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Stiffness and sensitivity criteria and their application to water resources assessment

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ABSTRACT

The performance assessment of water resources systems is a vital step in achieving sustainable development. A complicating factor in performance assessment is the randomness of inputs to water resources systems, such as that present in reservoir inflows. This study proposes weighted vulnerability for performance assessment of water resources systems. Weighted vulnerability is coupled with the application of stiffness and sensitivity criteria to quantify the plausible impacts of variable inputs (either controllable or uncontrollable) on water resources systems. These criteria identify the controllable and uncontrollable inputs with the largest effect on the performance of water resources systems. The application of weighted vulnerability, stiffness, and sensitivity criteria is herein applied to analyze the performance of the Aigoghmoush dam (East Azerbaijan, Iran).

1. Introduction

Water is a valuable economic, ecologic, and social asset (Fernández-Pacheco et al., 2015; Zolghadr-Asli et al., 2017). Overexploitation and careless use of water, however, has compromised the reliability of its supply and degraded its quality in many instances, leading to non-sustainable utilization of water resources (Gawande et al., 2015). The term sustainable development was introduced by the World Conservation Strategy (International Union for Conservation of Nature, 1980). Sustainable development implies economic and institutional development that ensures the continued use of natural resources to meet human needs and aspirations (World Commission on Environment and Development, 1987). Although sustainable development is a concept with potentially outstanding merits it would be remain abstract without quantifiable indicators. The introduction of the Sustainability Index (SI) by Loucks (1997), and, later on, the modified SI by Sandoval-Solis et al. (2010), demonstrated how mathematical and statistical concepts can quantify sustainability of water resources development.

Various criteria have been applied to assess the performance of water resources systems. Such performance criteria are as simple as the average of a specific output (Vigerstøl, 2002) or more complex entities such as the Probability Based Performance Criterion (PBPC) (Texas Commission on Environmental Quality, 2007). It is common to tailor the performance criteria to specific objectives of a water system. For instance, performance criteria have been proposed for water distribution systems (e.g. Tabesh et al., 2001), irrigation and drainage systems (e.g. Zolghadr-Asli et al., 2016), water supply management (e.g. Vilanova et al., 2015), and for water management with touristic objectives (e.g. Gössling, 2015).

Hashimoto et al. (1982a,b) reported the use of risk and reliability applied to the performance of water resources systems (see also, Nam and Choi, 2014). Since the introduction of the PBPC many studies have reviewed this criterion (e.g. Srinivasan et al., 1999), and several authors proposed changes in its definition (Ermini and Ataoui, 2013; Zolghadr-Asli et al., 2016). The most fundamental and common PBPC are resiliency, reliability, and vulnerability (RRV). Reliability is the probability of successful function of a system. Resiliency measures the probability of successful functioning following a system failure. Vulnerability is the severity of failure during an operation horizon. While reliability and resiliency are dimensionless, vulnerability may have dimensionality.

Many of the cited criteria have been applied to evaluate the performance of water resources systems within a specified period of time. These traditional criteria quantify the performance of a system and provide a glance of the system's status to the decision-makers. Yet, they are not ideally suited to inform decision-makers about variables that are the most influential on the state of a water-resources system. Additionally, these criteria are limited in their capacity to quantify the impacts of random inputs to water resources systems. This work introduces a comprehensive definition of vulnerability criteria, called

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weighted vulnerability that improves the traditional definitions of this criterion. Furthermore, this paper introduces a criteria-oriented framework to quantify the impacts of input variables on the performance of water resources systems. The input variables to water resources systems are herein classified as either controllable or uncontrollable inputs. The controllable variables contain inputs that can be managed by human action. The latter group consists of uncontrollable inputs that have a probabilistic nature (e.g., the depth of precipitation, the volume of inflow). The stiffness and sensitivity criteria are herein proposed to quantify the effect of controllable and uncontrollable inputs on water resources management, respectively. This criteria-oriented framework would allow reservoir managers, designers, and operators to quantitatively measure the influence of the input variables on the performance of water resources systems. Such measuring capability constitutes as advancement over previous studies dealing with performance criteria for water resources systems. The stiffness and sensitivity criteria are applied to evaluate the performance of the Aidoghmoush reservoir (East Azerbaijan, Iran) and demonstrate their value of performance assessment of water projects.

