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Systems Approach to Management of Water Resources—Toward Performance Based Water Resources Engineering

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Abstract: Global change, that results from population growth, global warming and land use change (especially rapid urbanization), is directly affecting the complexity of water resources management problems and the uncertainty to which they are exposed. Both, the complexity and the uncertainty, are the result of dynamic interactions between multiple system elements within three major systems: (i) the physical environment; (ii) the social environment; and (iii) the constructed infrastructure environment including pipes, roads, bridges, buildings, and other components. Recent trends in dealing with complex water resources systems include consideration of the whole region being affected, explicit incorporation of all costs and benefits, development of a large number of alternative solutions, and the active (early) involvement of all stakeholders in the decision-making. Systems approaches based on simulation, optimization, and multi-objective analyses, in deterministic, stochastic and fuzzy forms, have demonstrated in the last half of last century, a great success in supporting effective water resources management. This paper explores the future opportunities that will utilize advancements in systems theory that might transform management of water resources on a broader scale. The paper presents performance-based water resources engineering as a methodological framework to extend the role of the systems approach in improved sustainable water resources management under changing conditions (with special consideration given to rapid climate destabilization). An illustrative example of a water supply network management under changing conditions is used to convey the basic principles of performance-based water resources engineering methodology.

Keywords: water resources systems; performance-based engineering; simulation; resilience

1. Introduction

Two paradigms are identified by Simonovic [1] as 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 modeling tools (decreases with time), in an environment characterized by continuous, rapid technological development (sharp increase in development over time). The illustrative presentation of the complexity paradigm is shown in Figure 1a. The extension of temporal and spatial scales characterizing contemporary water resources management problems leads to an increase in the complexity of decision-making processes (which could be measured using a number of state variables on the vertical axis in Figure 1a). The evolution of systems analysis with increasing computational power (expressed for example using computational time required for the solution of a problem on the vertical axis in Figure 1a) results in more complex analytical tools being replaced by simpler and more robust search tools and very often by simple simulation (assessed using a number of mathematical relationships on the vertical axis in Figure 1a).

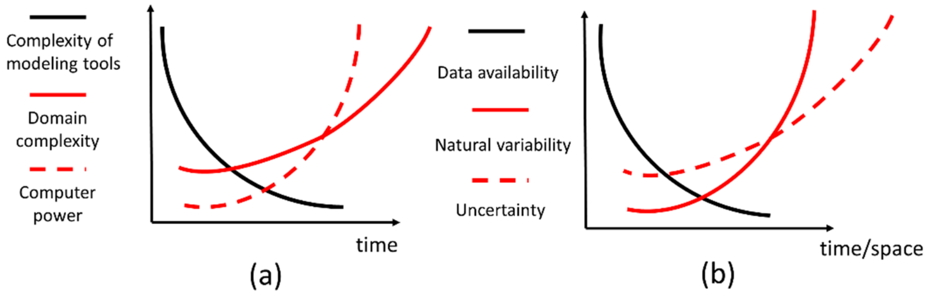

Figure 1. Illustration of the (**a**) complexity and (**b**) uncertainty paradigms (after [1]).

The second paradigm deals with the water resources-related data availability (represented for example by the number of observation stations on the vertical axis in Figure 1b) and the natural variability of the domain variables (for example measured by the range of values that a particular state variable can take on the vertical axis in Figure 1b) in time and space that affect the uncertainty (possibly expressed by the statistical dispersion of the values attributed to a measured quantity on the vertical axis in Figure 1b) of water resources management decision-making (Figure 1b). Data necessary for management of water resources are costly and collected by various agencies. The financial constraints of government agencies that are responsible for the collection of water-related data have resulted in reduction of data collection programs in many countries."

The traditional understanding of water resources management is that it is the management of water resources [2–5]. But the language behind the concept is simpler since there is a set of complex interactions between the water resources, people and the environment that they all share. The two paradigms call for a question: What are we managing? We try to manage environments (water, land, air, etc.). We keep try to manage the behavior of people 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 the way water resources are interacting 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, the interactions between the four subsystems must be appropriately mapped.

Individuals are the players in organizations and society and affect the way they behave. As individual decision-makers, they have a direct role in the use and management of water resources. Organizations are used by individuals as an instrument to obtain outcomes that they cannot produce. The structure of the organizations is developed to realize a particular set of goals. Structure of the organizations defines resource and information flows and governs the organizational behavior. Individuals and organizations are subsets of society. The society is a system that encompasses the relationships between people, the rules of behavior and the mechanisms that are used to regulate it. Societies are nested within the environment. The environment includes concrete elements such as water, air, raw materials, natural systems, as well as the universe of ideas including the expectation of future water shortages and future global change impacts that define concern for sustainable water resources management.

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 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.

Each subsystem relies on other subsystems and on the environment for its resources. The physical environment applies passive pressure on the subsystems and can limit action by exhausting resources. In that way, the resources can become more valuable (i.e., climate change).

Each of the subsystems utilizes information to make decisions on communicating with other subsystems and the environment. In the case where flows of information from outside of the subsystem are not available, it must rely on its own knowledge that increases the risk that the subsystem may lose connections with the other subsystems.

