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ORIGINAL PAPER

Risk analysis and management for water resources systems

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For decades, water shortages, unreliable water supplies, poor water quality, and flooding disaster have been considered as major obstacles to sustainable water resources development at the watershed scale. These have led to a variety of adverse impacts on the social-economic development and human life. One of the major reasons for the raised issues is the lack of efficient, equitable and sustainable water resources management as well as effective policy instructions from decision-makers. Issues of water resources management are highly complicated, involving a large number of social, economic, environmental, technical, and political factors, coupled with complex spatial variability and cascading effect. At the same time, a water resources system comprises plenty of interactive parts, such as rivers, streams, lakes, groundwater regimes, reservoirs, dams and bifurcations, as well as cities, towns, and water users. Climate change and human activity could affect the systems at a regional scale and lead to more significant spatial and temporal variations of water resources in the basin and thus the associated environmental and ecological conditions. There are many potential risks existing in water-related activities within a multi-user, multi-region and multi-reservoir context, such as water resources allocation, flooding prevention and control, environmental and ecological protection, and sustainable development. Such complexities have forced planners to contemplate and propose ever more comprehensive, complex and ambitious plans for water resources systems. Decisions pertaining to water resources management must be based on an in-depth understanding of vulnerabilities and risks.

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Therefore, it is desired that vulnerability and risk of the related water users to such variations be well assessed, in order to provide bases for effective water resources management and planning. This special issue is devoted to the latest research results of emerging technologies for initiate extensive discussions in terms of methodologies and case studies of risk analysis and management for water resources systems. A broad range of topics associated with modeling and experimental studies were selected to present, including pollution investigation and prediction, modelling formulation, flood risk assessment, water resources allocation, and wastewater recycle and reuse.

This issue includes three papers on pollution investigation and prediction. Generally, water pollution is a widespread and challenging issue for water supply to both developed countries and developing countries. Topics about risk analysis of arsenic groundwater in Bangladesh, non-point source (NPS) pollution load estimation in Three Gorges Reservoir of China and improved dissolved-oxygen (DO) prediction of Bow River in Calgary (of Canada) are discussed, respectively.

To begin with, Khan et al. propose a non-linear fuzzy-set based methodology to characterize and propagate uncertainty through a multiple linear regression (MLR) model to predict DO using flow and water temperature as the regressors in Bow River in the City of Calgary, Canada. To reflect uncertainty and variability existing in the input data, in their study, the output is depicted as probabilistic rather than deterministic and is used to calculate the risk of low DO concentration. To demonstrate the proposed method, data from the Bow River in Calgary, Alberta (year 2006–2008) are used. Low DO concentration has been occasionally observed in the river and correctly predicting and quantifying the associated uncertainty and variability of DO is of interest to the City of Calgary. Flow, temperature and DO data were used to construct five MLR models, using different combinations of linear and non-linear fuzzy membership functions. The results show that non-linear representation of variance is superior to the linear approach based on model performance; Normal and Gumbel based membership functions produced the best results. The outputs from two non-linear fuzzy membership models were used to calculate risk of low DO. The predicted risk was between 3.9 and 4.9 %. This is an improvement over the traditional method, which did not indicate a risk of low DO for the same time period. The results demonstrate that water resource managers can adequately use MLR models to predict the risk of low DO using abiotic factors.

Secondly, Ding et al. simulate the hydrological processes and associated pollution load processes in the Three Gorges Reservoir, through coupling a NPS pollution load estimation sub-model with an easy distributed hydrological model (named as EasyDHM). The Three Gorges Reservoir is the largest water conservancy project in China as well as the strategic reserve base of freshwater resources for the nation including flood control, power generation, navigation, environmental protection and water supply. Based on EasyDHM, an easy distributed NPS evaluation sub-model (abbreviated as EasyDNP) was then proposed for simulating point source (PS) and NPS pollution processes. The results indicate that, (i) during 2007–2008, the average annual pollutant loads in the study area are $\sim$87744.8 tons, among which total nitrogen loads are around 78443.8 tons accounting for 89.4 % of the total pollutant loads, while total phosphorus loads are about 9,301 tons accounting for 10.6 % of the total pollutant loads; (ii) the monthly pollution loads from April to October account for more than 90 % of the annual total amount; (iii) rainfall change mainly affects the pollution loads from April to August in the study area, and total nitrogen and total phosphorus loads are both possess positive effects on rainfall, particularly under the same rainfall variation situation. The results are helpful for local managers in not only making decisions of controlling PS and NPS pollutant discharges but also gaining insight into the river water quality management.