2. Methodology

This article proposes a method for quantifying the effect of input sets on the functionality of water systems relying on performance criteria.

2.1. Performance criteria

The flexibility and computational simplicity makes the PBPC and RRV a logic first choice for analysis of water resources systems' performance (Butler et al., 2014).

2.1.1. Reliability

Reliability characterizes the failure frequency of a water system (Klemeš et al., 1981). The reliability of a water resource system can be characterized in three different ways (Kritskiy and Menkel, 1952): 1 – Time-based; 2 – Quantity-based; and 3 – Occurrence-based (annual or monthly).

Time-based reliability (R_{time}) is the total duration during which the system is not in failure over the total duration of an operation horizon. Quantity-based reliability ($R_{quantity}$) is the amount of delivered water over the amount of total downstream water demand. Occurrence-based reliability ($R_{occurrence}$) is the number of non-failure years/months over the total number of years/months of the operation horizon (McMahon et al., 2006; Ashofteh et al., 2013). Occurrence-based reliability is an approximation of time-based reliability (Kritskiy and Menkel, 1952). It can also be defined as the probability of occurrence of successful performance during the operational horizon of a system. The system state (X_t) may be in either of two conditions when defining occurrence-based reliability (annually or monthly): Success (S) or Failure (F). X_t may represent a month in a year or a year depending on which type of occurrence-based reliability is used. Each water-resources system has a unique definition of success or failure. Many water resources systems with the objective of meeting consumers' water demand (D_t) rely on Eq. (1) to categorize the state of a system (Loucks, 1997):

$$X_t = \begin{cases} 1 \text{ if } R_t = D_t \\ 0 \text{ if } R_t < D_t \end{cases} \quad t = 1, 2, ..., T \tag{1}$$

in which, R_t = amount of water supplied in any period t, and T = total number of months or years in the operational horizon. The occurrence-based reliability, denoted by α, is computable with Eq. (2):

$$\alpha = \frac{\sum_{t=1}^{T} X_t}{T} \tag{2}$$

Reliability has a [0,1] range. Maximization of the reliability is a desirable goal in operating a water resources system. It is worth mentioning that this definition of reliability is the complement of the risk, that is, reliability plus risk equals 1 (Hashimoto et al., 1982b).

2.1.2. Resiliency

A resilient system has the capability to adapt to changing conditions (World Health Organization, 2009). Thus, the more resilient a system is, the better its capacity to recover from a failure event and return to a satisfactory state. The resiliency criterion, (γ), is defined as the conditional probability of a successful state event given that a failure event has occurred. Using the failure threshold introduced in Eq. (1), the resiliency of a water-resources system depends on the system state defined by Eq. (1) and is defined as follows:

$$W_t = \begin{cases} 1 \text{ if } X_t = 0 \text{ and } X_{t+1} = 1 \\ 0 \text{ else} \end{cases} \quad t = 1, 2, ..., T \tag{3}$$

Thus, the resiliency is given by:

$$\gamma = \frac{\sum_{t=1}^{T-1} W_t}{T - \sum_{t=1}^{T} X_t} \quad t = 1, 2, ..., T \tag{4}$$

Resiliency has a [0,1] range. Maximizing the resiliency is a desirable objective in operation of a water-resources system.

2.1.3. Vulnerability

Vulnerability measures the severity of failures. A vulnerable system is likely to face frequent and/or severe failures. Vulnerability (υ) of water resources systems can be calculated in several manners, each one having its own merits and drawbacks. Minimizing the vulnerability of a water system is desirable. The function introduced in Eq. (5) can be applied to quantify the severity of failure in water resources systems with the purpose of satisfying downstream water demand (Loucks, 1997):

$$Se_t = D_t - R_t \quad t = 1, 2, ..., T \tag{5}$$

in which, Se_t = severity of the failure in period t.