Since data does not have meaning by itself, interpretation between information and meaning is necessary and provided by values. They provide meaning to flows of information. Flows are then used to determine resource use by each subsystem. Value systems are embedded in the culture of society and organizations. They determine what resources individuals, organizations and societies need. Using value systems, the interpretation of information is provided and behavior of the subsystems is determined.

The decision-making choice is always related to the availability of resources. Feedback information on the availability of resources signals to the decision-maker (individuals, organizations, or society) the subsystem's response to the implemented management procedures. According to [6,7], the most effective options for sustainable water resources management are those that condition access to resources. Each subsystem is using different procedures (combination of options and various interactions) to maximize its access to resources.

The next section of the paper will briefly review the success of the systems approach in management of water resources systems up to now. It is followed by identifying one view of the future that presents the concept of performance-based water resources engineering. The following section illustrates the performance-based concept using an example of a water supply network management under changing conditions. The paper ends with the conclusions.

Systems Approach to Management of Water Resources—A Success Story

During the past five decades, since the introduction of the water resources systems analysis within the Harvard Water Program [8], we have witnessed a great evolution in water resources systems management [9–13]. Three of the characteristics of this evolution are noted in particular [12].

First—*the application of the systems approach to complex water management problems.* It has been recognized as the most important advance in the field of water resources management by providing an improved basis for decision-making.

Second—*transformation of attitude by the water resources management community towards environmental concerns.* The past five decades have brought many examples of initiatives taken for environmental assessment and planning, as well as significant investment in environmental technologies for recovering or removing pollutants.

Third—*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 (a) changing management objectives and (b) obtaining deeper understanding of the complicated inter-relationships between existing ecological, economic and social issues. Brown et al. [13] advocate for water resources systems analysis as a conceptual framework for sustainable management of water resources.

The evolution of water resources systems management is occurring in the context of rapid development of information technology which moved the computer directly into knowledge processing as a partner for more effective decision-making.

Let me repeat the basic definition of a system here. Simonovic [12] 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).

Let me summarize the current state of the water resources systems approach:

(i) A very reachable portfolio of applications and the evolution of water resources systems approach today offer a scientific interdisciplinary context for dealing with the complex practical issues of water management and prediction of the water resources future. Together they form the basis for a sustainable water management necessary to address the global water challenges of this century.

(ii) Systems approach is helping all those who are responsible for water resources management to organize water related information in order to distinguish between the noise and important information and improve the decision-making.

(iii) The data necessary to understand resource flows and the larger water resources management setting are being identified in close collaboration with the general public to understand the relationships between human behavior and environmental and economic impacts of water resources management decisions [2].

(iv) The systems approach is helping the improvement of water resources planning and forecasting. Clear articulation of assumptions, use of models, identification of feedback relationships, and monitoring system behavior can help decision-makers better anticipate future conditions and make smarter management decisions.

(v) The tools of systems analysis (simulation, optimization and multi-objective analysis) are helping to improve the quality of water resources related decision-making [4]. They provide decision-makers with the information for full understanding of the dynamics that direct the interactions between the social (people and economy), natural (water, land and air) and constructed systems (buildings, roads, bridges etc.).

(vi) The systems approach is contributing to the improvement in human behavior by using systems thinking. It enables everyone involved in water resources management to see themselves as a group of actors in making decisions that involve feedback, developing situations, and advancing the awareness of producing one outcome or another [3].

(vii) The systems approach today leads to greater practical and safer risk management policies for the simple reason that most water resources systems are nonlinear and therefore hard to predict [5]. Water resources management requires smarter and more adaptable participants, capable of learning and being able to anticipate changing conditions.

A success reached today must contribute to further evolution of the water resources systems approach to successfully address the serious water challenges faced by society. The future activities must continue: to deal with the most difficult 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 insure that ranks of water resources systems specialists will not decline (the opposite has been documented by [13]).

2. One View of the Future-Performance-Based Water Eesources Engineering

Performance-based engineering is dealing with the design, evaluation and building of engineered systems that meet—as economically as possible—the uncertain future demands of people and nature in the most economically efficient way. It is an approach to the analysis of any complex system. A system managed in this way should meet quantitative or predictable performance requirements, such as demand load or economic efficiency, without a specific 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 main 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 lifecycle considerations rather than a single criterion alone, such as construction costs for example.

Much of the current research on performance-based engineering focuses on earthquakes [14,15]. Performance-based engineering offers opportunities for better management of water resource systems faster and more cost effectively. It can be implemented for 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 the design and construction of engineered water resources systems. Adoption of performance-based engineering requires major changes in practice and education of water resources engineers. Perhaps most important is a shift away from the dependence on empirical 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 behavior.

2.1. Challenges

Water infrastructure facilities are designed and managed to withstand demands imposed by their service requirements and by 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 levels of performance in the built environment beyond what currently is provided by prescriptive standards and to better meet public expectations. This discussion introduces a performance-based engineering approach as the replacement for traditional use of prescriptive standards. Performance-based engineering offers an opportunity for heightening the role of simulation 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 [16].

