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WATER RESOURCES MANAGEMENT – TOWARDS PERFORMANCE BASED APPROACH

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ABSTRACT: Global change that results from population growth, global warming, and land use change (especially rapid urbanization) directly affects the complexity of water resources management problems and the uncertainty they are exposed to. Both, the complexity and the uncertainty, are the result of dynamic interactions of innumerable system parts within three major systems: (i) the physical environment; (ii) the social and demographic characteristics of the region under consideration; and (iii) the pipes, roads, bridges, buildings, and other components of the constructed environment (infrastructure). Recent trends in dealing with complex water resources systems include consideration of the entire region being affected, explicit consideration of all costs and benefits, elaboration of a large number of alternative solutions, and the greater participation of all stakeholders in the decision-making. Systems approaches based on simulation, optimization, and multiobjective analyses, in deterministic, stochastic and fuzzy forms, demonstrated in the last 50 years, an excellent potential for providing appropriate support for effective water resources management. This paper explores the future opportunities based on the advances in systems theory that can, on a broader scale, majorly transform the management of water resources. The paper identifies performance-based water resources engineering as a methodological framework to improve water resources management in the face of rapid climate destabilization so that sustainability becomes the norm, not the occasional success story.

KEY WORDS: engineering, robustness, redundancy, resourcefulness, rapidity, system resilience, system performance

1. Introduction

Two paradigms are identified by Simonovic [1] that are shaping contemporary water resources management: The first paradigm focuses on the complexity of the water resources management domain (increases with time), and the complexity of the modelling tools (decreases with time), in an environment characterized by continuous, rapid technological development (sharp increase in growth over time). The second paradigm deals with the water resources-related data availability (decreasing) and the natural variability of the domain variables (increasing) that affect the uncertainty (increasing).

The traditional understanding of water resources management is that it is the management of water [2], [3], [4], [5]. But the language behind the concept is more straightforward since there is a set of complex interactions between the water resources, people and the environment than they all share. The two paradigms

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call for a question: What are we managing? We try to manage domains (water, land, air, etc). We keep trying to manage people's behaviour within environments [6]. It seems that every time we introduce a change at one point, it causes an unexpected response somewhere else —the first fundamental systems principle.

It is argued by Simonovic [7] (based on [6]) that the system in our focus is a social system. It describes how water resources interact with people to clearly define the management problem and determine the best strategies for systems intervention. The water resources system includes four tightly connected subsystems: individuals, organizations, society, and the environment. To sustainably manage water resources, interactions between the four subsystems: must be appropriately mapped.

Every open system includes inputs of energies – resources – that are transformed into outputs. Systems inputs and outputs include resources, information and values. They link individuals, organizations, society and the environment. Information and resource flows link people and organizations. Value systems are attached to information and resource flows. They are generated by the individuals and/or organizations and provide meaning for information and resource flows.

During the past five decades, since the introduction of the water resources systems analysis, we have witnessed a great evolution in water resources systems. Three of the characteristics of this evolution are noted in particular [8]: (i) The application of the systems approach to complex water management problems. It has been recognized as the most important advance in water resources management by providing an improved basis for decision-making. (ii) Transformation of attitude by the water resources management community towards environmental concerns. (iii) Introduction of sustainability paradigm. The publication of the Brundtland Commission's report «Our Common Future» in 1987 started the application of the sustainability principles to water resources decision-making by changing management objectives and obtaining a deeper understanding of the complicated inter-relationships between existing ecological, economic and social issues.

For this paper, let me repeat the basic definition of a system. Simonovic [8] defines *«a system as a collection of various structural and non-structural elements that are connected and organized in such a way as to achieve some specific objective through the control and distribution of material resources, energy and information»*. The systems approach is characterized by emergence (the whole is different than the sum of its parts), *self-organization* (cooperation, interdependence and competition yield stabilizing homeostasis), *nonlinearity* (small changes in part of the system can have excessively significant effects across the whole), and *feedback loops* (the outputs of the system affect its inputs).

