gbest) by keeping track of their personal best (pbest). In a D dimension search space the pbest of the i th particle is represented as $\text{pbest}_i = (p_{i,1}, p_{i,2}, p_{i,3}, \cdots, p_{i,D})$ and the gbest of the whole swarm is represented as $\text{gbest} = (g_1, g_2, g_3, \cdots, g_D)$. The PSO algorithm updates the velocity and position of each particle by following Eqs. (2) and (3), respectively (Sabat et al. 2011).

$$V_i(t) = W^t_{int\,era} \cdot V_i(t-1) + C_{1t} \times r_1(t) \times \left(P_{best(i)} - X_i(t)\right) + C_{2t} \times r_2(t) \times \left(g_{best(t)} - X_i(t)\right) \tag{2}$$

$$X_i(t) = X_i(t-1) + V_i(t) \tag{3}$$

where C_{1t} and C_{2t} are the learning factors that determines the relative influence of cognitive and social component, respectively (Eqs. 4 and 5). r_1 and r_2 are real numbers chosen uniformly and at random in the range of [0,1]. The $g_{best(t)}$ is the global best in t th iteration and $P_{best\ (i)}$ is the personal best of i th particle in t th iteration.

To incorporate better compromise between the exploration and exploitation of the search space in PSO, time variant acceleration coefficients have been introduced as below. C_1 has been allowed to decrease from its initial value of C_{1i} to C_{1f} while C_2 has been increased from C_{2i} to C_{2f} using the following equations as below (Tripathi et al. 2007).

$$C_{1t} = \left(C_{1f} - C_{1i}\right)\frac{iter}{\max iter} + C_{1i} \tag{4}$$

$$C_{2t} = \left(C_{2f} - C_{2i}\right)\frac{iter}{\max iter} + C_{2i} \tag{5}$$

The presence of inertia weight balances between exploration and exploitation of the swarm. An inertia weight in the range of [1.2,0.9] was found to be a good choice, but the linearly decreasing inertia weight with increasing iterations also helps for faster convergence (Shi and Eberhart 1998). The inertia weight is decreased linearly with increasing iterations using Eq. (6).

$$W^t_{int\,era} = (W_1 - W_2) \times \frac{\max iter - iter}{\max iter} + W_2 \tag{6}$$

Where $W^t_{int\,era}$ is inertia weight at t th iteration, W_1 and W_2 are the maximum and minimum value of inertia weight, respectively. max*iter* refers to maximum number of iterations.To allow the PSO algorithm to explore the search space to a greater extent, while obtaining better diversity, a mutation operator has been applied, that is based on the one introduced by Tripathi et al. (2007).

2.4 Multi Objective PSO

Multiple non-dominated solutions are sought in multi objective PSO (MOPSO). In multi objective approach, the *pbest* and *gbest* vectors are not unique and their defining is different from single objective optimization problems. Numerous researches on MOPSO extensions of the particle swarm have been proposed since several decades (Coello Coello and Lechuga 2002; Parsopoulos and Vrahatis 2002; Tripathi et al. 2007; Tsai et al. 2010). The applied multi objective technique in this study is based on the combination of proposed approach by Tripathi et al. (2007) and Tsai et al. (2010).

The individual experience of each particle is captured in the "*pbest*" attribute, that corresponds to the best performance attained so far by it in its flight. The present solution is compared with the "*pbest*" solution, and it replaces the latter only if it dominates that solution.

The best solution obtained by the swarm is represented as "*gbest*". Due to the conflicting nature of the multiple objectives involved in multi objective problems, the choice of a single optimum solution is difficult. To overcome this problem, the concept of non-dominance is used and an archive of non-dominated solutions is preserved, from which a solution is picked up as the "*gbest*". In this developed MOPSO, the maximum archieve size is maintained. The selection of the "*gbest*" solution is implemented from the archive on the diversity basis. In MOPSO, the diversity measurement has been done using a distance measurement. This concept is similar to the crowding-distance measure.