According to IPCC [17] a large proportion (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 longer periods of low flows exacerbate many forms of water pollution, with impacts on ecosystems, human health, water infrastructure system dependability and operating costs [17].

The presence of 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 in nature. This assumption is not defensible when global change effects are considered. Furthermore, the uncertainties in global change effects projected over the 21st century are extremely large. Finally, achieving the necessary consensus on global change effects 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 nonstationarity in water-related natural hazard occurrence and intensity that arises as a consequence of global change? (ii) How should these uncertainties be integrated in time-dependent infrastructure performance analysis to estimate future behavior and to demonstrate compliance with performance objectives? (iii) How should we deal with lifecycle 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 modeling 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 in nature and the shortcomings of traditional prescriptive approaches to design, planning and operations are known [18]. Research is underway to extend the performance-based approach to water resources engineering (including hazards such as 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.

Main 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. Current, prescriptive water resources engineering frameworks rely on risk analysis tools for modeling uncertainties associated with water resources 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 for 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 multiple system disturbance events; (iii) possible utilization of nonlinear analysis; (iv) implementation of detailed local acceptance criteria; and (v) joint consideration of system structural and nonstructural components.

The performance-based water resources engineering process is illustrated in Figure 2. It starts with the identification of system disturbance as a consequence of global change. System disturbance could be a flood, an extreme precipitation event or a long-term drought event, just to name a few. Selection of performance criteria follows, that should allow for measurement of impacts that system disturbance may have on the system. For example, a performance criterion could be area inundated by flood waters, or the total damage from the drought event, and similar. Each system performance can be measured in its own units. The following step includes identification of alternative options (plans/designs/operations strategies) for responding to the disturbance. Options may include structural solutions (flood protection infrastructure for example) and nonstructural measures (change of regulations for example) alone or combined together. System performance capability is then tested by doing calculation of system performance in response to selected disturbance and alternative response according to a performance criterion. A system simulation approach is recommended for the implementation at this stage. It is a preferable approach because it does not pose any limitations for the complexity of system structure description. Calculated system performance is subject to multiple uncertainties. Risk approach could be one way to assess the system performance. However, the risk approach has many deficiencies. It is static (in time and space). It includes difficulties in assessing probability of extreme events and integrating physical, social, economic and ecological concerns at the same time. Here, it is proposed to integrate 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.

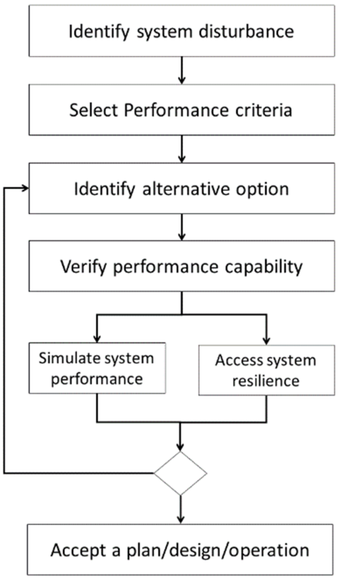

Figure 2. Performance-based engineering process.

The performance-based water resources engineering process in Figure 2 can be implemented (i) in an iterative way by examining alternative options (plans/designs/operational strategies) ahead of system disturbance or (ii) in a real-time by responding to system disturbance and managing recovery from it. Verification of system performance capability is done by combined use of simulation and quantitative resilience assessment (see Figure 2). More details on the tools for supporting the performance-based water resources engineering follow.

2.4. Simulation

The classical simulation approach involves understanding of system structure through decomposition of the problem that helps in the system description. The simulation process starts with 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.

The performance-based engineering approach can take advantage of system dynamics simulation, which is defined by Simonovic [12] "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 behavior. 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 change of system behavior over time. A dynamic system is a system in which the variables interact to generate changes over time. The way in which the system elements, or variables, vary over time is referred to as the system behavior. System dynamics simulation is not new to water resources engineering. Multiple applications are documented in the literature (for example see [7]).

System dynamics simulation lends itself well to the assessment of engineering system performance over time. Complex systems can be easily built using object-oriented system dynamics simulation software packages that allow for 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 investigation of nonlinear behavior 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.

In order 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 assessing complex water infrastructure system resilience. The methodology involves the utilization of 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 [19], followed by [20], is defined by Simonovic and Peck [19] 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 is defined in this way: (a) performs well during periods without system disturbance, and (b) captures a system's adaptation ability to respond during periods when the system is under disturbance. Quantitative resilience is the system characteristic applicable 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 3 illustrates generic system performance under a disturbing event. For example, let us consider water supply reservoir release under reduced inflow. System disturbance in this case is the reduced amount of inflow. The performance can be the 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 3 (after [19] and [21]). 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 3 using dashed lines). For example, proactive measures of water supply demand control may result in curve (a), and reactive measures of ground water supplemental supply may result in curve (b). It should be noted that changing the amount of supplemental supply may place curve (b) at a different location.