A success reached up today must contribute to the further evolution of the water resources systems approach to address society's severe water challenges today. The future activities must continue: to deal with the most challenging complex water problems (that include competing objectives, multidisciplinary cooperation, and changing values); to conduct further practice-based as well as fundamental research (balancing research for basic understanding and providing solutions to current water problems); and provide further capacity building to ensure that ranks of water resources systems specialists will not decline.

2. One view of the future – performance-based water resources engineering

Performance-based engineering deals with the design, evaluation and building of engineered systems that meet – as economically as possible – the uncertain future demands of people and nature. It is an approach to the analysis of any complex system. A system managed to meet quantitative or predictable performance requirements, such as demand load or economic efficiency, without a specifically prescribed method for attaining those requirements. This is very different from traditional prescribed standards (code provisions), which mandate specific practices, such as pipe size, levee height, and minimum drinking water quality, for example. Such an approach is very flexible in developing tools and methods to evaluate the entire water resources system management process. The primary assumption is that performance levels, and objectives can be measured, that performance can be predicted using analytical tools, and that the impact of improved performance can be evaluated to allow rational trade-offs based on life-cycle considerations rather than a single criterion alone, such as construction costs for example.

Current research on performance-based engineering focuses on earthquakes [9] and has been extended to water resources engineering [10]. Performance-based engineering offers opportunities for better management of water resource systems faster and more cost-effectively. It can be implemented for the revitalization of the decaying infrastructure. It can utilize emerging technologies to monitor the strength of existing facilities through sensor technology. It can be deployed in performance control with active control systems and smart materials.

Performance-based engineering also offers great opportunities for research and teaching of the processes involved in designing and constructing engineered water resources systems. The adoption of performance-based engineering requires significant changes in practice and education of water resources engineers. Perhaps most important is a shift away from the dependence on practical and experience-based tools and toward a design and assessment process based on a scientifically oriented systems approach that emphasizes accurate characterization and prediction of system behaviour.

2.1 Challenges

Water infrastructure facilities are designed and managed to withstand demands imposed by their service requirements and environmental events such as floods, droughts, ice, windstorms and earthquakes. Most of the water resources management decisions are being made according to current prescriptive standards (code provisions) and usually provide adequate levels of safety. However, changing conditions, extreme environmental and human-made events may still result in severe damage and economic losses. In an era of rapid changes in engineering design and construction practices and heightened public awareness of water infrastructure performance, engineers are now seeking to achieve performance levels in the built environment beyond what is currently provided by prescriptive standards and meet public expectations better. This discussion introduces a performance-based engineering approach as the replacement for the traditional use of prescriptive standards. Performance-based engineering offers an opportunity to heighten the simulation's role combined with quantitative resilience assessment.

2.2 Need for performance-based water resources engineering

Globally changing conditions, including rapid population growth, land-use change (especially urbanization) and climate change, are affecting water resources engineering planning, design and operations. Air and surface temperature and precipitation patterns and intensity are directly linked to climate change.

According to IPCC [11] a large portion (1/6) of the world's population live in snowmelt-fed river basins and will be affected by the seasonal changes in streamflow, a change in the ratio of winter to annual flows, and possibly the reduction in low flows. Sea-level rise will extend areas of salinization of groundwater and estuaries. These changes will result in a decrease in freshwater availability for human consumption and the needs of ecosystems. Increased precipitation intensity and variability is projected to increase the risk of flooding. Higher water temperatures, increased precipitation intensity, and more extended periods of low flows exacerbate many forms of water pollution, impacting ecosystems, human health, water infrastructure system dependability and operating costs [11].

Global change (especially climate change) complicates the development of risk-informed engineering standards significantly. Current assessments of reliability treat the operational and environmental demands as stationary. This assumption is not defensible when global change effects are considered. Furthermore, the uncertainties in global change effects projected over the 21st century are considerable. Finally, achieving the necessary consensus on global change impacts on the built environment within some standard committees will present challenges.