Hashimoto et al. (1982b) proposed Eq. (6) for vulnerability:

$$\upsilon = \text{Average}[\text{Max}(Se_t)] \quad t = 1, 2, ..., T \tag{6}$$

Eq. (6) proposes to use the average of the maximum severity observed in a sequence of failures during a period containing several sequences of failures as the vulnerability criteria. The vulnerability defined by Eq. (6) is easy to calculate, but it skips failure events in defining sequences of failures, which may introduce errors. Loucks et al. (2005) introduced Eq. (7) for quantifying the vulnerability:

$$\upsilon = \text{Average}(Se_t) \quad t = 1, 2, ..., T \tag{7}$$

Eq. (7) employs the average of all failure severities to represent the vulnerability criterion. The vulnerability as defined by Eq. (7) does not skip failures. Yet, not all the failures damage the system equally. Each failure event should be weighted according to its severity depending on the type and objective of a water-resources system.

Asefa et al. (2014) introduced Eq. (8) to quantify the vulnerability:

$$\upsilon = Max(\sum_{t \in F} Se_t) \quad t = 1, 2, ..., T \tag{8}$$

This method equates vulnerability with the maximum of the summation of failures in each sequence of failures. This method has a similar logic to Eq. (6), and therefore, it has the same disadvantages.

Some of the reviewed methods that have been proposed to quantify the vulnerability avoid using all the failure events [see Eqs. (6) and (8)]. The one that uses all the events [Eq. (7)] weighs the failures equally, as though they harm the system equally. This article introduces a new vulnerability to avoid such shortcomings.

2.1.4. Weighted vulnerability

The weighted vulnerability criterion (v_w) relies on the summation of all the unequally weighted failure events. This criterion does not skip any failure events and assigns weight according to severity, thus avoiding the limitations of other formulas applied to calculate the vulnerability. The weighted vulnerability is given by Eq. (9):

$$v_W = \sum_{t \in F} Se_t \times e_t \tag{9}$$

in which, e_t = the weight of a failure event at time t.

Different methods can be applied to weight each failure event depending on the type and objective of each water resources system. Reservoirs that operate to meet downstream water demands tend to distribute water shortfalls of the system over the operation horizon, thus making them less severe events, rather than dealing with few but catastrophic failure events. To do so, a nonparametric distribution is introduced in Eq. (10) to replace e_t in Eq. (9), yielding the weighted vulnerability written in Eq. (11):

$$e_t = \frac{Se_t}{\sum_{t \in F} Se_t} \quad t = 1, 2, ..., T \tag{10}$$

$$v_W = \sum_{t \in F} \frac{(Se_t)^2}{\sum_{t \in F} Se_t} \tag{11}$$

This method assigns more weight to the more severe failure events, which causes systems with more severe failures to be considered more vulnerable. Eq. (11) prevents severe failure events in the water system by minimizing the weighted vulnerability.

2.1.5. The stiffness criterion

Most water resources systems are designed for long-term operation (Zolghadr-Asli et al., 2016). Knowing which input has the most impact on water resources systems' performance is essential for sound design, operation, planning, and management. Recall input sets to a water system are divided into two classes, controllable and uncontrollable. A controllable input can be planned and managed. The performance of a water system can be steered in the desired direction by manipulating these inputs. In contrast to controllable inputs uncontrollable inputs are of random nature and cannot be managed.

The initial step to calculate the stiffness criteria is to form a mathematical relation between the controllable inputs and the state of the system. A simple model to express the effect of a controllable input on the state of a system is regression analysis. There are different regression methods. Simple regression, for example, is given by Eq. (12), and involves an intercept (β_0) and a slope (β_1). The regression equation converts the independent variables into an approximation of the dependent variable ($\hat{y}$). The difference between the dependent variable (y_t) and the approximation of the dependent variable ($\hat{y}$) is called the prediction deviation (def_t). The best regression line is determined by the method of least squares, leading to:

$$\hat{y}_t = \beta_0 + \beta_1 x_t \tag{12}$$

$$\beta_0 = \frac{\sum y_t}{n} - \beta_1 \frac{\sum x_t}{n} = \bar{y} - \beta_1 \bar{x} \tag{13}$$

in which, $\bar{y}$ = average of the dependent variable and $\bar{x}$ = the average of the independent variable.