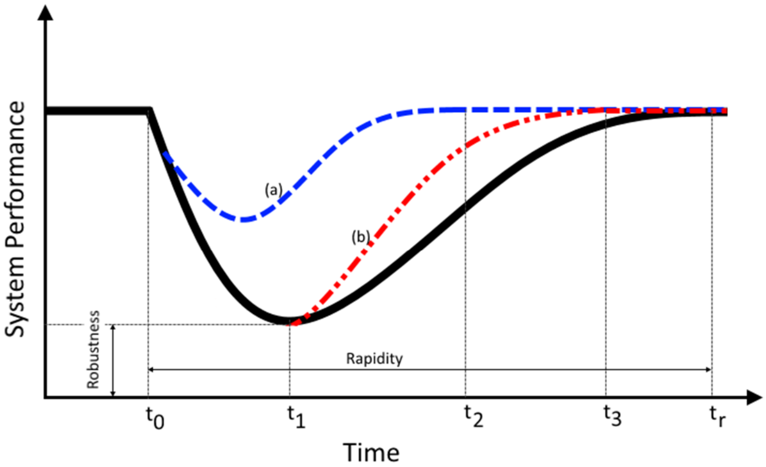

Figure 3. Generic representation of system performance (after [19]).

While traditional risk-based engineering focuses on the reduction of predisturbance vulnerabilities, resilience is realized by considering adaptation options that allow for the system to adapt to changing conditions and increase the ability of the physical, social, economic sectors to maintain some level of performance during the disturbance.

Change of system performance forms the basis for quantification of system resilience. The transformation of system performance into system resilience is captured in Figure 4. Illustration in Figure 4 is not related to the simple example from Figure 3. Notation in Figure 4 includes: t_0—time of the the beginning of the disturbance; t_1—time of the end of system disturbance; t_r—time of the end of the recovery period; $P(t)$—system performance; P_0—initial system performance level; $P_{e'}(t)$—degraded ending system performance level; $P_{e''}(t)$—improved ending system performance level; the area between P_0 and performance line (full black line) $P(t)$ represents the loss of system performance; and the shaded area under the performance line $P(t)$ denotes the system resilience.

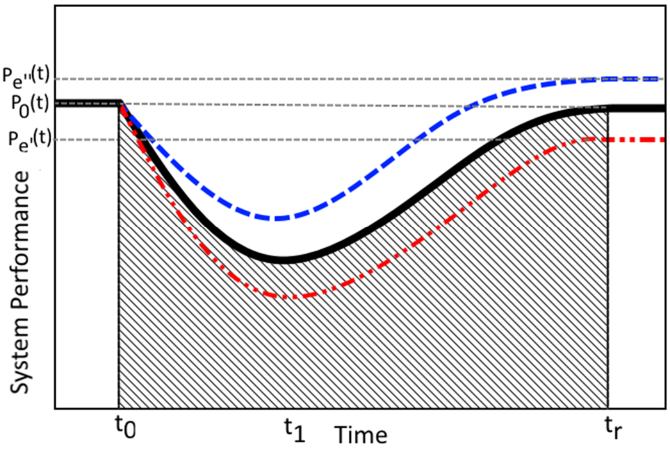

Figure 4. Illustration of transformation of system performance into resilience.

In mathematical form, the loss of performance *(ρ)* shown in Figure 4 as the area between the start of the system disruption event (t_0) and the end of the disturbance recovery process (t_r):

$$\rho(t) = \int_{t_0}^{t} [P_0 - P(\tau)]d\tau,\ t \in [t_0, t_r] \tag{1}$$

where $P(\tau)$ represents degree of system performance and P_0 is the initial system performance level. The remaining system performance (shaded area in Figure 4) is defined as system resilience $r(t)$, and is obtained by normalizing the value of *(ρ)*:

$$r(t) = 1 - \left(\frac{\rho(t)}{P_0 \times_t (t - t_0)}\right) \tag{2}$$

Normalization eliminates the units of system performance and substitutes them with units of resilience between 0 and 1. Generic presentation of resilience is provided in Figure 5 (this illustration is also not related to the simple example from Figure 3).

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

$$\frac{\partial r(t)}{\partial t} = AC(t) - P(t) \tag{3}$$

where *AC* stands for adaptive capacity. The solid black line in Figure 5 represents the consequence of integrated system performance (shaded area in Figure 4) under the disturbance with current system adaptation capacity. There are three conceivable outcomes in resilience simulation: (i) return of resilience value to predisturbance level (value of 1), captured by the solid black line in Figure 5; (ii) improved resilience value compared to predisturbance level (ending system performance level $\mathrm{P}_{e''}$ (t), resilience value > 1), shown by the blue dashed line in Figure 5; or (iii) declined resilience value compared to predisturbance level (ending system performance level $P_{e'}(t)$, value < 1), shown by the dashed and dotted red line in Figure 5.