3 Case Study

Ilam reservoir is the principal source of drinking water to more than 230,000 people of Ilam city in west of Iran. The Ilam reservoir surface area, active storage, and maximum depth are 340 ha., 65 MCM, and 60 m in normal water level, respectively. The average hydraulic retention time of the reservoir is about 1.2 years. The reservoir was constructed 10 years ago on the Konjancham river in Ilam province and is operated by the Ilam Regional Water Resources Company (IRWRC) for the purposes of drinking and agricultural uses, flood control, and low flow regulation to environmental demands. The reservoir is dendrite reservoir which resembles several branching tributaries that flow toward Center River. Golgol river, Chaviz river, and Ema river form the primary tributaries to the reservoir. Increased concerns over the spill pollution rate in Ilam reservoir due to its proximity to Ilam city, increasing urbanization and expanding agricultural production within the watershed accelerated many investigations within this.

Applying the CE-QUAL-W2 modeling framework requires that a reservoir water body should be segmented into a number of completely mixed water cells. An iterative process has been implemented to determine the proper segmentation of the reservoir based on the bottom bathymetry. In this research, the reservoir is schematized to consist of three reservoir branches, which are one main reservoir water bodies around the water intake (Golgol branch) and two subsidiary (Ema and Chaviz branches). Then, each reservoir branch is segmented along longitudinal direction as well as water depth direction. The main water body is divided to consist of ten longitudinal segments at the surface with the length 500 m. Each segment is then divided into 2 m layers in the water column. Study Area of Ilam Reservoir, its main tributary, and the model segmentation is presented in Fig. 2.

The comprehensive input data for CE-QUAL-W2 hydrodynamic modeling include reservoir topography, meteorological, inflow, temperature of stream information, and outflow. The hydrodynamic model of Ilam Reservoir has been calibrated with data in 2008. The model predicted water surface elevation (WSE) and thermal profiles show good match with daily WSE and monthly thermal profiles field data in 2008.

4 Model Application

To mitigate the unsuitable effect of suddenness pollution spill in Ilam Reservoir as a drinking source of Ilam city, PSRMM has been applied to enhance the decision making process. Providing safe and reliable supply of water for costumers is a main mission of water resources authority in Iran. Recent accident pollution injection into reservoirs supplying drinking waters in Iran increased the concerns about reservoir availability restriction due to contamination. Therefore equipped emergency systems such as PSRMM could be effective tools in providing emergency planning at accident reservoir pollution and mitigating the inadvisable and/or adverse effects. Furthermore, the health importance of thousand municipal and agricultural users of Ilam reservoir signifies the pollution spill response management model application.

The developed PSRMM provides information on the occurrences, persistence, temporal and spatial distributions of hazardous material in the reservoir and optimal reservoir operation strategy in selective withdrawal scheme. In this study, several spill scenarios were evaluated, each involving leakage of conservative hazardous materials on or adjacent to the reservoir branches during a hypothetical truck collisions (see Table 1). Without lose of