A number of key questions must be addressed to consider the imperatives of global change in standards development, among them: (i) How should one model the non-stationarity in water-related natural hazard occurrence and intensity that arises as a consequence of global change? (ii) How should these uncertainties be integrated into time-dependent infrastructure performance analysis to estimate future behaviour and demonstrate compliance with performance objectives? (iii) How should we deal with life-cycle cost issues when implementing global change effects in practical design criteria? One possible answer proposed in this discussion is: performance-based engineering based on system simulation modelling and resilience assessment.

2.3 Implementation of performance-based water resources engineering

Performance-based engineering has gained traction in earthquake engineering, where the incentives are strongly economic, and the shortcomings of traditional prescriptive approaches to design, planning and operations are known [9]. Research is underway to extend the performance-based approach to water resources engineering (including hazards like flooding, drought, sea level rise and tsunami), and to develop planning, design and operations procedures in which the consequences of competing hazards are properly balanced, and investments in damage reduction and recovery can be made appropriately [10].

Primary deficiencies of the prescriptive framework include: (i) checking only a single performance level; (ii) applying only a single system disturbance event; (iii) linear static or dynamic analysis; and (iv) no local acceptance criteria. The current prescriptive water resources engineering framework relies on risk analysis tools for modelling uncertainties associated with water resource decision-making related to system loads and responses.

Very different tools will be essential to the successful implementation of performance-based water resources engineering in providing a framework for managing the impacts of external disturbances on the performance of the built environment and guiding water resources management decisions related to the recovery of existing water infrastructure systems affected by changing conditions. These tools should allow: (i) checking multiple performance levels; (ii) application of numerous system disturbance events; (iii) possible utilization of non-linear analysis; (iv) implementation of detailed local acceptance criteria; and (v) joint consideration of system structural and non-structural components.

The performance-based water resources engineering process is illustrated in Figure 1. It starts with identifying system disturbance as a consequence of global change. System disturbance could be a flood, an extreme precipitation event or a long-term drought event, to name a few. The selection of performance criteria follows, which should measure impacts that system disturbance may have on the system. For example, a performance criterion could be area inundated by floodwaters, or the total damage from the drought event, and similar. Each system performance can be measured in its units. The following step includes identifying alternative options (plans/designs/operations strategies) for responding to the disturbance. Options may include structural solutions (flood protection infrastructure, for example) and non-structural measures (change of regulations, for example) alone or combined. System performance capability is then tested by doing a calculation of system performance in response to selected disturbance and alternative response according to a performance criterion. A system *simulation approach* is recommended for implementation at this stage. It is a preferable approach because it does not pose any limitations on the complexity of system structure description. Calculated system performance is subject to multiple uncertainties. The risk approach could be one way to assess the system's performance. However, the risk approach has many deficiencies. It is static (in time and space). It includes difficulties in determining the probability of extreme events and integrating physical, social, economic and ecological concerns simultaneously. Here, it is proposed to incorporate system performance into a single measure of *dynamic system resilience* (in time and space) that can be easily implemented in the broader evaluation of alternative options not limited to the assessment of direct and indirect losses only.

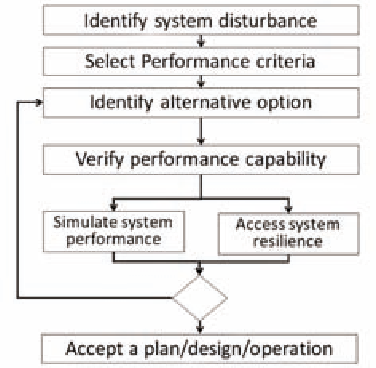

Fig. 1. Performance-based engineering process.

The performance-based water resources engineering process in Figure 1 can be implemented in (i) an iterative way by examining alternative options (plans/designs/operational strategies) ahead of system disturbance or (ii) in real-time by responding to system disturbance and managing recovery from it. Verification of system performance capability is done by the combined use of simulation and quantitative resilience assessment.