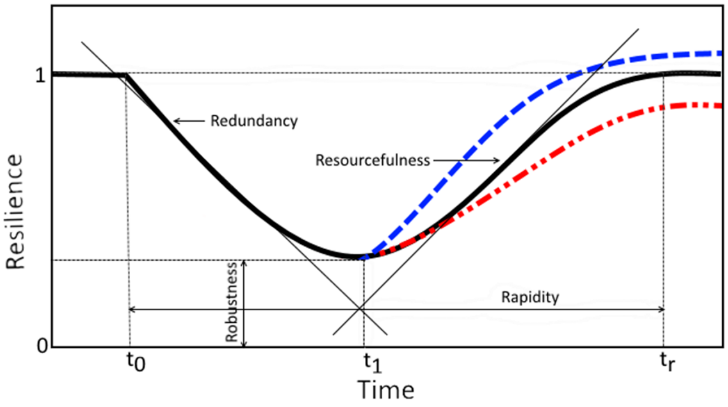

Figure 5. Generic representation of system resilience.

Introduction of 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 5. The slope of the declining resilience curve section (time $t_0 < t < t_1$; slope $P_t - SP_{t0}/t\text{-}t_0$) 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 $P_t\text{-}P_{tr}/t\text{-}t_r$) 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 actions 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 analyses of water resources system performance. 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. Various planning/design/operations options including capital upgrades and maintenance could be compared by using resilience to measure the loss of performance due to undesirable events, system response time and level of performance after recovery. Overall system resilience can be assessed by looking at the resilience of individual system components and taking into consideration their interactions.

3. An Illustrative Example

A simplified water supply network problem, modified after Kong et al. [22], is selected only as an illustrative application of the performance-based water resources engineering methodology. Water supply is one of the essential services that provides support for the economic productivity, security, and population quality of life. There are practical links between disaster risk management, global change adaptation and sustainable development leading to the reduction of disaster risk and re-enforcing resilience as a new development paradigm. Both, system disturbance types, natural (such as floods, severe weather, earthquakes, hurricanes, and similar) or human caused (such as terrorist threats, chemical spills, and similar), always affect geographically restricted areas. In this example, a geographical location of interest (where the water supply network components are located) is presented using the cell space method. The water supply network model is founded on the network theory. The model of a system includes two basic components, nodes and edges. Water supply network is represented as a complex system of intakes, reservoirs, pumping stations, pipelines, conduits, and other components by which water is collected, cleaned, stored, and distributed to an urban area. In this network, intakes, reservoirs and pumping stations are denoted as nodes with different characteristics and water distribution pipes, and conduits are denoted as edges. Water supply network is a directed network, as the water flows from an intake to pumping stations and storage facilities through distribution pipes. In the directed networks, the downstream nodes and edges will not be able to operate unless all the upstream nodes and edges function normally. A detailed mathematical simulation model of network structure and dynamic behavior is available in [22].

The network example system includes 16 (4 × 4) cells shown in Figure 6. To simplify the network model simulation, one node is assumed to exist in every cell, as shown in Figure 6. Blue color filled nodes are representing main components of the water supply network, such as intakes, treatment plants, etc. Blue color empty nodes represent storage facilities such as pump stations, reservoirs, etc. The edges are used for representation of water transmission pipes and conduits. The example network includes 16 main components, storage facilities and pump stations, and 17 water transmission pipes and conduits.

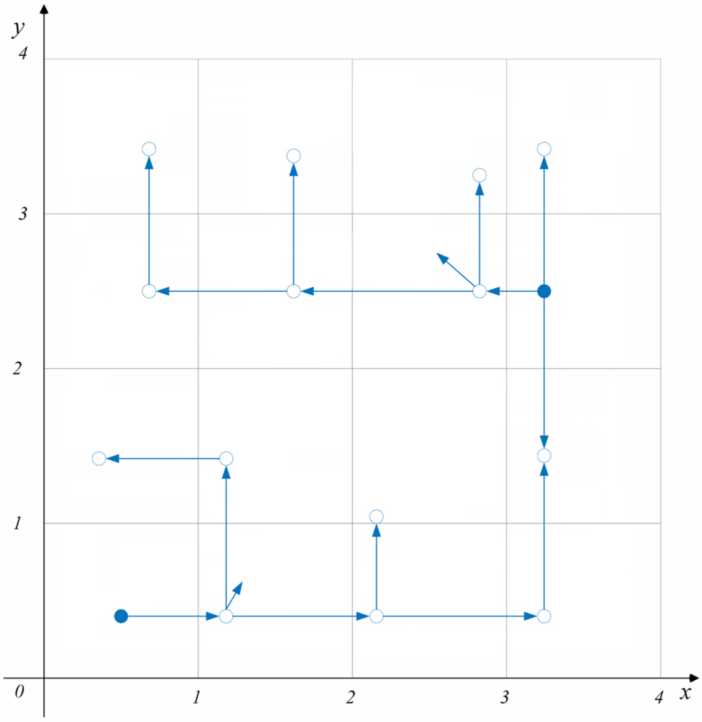

Figure 6. Example water supply network.

The problem to be addressed in this illustrative example is the problem of network recovery after a major flood disaster. In the network theory, disturbance to the infrastructure system is always captured by the removal of nodes and/or edges from the system network. It is assumed that components of the water supply network layer in the same cell are affected simultaneously. Fluvial flooding develops slowly and can last for days and weeks. The water usually spreads over a large area and inundates infrastructure network components located in the floodplains.