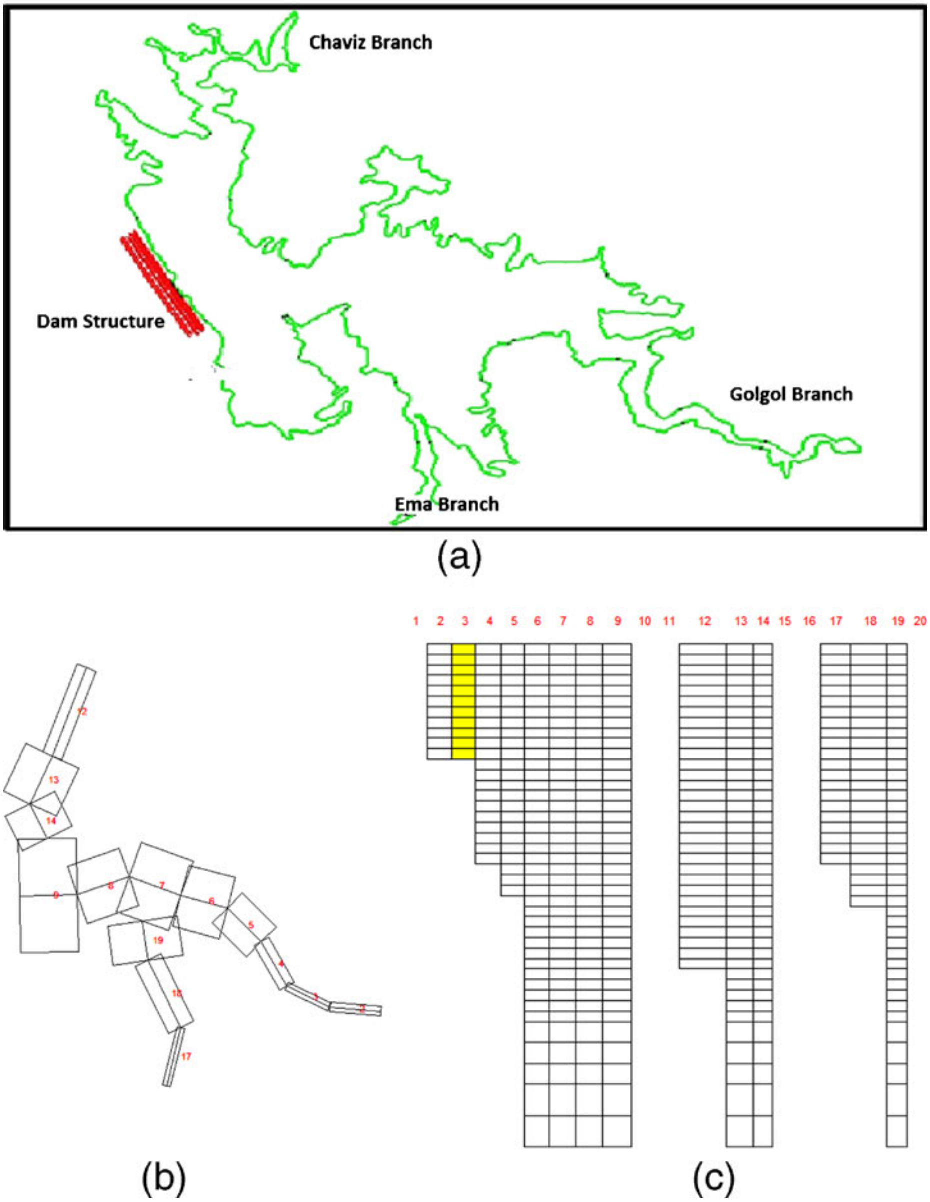

Fig. 2 **a** Study area of Ilam Reservoir and its major tributaries; **b**, **c** Ilam Reservoir model segmentation

generality, each of these scenarios has been assessed for three different flow conditions in each time (low, average, and high flow conditions).

Accurate calibration and validation of the predictive simulation model is required in the PSRMM system. In this study, pollution spill injection has been modeled conservatively to obtain a worst case scenario for real time reservoir operation. The 2D hydrodynamic and water quality simulation model identifies the temporal and spatial threat zones and estimates the response level in reservoir during spill events. Short term operation has been optimized

Table 1 Spill scenarioes

No.	Scenario	Conservative hazardous material standard quality	
1	Maximum Probable (7,000 Kg/12 h) spill adjacent to Golgol Branch	a) 0.2 mg/L	b) 0.1 mg/L
2	Average Probable (5,000 Kg/8 h) spill adjacent to Golgol Branch	a) 0.2 mg/L	b) 0.1 mg/L
3	Minimum Probable (2,500 Kg/8 h) spill adjacent to Golgol Branch	a) 0.2 mg/L	–
4	Maximum Probable (7,000 Kg/12 h) spill adjacent to Chaviz Branch	a) 0.2 mg/L	b) 0.1 mg/L
5	Average Probable (5,000 Kg/8 h) spill adjacent to Chaviz Branch	a) 0.2 mg/L	b) 0.1 mg/L
6	Minimum Probable (2,500 Kg/8) spill adjacent to Chaviz Branch	a) 0.2 mg/L	–

for different scenarios with varying amounts of conservative hazardous materials, different spill duration, spill locations, and various water quality standards in the reservoirs. For comparative purposes, the results of scenario 2-a for average flow condition are presented and discussed in detail.