$$\beta_1 = \frac{\sum x_t y_t - \frac{\sum x_t \sum y_t}{n}}{\sum x_t^2 - \frac{(\sum x_t)^2}{n}} = \frac{\sigma_{(x,y)}}{\sigma_x^2} \tag{14}$$

where, $\sigma_{(x,y)}$ = covariance of x and y; and σ_x^2 = variance of the independent variable.

The stiffness criterion [$\varphi_{(x,y)}$] is defined as the inverse of the absolute value of the best regression line's slope [$\beta_{1\max(x,y)}$] as shown in Eq. (15):

$$\phi_{(x,y)} = \frac{1}{|\beta_{1\max(x,y)}|} \tag{15}$$

The stiffness criterion has a [0, ∞) range. A large value of the stiffness criterion indicates a small influence of the independent variable (controllable inputs) on the dependent variable [i.e., the performance criteria (or RRV)]. Eq. (15) relies on the absolute values of regression line's slope. This choice makes positive values (positive relation) and negative values (negative relation) comparable. The stiffness criterion permits planners and managers of water resources systems to ascertain the amount of influence of each individual system input on every performance criterion. The stiffness criterion therefore serves as a compass to guide system management towards optimal performance.

2.1.6. Sensitivity criteria

The uncertainty inherent in water systems due to randomness and lack of knowledge affects their response (Simonovic, 1997). Uncontrollable inputs (z) are the main cause of randomness in water resources. They alter the effect of controllable inputs on the performance criteria. For instance, consider the case of the stiffness criteria, which, mathematically, can be expressed by a regression line and can be affected by the randomness of uncontrollable inputs. A sensitivity criterion [$\Omega_{(x,y,z)}$] is herein proposed to quantify the magnitude of uncontrollable inputs. In essence, the stiffness quantifies the effect of controllable inputs (x) on the performance criterion (y), whereas the sensitivity measures the effect of the uncontrollable input (z) on controllable inputs and, thus, on the performance criterion. The formula proposed to calculate sensitivity is given by Eq. (16):

$$\Omega_{(x,y,z)} = \sigma^2_{[\phi_{(x,y)}]} \tag{16}$$

in which, $\sigma^2_{[\phi_{(x,y)}]}$ is equal to the stiffness criterion's variance due to the uncontrollable input z.

The sensitivity criterion [$\Omega_{(x,y,z)}$] measures the impact of the uncontrollable inputs (z) on the performance criteria (y) by using the controllable inputs (x) as an intermediate effect. The greater the sensitivity of a system (higher value of sensitivity criteria), the more drastic its effect on the performance criterion exerted by the uncontrollable inputs. The sensitivity criterion is used to measure which controllable inputs have the least (better) effect introduced by the uncertainties of a water system. It is important to realize that the stiffness and sensitivity criteria are used for comparison purposes only, and their individual values have no other purpose.

2.2. Reservoir modeling

Reservoirs serve numerous functions. They can be used to store water, control flood events, generate energy (hydropower), or serve as recreational facilities (Aboutalebi et al., 2015; Bozorg-Haddad et al., 2015). Basically, the inputs to reservoir models are precipitation (P) and river Inflows (I). Their main outputs are evaporation (E), water releases (R), and reservoir spill (Sp). The difference between inputs and outputs in the reservoir defines the change in reservoir storage (ΔS). The general water balance for a typical reservoir is given in Eq. (17). It is assumed that there are no net exchanges of water between the subsurface and the reservoir:

Water balance equation:

$$I_t - R_t - Sp_t - \left[loss_t \times \left(\frac{A_t + A_{t+1}}{2} \right) \right] = \Delta S \quad t = 1, 2, ..., T \tag{17}$$