Following the performance-based engineering process (see Figure 2) the *first step* is the identification of disturbance. It is assumed that (i) flood occurs once, (ii) affects a large area, and (iii) lasts over a longer time. Many water supply network elements located in the floodplains are affected, due to submergence. In this example, water supply network elements located in the four bottom and four right cells (see Figure 6), with coordinates $\{0 \le x \le 4, 0 \le y \le 1\} \cup \{3 \le x \le 4, 1 \le y \le 4\}$, are assumed to be affected. The selected flood could be a historical event or any statistical flood event. The whole process can be repeated for as many disturbance events as the user would like to investigate.

In the *second* step performance criteria is selected as a simple state of the water supply network. To simplify the simulation, the network is considered to be in one of two states: function and malfunction—denoted with the value of 1 or 0 as shown in Figure 7.

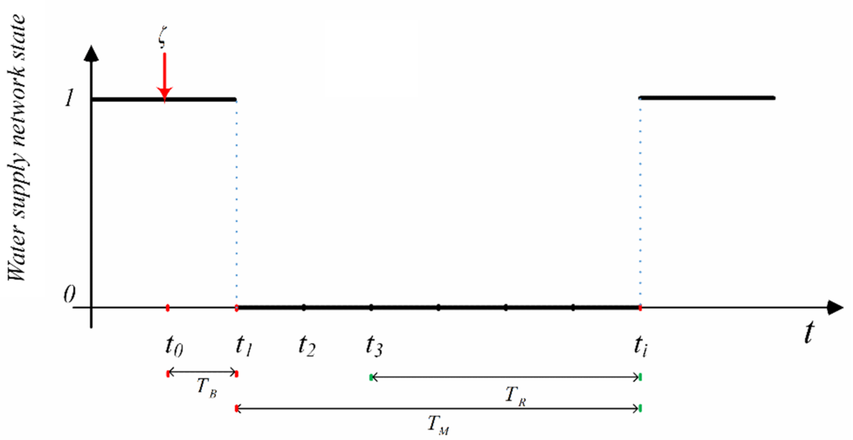

Figure 7. Performance dynamics of the example water supply network after a large flood.

The notation used in Figure 7 includes: t_0—time of occurrence of disturbing event (assumed flood in this case); T_B—buffering time; T_R—repair time; T_M—network malfunction time.

In the *third step* a set of five repair options taken from [22] is being identified[: (i) first repair components that failed first (*RS-FF*)—this approach is usually used during the emergency when time and space may not be available for a more comprehensive response; (ii) first repair components that failed last (*RS-FL*); (iii) first repair important components independently (*RS-IE*)—this strategy is used to maximize the benefits of a water supply sector in an interconnected case (for example when water supply is connected to electricity supply network, information network, etc.); (iv) first repair the obviously dependent components (*RS-OD*)—this approach considers obvious or physical interdependencies of infrastructure elements (for example, node–node, node–edge and node–edge-cluster dependencies); and (v) first repair the hidden dependent elements (*RS-HD*)—the fifth repair approach takes interdependencies between the water supply network and other networks that water may be connected to (usually illustrated as node–edge-path dependencies).

The *fourth step* of performance-based engineering process involves verification of system capability by simulating system performance and performing resilience assessment. The example water supply network system performance simulation is performed following the flow diagram in Figure 8. System performance is assessed for all five response strategies. General water supply system simulation (in Figure 8) is adopted to all five response strategies (details are available in Kong et al., 2019).

Simulation results, presented in Figure 9, clearly show the difference in system performance as a function of the response strategy. The black line (P_0) in Figure 9 shows system performance without any response. The other five lines are describing system performance according to the selected five response strategies (see the Figure 9 legend). Water supply network performance under *RS-OD* and *RS-HD* outperforms performance under other response strategies, and *RS-FL* and *RS-IE* result in the worst performance. Simulation results under all five strategies confirm that in this example case, the water supply system cannot exceed the initial performance level after the flood. The possible explanation for these results is that no water supply network system improvements can be built in a short period of time. Therefore, the additional resilience characteristic of rapidity and the end of recovery time are determined as the time when the system performance recovers to the preflood performance level.

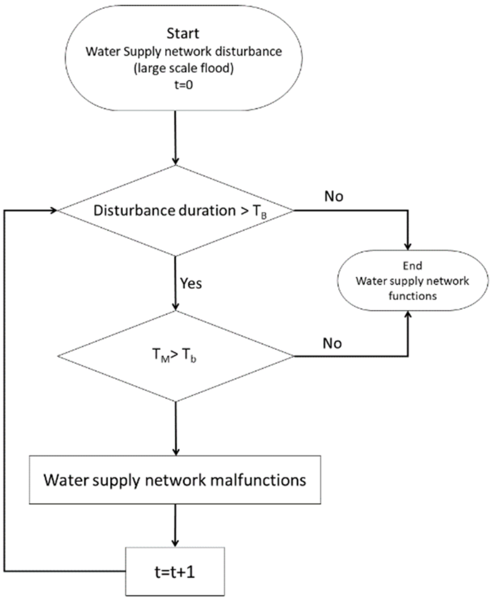

Figure 8. Flow diagram of the water supply network performance simulation under a large flood.