To examine the model applicability, a simulation period of 31 days (Julian Day 400 to 431/ February to March in year) has been selected in this research. As an example of the capabilities of the proposed PSRMM, a hypothetical spill of 5,000 kg of conservative chemical material released adjacent to the Golgol branch inflow as a main tributary of Ilam reservoir. The hypothetical truck collisions caused accidental pollutions spills over a period of 12 h. The hypothetical water quality standard is assumed to be 0.2 mg/L (scenario 2-a).

An immediate scenario analysis (simulation routine of PSRMM) has been accomplished to evaluate the temporarily suspended periods at the drinking water utilities (based on defined quality standard in Table 1). As a precautionary measure, operations at drinking water utilities along the Ilam reservoir is assumed to be temporarily suspended over a period of about 31 days which may be treated as upper bond of simulation period. In fact preliminary studies show that under low operating condition (lower bound of intake capacity) the reservoir will get back to normal condition within 31 days.

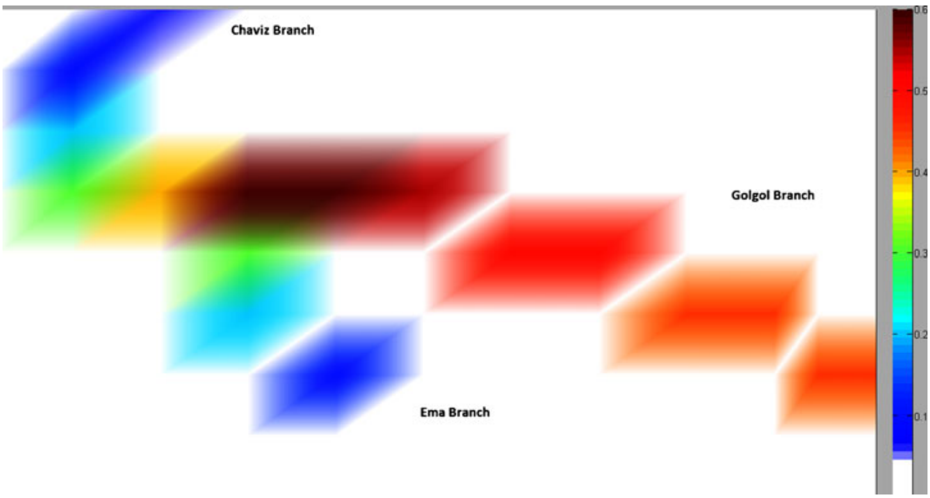

Fig. 3 Spatial response levels in Ilam Reservoir 12 elapsed days after spill event of scenario 2-a occurance

As mentioned earlier the fate and transport of pollution in Ilam reservoir, the contaminant plume, and the threat zones is estimated with simulation routine of PSRMM. Figure 3 illustrated the spatial response level in Ilam reservoir 12 days after scenario 2-a occurrence. Average hazardous material concentration in Ilam reservoir segmentation is evaluated by the numerical hydrodynamic and water quality simulation model, CE-QUAL-W2. As it can be seen in Fig. 3, the average hazardous material concentration at all segments in Golgol branch is above 0.2 mg/L (12 elapsed days after scenario 2-a occurrence). The first application of SO routine of PSRMM is on average probable of hazardous material injection adjacent to Golgol branch during the average flow conditions. To evaluate the performance of the developed model, a management period starting from Julian day 400 to 431 (February to March) is considered.

PSRMM developed a data management and decision support system that seamlessly integrates inflow and meteorological data, water quality simulation model, optimization algorithms tool to manage emergency pollution spill in reservoir. The presented results of developed PSRMM in this study relied on the inflow and meteorological data on the average condition in the spill event period.