2.4 Simulation

The classical simulation approach involves understanding system structure by decomposing the problem that helps in the system description. The simulation process starts with the identification of elements and their mathematical description. The procedure continues with the development of a computer program based on the mathematical description of the model. In the next step, each model parameter is calibrated, and the model performance is verified using different data. The computer program of the model is then operated using various input data. Detailed analysis of the output is the final step in the simulation process.

Performance-based engineering approach can take advantage of system dynamics simulation which is defined by Simonovic [8] «*as a rigorous method of system description, which facilitates feedback analysis via a simulation model of the effects of alternative system structures and control policies on system behaviour. In the context of water resources engineering, a system is defined as a collection of elements which continually interact over time to form a unified whole*». The underlying map of interactions between the system elements is called the system structure. The term dynamics in the definition refers to a change of system behaviour over time. A dynamic system is a system in which the variables interact to generate changes over time. How the system elements, or variables, vary over time is referred to as the system behaviour. System dynamics simulation is not new to water resources engineering.

System dynamics simulation lends itself well to an assessment of engineering system performance over time. Complex systems can be easily built using object-oriented system dynamics simulation software packages that allow a high level of detail to be included in the description of system structure. By running deterministic simulations of potential system planning, design and operating conditions, the system dynamics model facilitates the investigation of nonlinear behaviour in complex water resources infrastructure systems. Outputs from the system dynamics simulation model include the values of variables at each time step in the simulation. Such information gives insight into the system response and recovery, which can be assessed using dynamic resilience.

To move away from static estimates of risk towards dynamic estimates of system performance before, during and after the occurrence of an undesirable event, a new approach is necessary that deals with system performance over time. The main recommendation of this discussion is to implement systems dynamics simulation as a foundation for the assessment of complex water infrastructure system resilience. The methodology involves utilizing simulation to generate change in infrastructure system performance as a consequence of a wide range of operating conditions. The simulation outputs provide information that can be used to estimate dynamic system resilience by assessing the change in system performance and its adaptive capacity.

2.5 Quantitative resilience assessment

The quantitative dynamic resilience measure, first introduced by [12] following [13], is defined by Simonovic and Peck [12] as *«the ability of a system and its component parts to anticipate, absorb, accommodate or recover from the effects of a system disruption in a timely and efficient manner, including through ensuring the preservation, restoration or improvement of its essential basic structures and functions»*. Resilience defined in this way (a) performs well during periods without system disturbance, and (b) captures the system's adaptation ability to respond during periods when the system is under disturbance. Quantitative resilience as the system characteristic applies to built and natural physical environments; social and economic systems; and institutions and organizations. Resilience is founded on two basic concepts: *system performance level and its adaptive capacity*. Figure 2 illustrates generic system performance under disturbing events. For example, let us consider water supply reservoir release under reduced inflow. System disturbance, in this case, is a reduced amount of inflow. The performance can be water supply reservoir release amount expressed in flow units (m^3/s). Generic system performance used for the quantification of dynamic resilience is shown in Figure 2a (after [12] and [14]). Application of numerous adaptation measures results in the change of the performance curve shape (two options presented as (a) and (b) are presented in Figure 2 using dashed lines). For example, proactive measures of water supply-demand control may result in the curve (a) and reactive measures of supplemental groundwater supply may result in the curve (b).

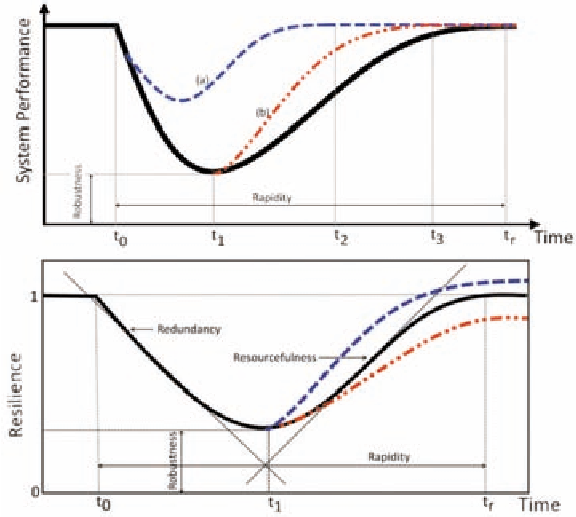

Fig. 2. A generic representation of (a) system performance; (b) system resilience.