Thirdly, McBean analyzes the risk characterization for arsenic-impacted water sources including ground-truthing in Bangladesh. In the early 1980s, there were ten million tubewells implemented in Bangladesh to access the shallow groundwater for water supply. However, the widespread implementation of tubewells was later determined to be highly problematic due to arsenic contamination in the groundwater. High arsenic can cause serious threaten to human health. Thus, for substantial areas in Bangladesh, groundwater cannot be utilized for water supply without treatment to reduce arsenic levels. In this study, the author indicates that it is necessary to predict arsenicosis by calculating the incremental excess lifetime cancer risk. Improved indicators of high arsenicosis rates are presented as the ratios of arsenic/iron. By observing the correlations between arsenic and iron and the prevalence of arsenicosis patients, the relationships among the concentration of arsenic and iron, and the percentage of contaminated wells are significant for determining the prevalence of arsenicosis. The results indicate that, higher arsenic concentrations and higher percentages of contaminated wells with lower iron concentrations, could lead to higher prevalence of arsenicosis patients. However, when the concentrations of arsenic and iron are both high, the ratio of arsenic/iron can decrease.

Over the past decades, the frequency and intensity of floods have increased due to deteriorated ecosystems, decreased vegetation cover, reduced stream capacity, varied runoff pattern, and changed climate condition. Flood management is becoming an issue of growing importance and complexity throughout the world under climatic variability and human activity. Losses cannot be avoided when major floods occur. A range of mathematical techniques are developed for aiding decision-making in flood disaster mitigation and management of watershed systems. In this issue, two papers related to flood risk assessment and management are presented.

The study of Maqsood and Huang is about introducing a hybrid optimization approach for flood management under multiple uncertainties. An inexact two-stage integer programming (ITIP) model and its dual formation are developed by integrating the concepts of mixed-integer and interval-parameter programming techniques into a general framework of two-stage stochastic programming. The ITIP provides a linkage to pre-defined management policies, deals with capacity-expansion planning issues, and reflects various uncertainties expressed as probability distributions and discrete intervals for a flood management system. Marginal costs are determined based on dual formulation of the ITIP model, and their effects on the optimal solutions are examined. The developed model is applied to a case study of flood management. The solutions of binary variables represent the decisions of flood-diversion-capacity expansion within a multi-region, multi-flow-level, and multi-option context. The solutions of continuous variables are related to decisions of flood diversion toward different regions. The solutions of dual variables indicate the decisions of marginal costs associated with the resources of regions' capacity, water availability, and allowable diversions. The results show that the proposed approach could obtain reliable solutions and adequately support decision making in flood management.

Another study of Yu et al. proposes a joint Monte Carlo and fuzzy possibilistic simulation (MC-FPS) approach for flood risk assessment. Previously, uncertainties associated with both the flood inundation modeling and damage data survey and evaluation process are normally neglected, which unavoidably under- or over-estimate the final damage evaluation. Therefore, the their study, Monte Carlo simulation is used to evaluate parameter uncertainties associated with inundation modeling, and fuzzy vertex analysis is employed for promulgating human-induced uncertainty in flood damage estimation. A study case adapted from reference is selected to demonstrate the applicability of the proposed method. The results indicate that the outputs from MC-FPS will present as fuzzy flood damage estimate and probabilistic-possibilistic damage contour maps. The stochastic uncertainty in the flood inundation model and fuzziness in the depth-damage functions derivation will cause similar levels of influence on the final flood damage estimate. Under the worst scenario (i.e. a combined probabilistic and possibilistic uncertainty), the estimated flood damage could be 2.4 times higher than that computed from conventional deterministic approach; considering only the pure stochastic effect, the flood loss would be 1.4 times higher. It is also indicated that the uncertainty in the flood inundation modeling has a major influence on the standard deviation of the simulated damage, and that in the damage-depth function has more notable impact on the mean of the fitted distributions. Through applying MC-FPS, rich information could be derived under various α-cut levels and cumulative probabilities, and it forms an important basis for supporting rational decision making for flood risk management under complex uncertainties.