During accident pollution spill in Ilam Reservoir, the SO routine of PSRMM derived the optimal reservoir operational strategy based on selective framework to minimize the reservoir cleanup time and to reduce the frequency and magnetude of water quality standard violations. The provided solutions aims to improve the environmental functionality during pollution spill injections with regard to two defined objectives. The SO routine of PSRMM is based on the linked CE-QUAL-W2 model and MOPSO algorithms. The various generated boundary conditions (different reservoir operational strategy in selective scheme) by MOPSO are defined the fate and transport process of contaminant in reservoirs which is evaluated by CE-QUAL-W2 model. The techniques of MOPSO algorithm guide the search direction to derive the pareto optimal solutions.

The defined objective functions in this study are conflict with each other. Decreasing the reservoir recovery time is conversely proportional with downstream worst water quality concentration. Releasing large valume of contaminated water to downstream accelerates the reservoir clean up time and/or reduces the reservoir recovery time (*R.R.T*). On the other hand, releasing large valume of contaminated water decrease the pollutant degradation process in the reservoir. Therefore hazardous material concentration (the magnitude of water quality standard violation) would be increased in released water. The Defined objective function in this research is as below (Eq. 7)

$$\begin{aligned} &ObjectiveFunction(1) = \\ &Min\left(\alpha + \beta.\tfrac{NSV}{S.P.} + \gamma.\tfrac{NMWL}{S.P} + \lambda.\tfrac{NMaxWL}{S.P}\right)R.R.T \\ &ObjectiveFunction(2) = Min(.MaxC_{out}) \end{aligned} \tag{7}$$

where α, β, γ, and λ are weights assigned to the reservoir recovery time (*R.R.T*), number of water quality standard violation (*NSV*), the number of the minimum water surface level violation (*NMWL*), and the number of the maximum water surface level violation (*NMaxWL*). $MaxC_{out}$ and *S.P* are the maximum quality concentration of released hazardous material and simulation period which is equal to 31 days in this study. The constraints such as minimum and maximum permissible reservoir volumes, and minimum and maximum allowable release rates, and no of water quality standard violation is considered in this research. The penalty approach is used to reformulate the constrained problem into an unconstrained problem. Ilam Dam has three outlets; the bottom outlet is used for sediment flushing and the middle outlet (outlet 1) and upper outlet (outlet 2) can be used for selective withdrawal scheme. Decision variables of the optimization model with the water quality objective are the release from the outlet 1 and outlet 2 in the pre-determined ranges. The decision variables of this evolutionary algorithm are number of outlet multiplied to simulation days (2×31). The presented result is obtained after testing and evaluating different parameter combinations.

The coupled numerical simulation model (CE-QUAL-W2) and optimization algorithm (MOPSO) makes it possible to incorporate various complex pollution transport processes and well developed numerical techniques to obtain optimal operation policies without increasing the complexity of the optimization model.

To protect Ilam downstream environment and reducing the magnitude and frequency of water quality standard violations, the SO routine of PSRMM is executed based on defined objective function in Eq. (7). The optimal certain releases from each outlet are determined considering quality of water released from the reservoir. The determined pareto optimal solutions of SO routine of PSRMM in Ilam Reservoir control the released water quality concentration, increase the pollutant degradation and rate of hazardous material removal in Ilam Reservoir. The Linked simulation-optimization model determines the optimal operational strategies in selective withdraw framework. The pareto optimal front of MOPSO_CE-QUAL-W2 as a element of PSRMM has been represented in Fig. 4.

The detail of reservoir cleanup time, the magnitude of pollutant concentration and the frequency of the water quality standard violations obtained based on SO routine and simulation analysis routine of PSRMM (Fig. 4) are presented in Table 2. As is clear, decreasing the reservoir clean up time (*R.R.T*) is convrsely proportional with maximum downstream hazardous material concentration and/or magnitude of water quality standard violations. Releasing large volume of contaminated water to the downstream, decreases the pollutant diffusion and degradation process in the reservoir. Therefore the magnitude of pollutant concentration in the released water will be increased whereas the *R.R.T* would be decreased. For example in Solution (3), large *R.R.T* (25 days) is proportional with lower magnitude of hazardous material concentration and lower frquency of water quality standard violations (0.4913 mg/L and 18 days, respectively).