While traditional risk-based engineering focuses on reducing pre-disturbance vulnerabilities, resilience is realized by considering adaptation options that allow the system to adapt to changing conditions and increase the physical, social, and economic sectors' ability to maintain some level of performance during the disturbance. Change of system performance forms the basis for quantification of system resilience. Notation in Figure 2 includes: t_0 – the time of the beginning of the disturbance; t_1 – the time of the end of system disturbance; t_r – the time of the end of the recovery period. In the mathematical form, the integral of the area under the performance curve in Figure 2a (the remaining performance after the distirbance) is defined as system resilience. After normalization, it is represented as a curve in Figure 2b. Normalization eliminates the units of system performance and substitutes them with units of resilience between 0 and 1.

The calculation, using system dynamics simulation, of resilience is performed at each point in time by solving the following differential equation:

$$\frac{\partial r(t)}{\partial t} = AC(t) - P(t) \tag{1}$$

where AC stands for adaptive capacity; $r(t)$ for system resilience; and $P(t)$ for system performance. The solid black line in Figure 2b represents the consequence of integrated system performance under the disturbance with current system adaptation capacity.

The introduction of a dynamic measure of resilience into performance-based water resources engineering offers additional information that can be of value in the decision-making process. The shape of the resilience curve is defined by the system adaptive capacity, and it provides additional insights into system robustness, redundancy, resourcefulness and rapidity. They are graphically presented Figure 2b. The slope of the declining resilience curve section (time $t_0 < t < t_1$; slope $P_t - SP_{t0} / t - t_0$) defines system *redundancy* (defined as the inclusion of extra system components which are not firmly necessary to maintain system functioning, in case of failure of other components). The slope of the rising section of the resilience curve (time $t_1 < t < t_r$; slope $P_t - P_{tr} / t - t_r$) offers information about system *resourcefulness* (defined as the ability to mobilize resources necessary to overcome difficulties caused by system disruption). *Robustness* of the system (defined as the minimum value of the remaining system performance after the disturbance) and *rapidity* (duration of system performance under the disturbance) are clearly illustrated with the system resilience level at time t_1 and difference in time between t_0 and t_r, respectively. Implementation of numerous adaptation options results in the change of resilience curve shape.

The performance-based water resources engineering approach proposed in this paper rests on the power of system simulation and quantitative dynamic resilience. The simulation approach is a tool for the analysis of water resources system performance. The use of resilience as a metric for the assessment of system response to changing conditions provides a much more complete insight into the characteristics of the system structure and system response, allowing for a more meaningful investigation of system vulnerabilities.

3. Conclusions

The systems approaches to managing water resources provide proven strategies for more efficient resolution of water resources management challenges imposed by global change. Looking forward from the current practice, this paper explores the future opportunities based on the advances in systems theory that can, on a broader scale, majorly transform the management of water resources. Performance-based engineering is proposed as the replacement for the current prescriptive approach based on the risk-informed engineering standards, which are very difficult to implement in the presence of global change (especially climate change).

Performance-based engineering is the design, evaluation and construction of engineered systems that meet the uncertain future demands of owner-users and nature. It is an approach to the analysis of any complex system. The performance-based water resources engineering offers an opportunity to heighten the role of systems science, especially simulation, combined with quantitative resilience assessment to address various sources of uncertainty. The implementation of the performance-based water resources engineering is presented as a five-step approach that is taking advantage of system simulation and assessment of quantitative resilience. A performance-based engineering approach is suggested to use the system dynamics simulation as defined earlier in the paper. Evaluation of system performance obtained by simulation is to be done using the quantitative dynamic resilience measure.

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