Over the past decades, water shortages and unreliable water supplies have been considered as one of the major barriers to sustainable water resources management, which often threaten human health, impair prospects for agriculture and jeopardize survival of ecosystems. Controversial and conflict-laden water resources allocation issue has challenged decision makers. The growing population and shrinking water availability have exacerbated such competitions, leading to complexities in generating desired decisions, particularly under varying natural conditions and deteriorating quality of water resources. As a result, a large number of systems analysis methods were undertaken for allocating and managing water resources in efficient and environmentally benign ways. This special issue contains three papers in the areas of modelling formulation for water resources allocation problems.

To begin with, in the research of Wang et al. a water consumption model is integrated into a scenario-based planning support system (SB-WCPSS) for planning water resources management in Cincinnati, Ohio, USA. This paper presents an effective way to support three of the five EPA water resource adaptation program goals: clean air and global climate change, clean and safe water, and compliance and environmental stewardship. SB-WCPSS is developed to establish the connections between domestic water consumption and planning alternatives in the context of climate change. The objective of the SB-WCPSS is to enable planners to relay water conservation methods into the plan making process in ways that are easily understood. In the application, water consumption consists of land use based indoor, turf, and pool water usages. By specifying anticipated future land uses and associated water consumption rates, temperature and precipitation, SB-WCPSS users can analyze and compare water consumptions under various scenarios. Parcel-based daily water consumptions are computed and summarized spatially. The results manifest that water conservation strategies, such as xeriscape, can reduce turf water usage. Indoor water consumption depends on the number of people who use water and how they use water. The study shows that the SB-WCPSS structure is sound and user friendly. With the help of scenario-based planning approaches, planners can involve the public in the collaborative environmental planning and decision-making process in order to help communities better understand the challenges and opportunities and make informed decisions.

Furthermore, Gu et al. develop an inexact stochastic fuzzy programming (ISFP) approach for optimization of the industrial structure subjected to limited water resources in the City of Jinchang, Gansu province, China. Jinchang is one of the thirteen water resources shortage cities of China, such that water resources have continued to be an important factor to restrict the city's socio-economic development. ISFP incorporates inexact stochastic programming within inexact fuzzy chance-constrained programming to optimize the industrial distribution and improve the water-carrying capacity. Chemical oxygen demand (COD) in three industries in wastewater per unit gross domestic product (GDP) and the working population of the three industries per add-value are presented as fuzzy sets with trapezoidal membership function; the other elements in the system are presented in terms of intervals or random variables. Uncertainties associated with environment capacity are expressed as fuzzy-random variables with known membership function and probabilistic distributions. The results obtained are useful for generating optimal industrial structure as well as quantifying the relationship between regional economic development and water resources carrying capacity.

Zhu et al. propose an inexact full-infinite two-stage stochastic programming (IFTSP) model for managing agricultural irrigation water in Zhangweinan river basin. Zhangweinan river basin is one of the main food and cotton producing regions in North China, which covers a population of about 30 million and the cultivated area reaches to 293×10^3 ha. This basin is a typical severe water resource shortage area in the north of China, effective and efficient risk assessment of agricultural irrigation water management is desired. The authors proposed IFTSP model for managing irrigation water in responses to the risk of agricultural water shortage. The proposed method can deal with uncertainties including crisp intervals, probability distributions, and functional intervals. It can also provide an effective linkage between conflicting economic benefits and associated penalties attributed to the violation of predefined policies for water allocation. Results obtained are helpful for identifying desired agricultural irrigation targets with a maximized system benefit and a minimized system-failure risk. Decision makers can adjust the existing agricultural irrigation patterns, and coordinate the conflict interactions among economic benefit, system efficiency, and agricultural irrigation under uncertainty.

The inherent complexities and stochastic uncertainties that exist in real-world water resources systems have essentially placed them beyond the conventional deterministic optimization methods. Chen et al. propose a robust risk analysis method (RRAM) for water resources decision making under uncertainty, through incorporating interval-parameter programming and robust optimization within a stochastic programming framework. The RRAM is generally suitable for risk-aversive planners under high-variability conditions. Penalties are exercised with the recourse against any infeasibility, and robustness measures are introduced to examine the variability of the second-stage costs that are above the costs of the expected levels. A case study is provided for demonstrating applicability of the developed method. The solutions obtained are analyzed for generating decision alternatives under various system conditions. A plan with a higher robust level would better resist from system risk. Thus, decision with a lower robust level can correspond to a higher risk of system failure. The results demonstrate that there is a tradeoff between system cost and system reliability.

Wastewater assessment and reuse practices are receiving more and more attention due to increasing water scarcity, concerns about the effect of wastewater discharges on receiving water, and availability of high-performing and cost-effective water reuse technologies. In this special issue, there are two papers in the areas of wastewater assessment and reuse.