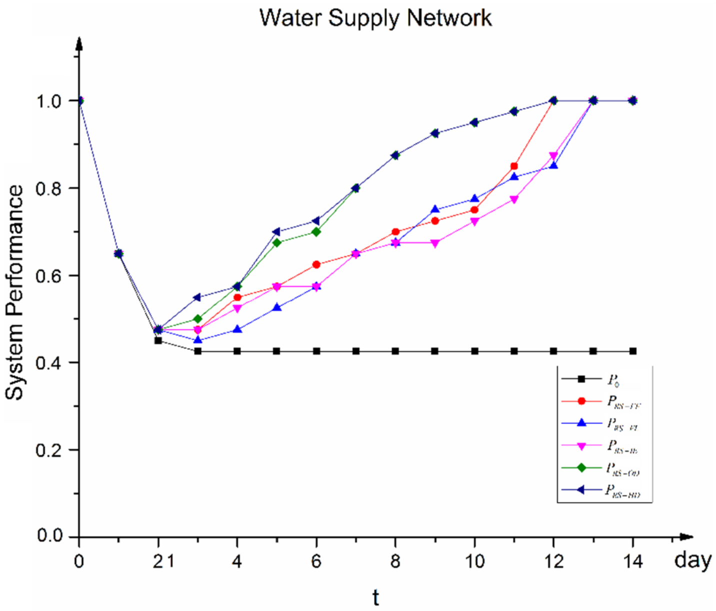

Figure 9. Performance of the example water supply network after a large flood under five response strategies.

The resilience of the example water supply network under various response options is calculated using a modified Equation (2), adjusted for the network systems [22].

The final, *fifth step*, of the performance-based water resources engineering includes the decision-making based on the results of system simulation and resilience assessment. The example water supply network resilience values follow the system performance and are shown in Figure 10. Resilience is the integral of the system adaptive capacity. The higher value, the more resilient the system. As shown by Equations (1) and (2), the adaptive capacity, *AC*, is a function of response option *RS*. Application of different response strategies *RS* results in different system resilience of the same water supply network. In the example case, the resilience value under *RS-HD* is the highest. As the number of destroyed elements is always lower than the number of malfunctioning elements. The rapidity (recovery time) under *RS-HD* is longer than the recovery time under *RS-OD*. If the average resilience during the recovery time is compared, the *RS-HD* approach results in a higher resilience than the *RS-OD*, and the recovery time (rapidity) of the latter is longer. This phenomenon is common for water supply networks that include multiple interdependencies. The results clearly show that the recovery time (rapidity) should be taken into consideration for a more wide-ranging decision making.

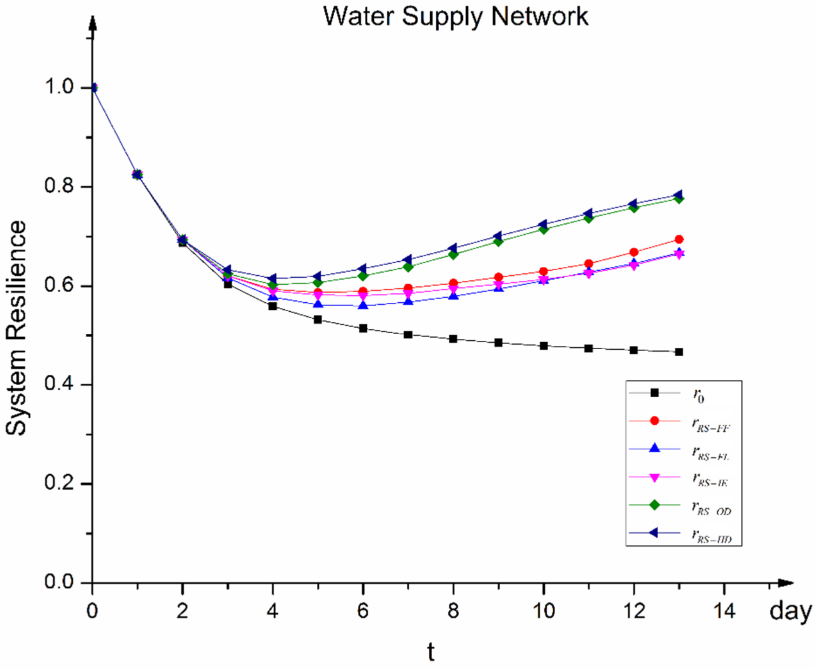

Figure 10. Resilience of the example water supply network after a large flood under five response strategies.

The application of performance-based analysis in the example case shows that from the five proposed repair options, two (*RS-HD* and *RS-OD*) are clearly outperforming the others. Both of them include more interdependencies in the system recovery process. They are recommended for application and further enhancement of the decision-making that can be done by including other characteristics of the quantitative resilience measure, as for example, rapidity.

4. 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 management of water resources. The 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 for heightening the role of systems science, especially simulation, combined with quantitative resilience assessment for addressing 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. Performance-based engineering approach is suggested for use in system dynamics simulation as defined earlier in the paper. Assessment of system performance obtained by simulation is to be done using the quantitative dynamic resilience measure.