The time series of released water quality concentrations during management period has been shown in Fig. 5. Two scenarios are analyzied in simulation routine of PSRMM based on inflow rate. In scenario 1; the daily release are equal to daily inflow which is withdrawn

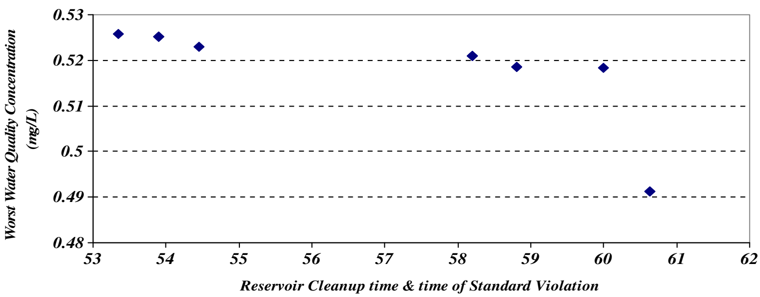

Fig. 4 The trade of between worst water quality concentration and reservoir cleanup & no. of standard quality violation

Table 2 The detailed results of pareto optimal solutions and scenario analysis routine of PSRM model

	Solution (1)	Solution (2)	Solution (3)	Solution (4)	Solution (5)	Solution (6)	Solution (7)	Scenario*1	Scenario *2
Reservoir cleanup times (Days)	24	22	25	24	22	24	22	23	23
No of water quality standard violations (Days)	18	19	18	21	20	19	18	18	20
Worst water quality concentration (mg/L)	0.521	0.5252	0.4913	0.5259	0.5183	0.5209	0.5258	0.5768	0.5519

* Derived Operation Strategy by User which is evaluated by Simulation Routine of PSRMM

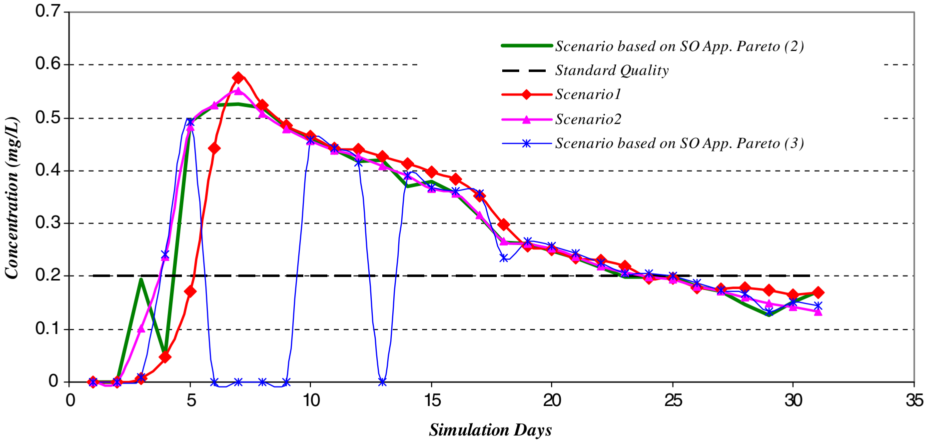

Fig. 5 Time series released downstream water quality concentration

from middle outlet. In scenario 2, the daily releases are equal to daily inflow which is withdrawn from middle and upper outlet equally. As it can be seen in Fig. 5, the SO approach decreases the magnitude of hazarous material concentration and the frequency of standard violations compared with user defined scenarios analyzed with simulation routine of PSRMM. The resrvoir recovery time (*R.R.T*) in SO approach (pareto solution 2 and 3) is reduced compared with user defined scenarios.

The time series of reservoir operation in optimum scenario defined by SO routine of PSRMM, pareto solution 3, shows zero release in some days. This strategy allows the contaminant to be settled in lower layers and/or diffused within the reservoir to mitigate the withdrawn water quality concentration although the reservoir cleanup time would be longer compared with strategy (2).

The time series withdrawn water from each Ilam Reservoir outlet according to the one of the pareto optimal solution is presented in Fig. 6.