Firstly, the study of Nasiri et al. is about formulating a system dynamics approach for urban water reuse planning in Kalamazoo-Michigan, Great Lakes Region. The developed model is used to simulate and optimize the overall water system cost (including water, wastewater and water reuse components), accounting for future scenarios of population, economic growth and climate change. The uncertainties and stochastic behavior are admitted in scenario parameters of the model. In this sense, it would be interesting to admit some degrees of uncertainty in definition of non-scenario parameters of the model. The main finding of this study is that a decision regarding water reclamation and reuse is a case-specific one and needs to be addressed through an integrated water-wastewater system optimization model given the future scenarios of climate change, population, and other regional and technological factors. Results indicate significant levels of water reuse after an infrastructure build delay. The model also indicates that a decision to implement water reuse yields remarkably lower water withdrawals and lower water treatment costs even in a location with a relatively abundant water supply like Kalamazoo. This study emphasizes the fact that a true understanding of the practice of water reuse cannot be achieved without taking regional and climatic parameters into account. In addition, the developed model can be used to assess water-reuse decision making in other jurisdictions such as areas with water scarcity, a more receptive population, or where desalination is or will be an option for increasing water supply.

Secondly, the research of Hao et al. is to formulate a comprehensive evaluation method for the assessment of the operational efficiency of wastewater treatment plants (WWTPs). The utilization of the environmental water resources in China has increasingly become a hot problem. The construction of WWTPs has been included in state and local long-term, mid-term or annual plans. Therefore, it is essential to evaluate and analyze the operational efficiency of a WWTP objectively and comprehensively. The authors use fuzzy matter-element model to achieve a comprehensive assessment and analysis of the operational efficiency of WWTPs. For demonstrating the applicability, the developed method has been applied to a city in Northern China. According to the results of the comprehensive evaluation, the operational efficiency of the WWTP using an anaerobic/anoxic/oxic (A/A/O) process is generally better than other wastewater treating technologies. Particularly, the removal efficiencies of nitrogen and phosphorus pollutants could increase, higher than the standards of normal WWTPs. Thus, the operation level of WWTPs could be improved by increasing the total nitrogen removal rate and decreasing the excess sludge cake quantity. The evaluation results can be used to guide the construction, operation and management of WWTPs in the other regions of China.

This issue also includes one paper related to a non-biological carbon dioxide (CO_2) absorption by saline-alkali soils (A_a) at desert ecosystems studied by Chen et al. which has significance to water resource management in Tarim River Basin. Tarim River is the largest inland river in China, which is also one of the most serious water-shortage regions of China and its ecological system is also extremely vulnerable with significant vegetation loss and wind erosion of the land surface. In this study, a non-biological CO_2 absorption by A_a at desert ecosystems in Tarim River Basin has been presented. The authors focus on bare saline-alkali soils to cut down uncertainty. They demonstrate that diurnal time lag between A_a and microbial soil respiration (R_m) is about 2 h, and the contributions of A_a definitely prolongs the period of R_m to maximum; a significant time lag (about 1 h) exists between F_a and R_m, which can be merged after reconciling F_a as a direct sum of total CO_2 influx and efflux. The results obtained suggest that the surprised time lag between F_a and R_m be attributed to the contributions of A_a and R_m in i_{ma}, which could disclose the mechanisms of A_a and it might be a hidden loop in the carbon cycle.

In summary, the effective risk analysis and management for water resource systems are becoming one of the most important goals pursued by governments, industries, communities, and researchers. These 12 papers are concerned with various water-related activists and the associated socio-economic and environmental impacts under a variety of system conditions, where a number of innovative perspectives and findings are proposed. These research works can help (a) formulate innovative and effective systems analysis approaches for supporting water resources allocation, flooding prevention and control, environmental and ecological protection, and sustainable development improving; (b) assess potential risks existing in water-related activities within a multi-user, multi-region and multi-reservoir context for enhancing the reliability of water resource systems, and (c) generate sound decision alternatives for generating desired policies that target on more effective water resource management. This special issue reports the latest research results in risk analysis and management for water resource systems. Papers submitted to this issue contribute to the development of innovative simulation and optimization models or new applications of risk analysis methods to real-world case studies to aid decision makers to propose ever more comprehensive and ambitious plans for managing water resources systems. We wish to extend our thanks to those who contributed to this issue.