A simple water supply network problem is selected as an illustrative application of the performance-based water resources engineering. The problem addressed in this illustrative example is the problem of water supply network recovery after a major flood disaster. A set of five network repair options is evaluated by using network performance simulation and resilience assessment.

The performance-based water resources engineering can be implemented in solving complex planning, design and operations problems. It is identified as a methodological framework to improve water resources management in the face of rapid climate change so that sustainability becomes the standard, not the infrequent, success story.

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References

1. Simonovic, S.P. *Systems Approach to Management of Disasters: Methods and Applications*; John Wiley & Sons Inc.: New York, NY, USA, 2011; p. 348. ISBN 978-0-470-52809-9.
2. UN-WWAP (United Nations World Water Assessment Programme). *UN World Water Development Report 1: Water for People, Water for Life*; UNESCO and Berghahn Books: Paris, France; New York, NY, USA; Oxford, UK, 2003.
3. UN-WWAP. *UN World Water Development Report 2: Water, a Shared Responsibility*; UNESCO and Berghahn Books: Paris, France; New York, NY, USA; Oxford, UK, 2006.
4. UN-WWAP. *UN World Water Development Report 3: Water in a Changing World*; UNESCO: Paris, France; Earthscan: London, UK, 2009.
5. UN-WWAP. *UN World Water Development Report 4: Managing Water under Uncertainty and Risk*; UNESCO: Paris, France, 2012.
6. Martin, P. Just What are We Trying to Manage, Anyway? Profit Foundation Pty Ltd.: Melbourne, Australia, 2000.
7. Simonovic, S.P. Water Resources Management: A Systems View. *Water Front* **2009**, *1*, 12–13.
8. Maass, A.; Hufschmidt, M.; Dorfman, R.; Thomas, H.; Marglin, S.; Fair, G. *Design of Water-Resource Systems: New Techniques for Relating Economic Objectives, Engineering Analysis, and Governmental Planning*; Harvard Univ. Press: Cambridge, MA, USA, 1962.
9. Loucks, D.P.; Stedinger, J.R.; Haith, D.A. *Water Resources Systems Planning and Analysis*; Prentice Hall: Englewood Cliffs, NJ, USA, 1981.
10. Yeh, W.W.G. Reservoir management and operations models: A state-of-the-art review. *Water Resour. Res.* **1985**, *21*, 1797–1818. [CrossRef]
11. Loucks, D.P.; van Beek, E. *Water Resources Systems Planning and Management: An Introduction to Methods, Models and Applications*; UNESCO: Paris, France, 2005; p. 680.
12. Simonovic, S.P. *Managing Water Resources: Methods and Tools for a Systems Approach*; UNESCO: Paris, France; Earthscan James & James: London, UK, 2009; p. 576. ISBN 978-1-84407-554-6.
13. Brown, C.M.; Lund, J.R.; Cai, X.; Reed, P.M.; Zagona, E.A.; Ostfeld, A.; Hall, J.; Characklis, G.W.; Yu, W.; Brekke, L. The future of water resources systems analysis: Toward a scientific framework for sustainable water management. *Water Resour. Res.* **2015**, *51*, 6110–6124. [CrossRef]
14. Porter, K.A. An Overview of PEER's Performance-Based Earthquake Engineering Methodology. In Proceedings of the Ninth International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP9), San Francisco, CA, USA, 6–9 July 2003.
15. FEMA. *Seismic Performance Assessment of Buildings, Volume 1—Methodology*; Federal Emergency Management Agency: Washington, DC, USA, 2012.
16. UNESCO UN-Water. *United Nations World Water Development Report 2020: Water and Climate Change*; UNESCO: Paris, France, 2020; p. 235.

17. IPCC—Intergovernmental Panel on Climate Change. Summary for Policymakers. In *Climate Change, The Physical Science Basis*; Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013.
18. Attar, A.; Lounis, Z. (Eds.) NRC—National Research Council Canada. Climate Change & Codes Implementation. In Proceedings of the International Workshop, Ottawa, ON, Canada, 18–19 January 2017; p. 224.
19. Simonovic, S.P.; Peck, A. Dynamic Resilience to Climate Change Caused Natural Disasters in Coastal Megacities—Quantification Framework. *Br. J. Environ. Climate Change* **2013**, *3*, 378–401. [CrossRef] [PubMed]
20. Cutter, S.L.; Barnes, L.; Berry, M.; Burton, C.; Evans, E.; Tate, E.; Webb, J. A place-based model for understanding community resilience to natural disasters. *Global Environ. Change* **2008**, *18*, 598–606. [CrossRef]
21. Simonovic, S.P. From risk management to quantitative disaster resilience: A paradigm shift. *Int. J. Safety Security Eng.* **2016**, *6*, 85–95. [CrossRef]
22. Kong, J.; Simonovic, S.P.; Zhang, C. Resilience Assessment of Interdependent Infrastructure Systems: A Case Study Based on Different Response Strategies. *Sustainability* **2019**, *11*, 6552. [CrossRef]