Like other evolutionary algorithms, a number of parameters of MOPSO need to be set. These parameters include the population size, minimum and maximum weights, and initial/final acceleration constants and so. In this study, these parameters are obtained after testing

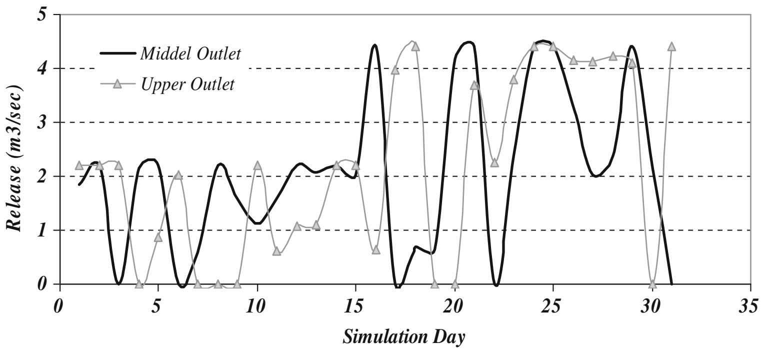

Fig. 6 Time series withdrawn from each reservoir outlet (one of the pareto solution)

Table 3 MOPSO parameters in SO routine of PSRMM

Parameter	Symbol	Value
Population size		40
Max iteration	max*iter*	200
Interia weight	W_1	0.9
Interia weight	W_2	0.4
Initial acceleration constant	C_{1i}, C_{2i}	1.4, 0.45
Final acceleration constant	C_{1f}, C_{2f}	0.5, 1.2

and evaluating various parameter combinations. These parameters are summarized in Table 3.

5 Conclusion

In this research, PSRMM was proposed to assist in accident spill response efforts on Ilam reservoir. The simulation analysis and SO routine are the main components of PSRMM. PSRMM included spatial system analyzing (SSA) model, a 2D hydrodynamic and water quality simulation model (CE-QUAL-W2) coupled with Multi Objective Particle Swarm Optimization (MOPSO) technique. An immediate scenario analysis has been done to evaluate the temporarily suspended periods at the drinking water utilities (water quality standard; 0.2 mg/L) in Ilam Reservoir. Then SO routine of PSRMM controls the reservoir release concentration and reservoir cleanup time with providing pareto optimum reservoir operational strategies in selective withdraw framework.

The linked CE-QUAL-W2 model, as a detailed description of systems responses to planning and design solutions, and MOPSO provided the pareto optimum solutions which minimized the reservoir cleanup time, the frequency and magnitude of water quality standard violations. The meaningful management strategies, pareto optimum solutions provided by MOPSO, affect the system responses to mitigate the adverse effects of pollution spill injections in Ilam reservoir and/or degrade the contaminates in Ilam reservoir as a drinking source of Ilam city.

The water quality simulation model (CE-QUAL-W2) provided propagation and identification of impact locations and response resources in proximity of the spill. The coupled simulation-optimization model as PSRMM component improving the response time and providing the mitigation strategy through optimal reservoir operation in selective withdraw scheme in the accident pollution spill events. Theoretical analysis and simulated results indicated that the SO routine in PSRMM is capable of reasonably predicting acute effects of chemical spills injection on downstream water quality concentrations and Ilam reservoir cleanup times.

In fact, the proposed PSRMM functionality relies on the assumption that inflow rates and whether parameters are estimated based on low, average, and high statistical conditions. Considering the uncertainties related to model input data to minimizing regret solutions or establishing an accurate long term forecasting system to predict inflow rate and meteorological conditions are the suggestions for future model improvement. Enhancing the PSRMM capabilities with integrating the proposed components with GIS, Water Treatment Process Simulation Model, and EPANET would be an efficient suggestion for future research. Application the modified CE-QUAL-W2 model incorporating a sub model for toxic contaminants is another enhancement to provide emergency planning in incident toxic chemical injection in reservoirs. Considering different hazardous materials, constituents with kinetic reaction rates and/or the subset of interrelated constituents are additional research study.

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