Reservoir spill is given by Eq. (18). Eq. (18) produces twice the spill in its numerator when the ending storage in any period exceeds the capacity of the reservoir ($S_{\max}$), which is then divided by 2 to yield the correct value of reservoir spill. On the other hand, Eq. (18) produces a correct spill (equal to zero) when the ending storage is less than S_{max}:

$$Sp_t = \frac{S_t + I_t - R_t - \left[loss_t \times \frac{A_t + A_{t+1}}{2}\right] - S_{max} + \left|S_t + I_t - R_t - \left[loss_t \times \frac{A_t + A_{t+1}}{2}\right] - S_{max}\right|}{2} \quad t = 1, 2, \ldots, T \tag{18}$$

$$loss_t = E_t - P_t \quad t = 1, 2, \ldots, T \tag{19}$$

in which, S_{max} = the capacity of the reservoir, or the maximum volume of water that the reservoir can hold, A_t = The average reservoir's water surface (km^2) during period t, and $loss_t$ = the difference between evaporation depth and precipitation depth in each time period t.

In modeling a reservoir there are also constraints that bound the value of variables. Eqs. (20) and (21) are the physical constraints of the model:

$$S_{min} \leqslant S_t \leqslant S_{max} \quad t = 1, 2, \ldots, T \tag{20}$$

$$0 \leqslant R_t \leqslant D_t \quad t = 1, 2, \ldots, T \tag{21}$$

in which, S_{min} = the dead storage of the reservoir.

3. Case study

The Aidoghmoush River basin is located in East-Azerbaijan, Iran. It is approximately 1800 km^2 in area. The Aidoghmoush River, nearly 80 km long, is the largest river in the basin. The Aidoghmoush dam and a water distribution network were constructed to promote the district's agriculture. The constructed area (reservoir and distribution network) falls within latitudes 47° 33′ to 47° 49′ and longitudes 37° 16′ to 37° 31′. The reservoir's normal level is 1341.5 m above sea level and has a $145.7 \times 10^6\, m^3$ capacity with $8.7 \times 10^6\, m^3$ dead storage. The surface-storage formula is approximately linear with 0.056 slope and 0.798 intercept, as written in Eq. (22):

$$A_t = 0.056 S_t + 0.798 \quad t = 1, 2, \ldots, T \tag{22}$$

The Aidoghmoush irrigation network is mainly supported by the Aidoghmoush reservoir. It is one of the largest irrigation networks of Iran, thus highlighting the Aidoghmoush reservoir's strategic role in terms of water and food security for the region. Several authors have forecasted that the Aidoghmoush system might not be able to support the region's future water demand due to climate change increasing agricultural water demands (Ashofteh et al., 2014, 2016). The Aidoghmoush reservoir's operation was herein modeled from 1991 to 2000. Inflow, water demand, and storage loss during this period are depicted in Fig. 1. The total annual demand and storage loss for each year are constant values equal to $145 \times 10^6\, m^3$ and 1546 mm, respectively. The years 1994 and 1999 are the years with the largest and smallest average annual inflows equal to $23.21 \times 10^6\, m^3$ and $1.49 \times 10^6\, m^3$, respectively.

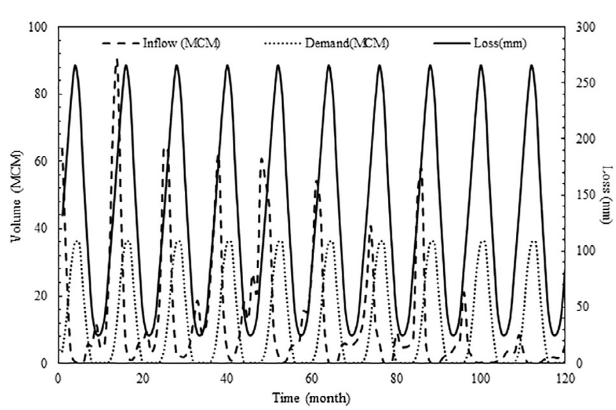

Fig. 1. Time series of inflow, water demand, and storage loss during the years 1991 through 2000.

Reservoir inflow is an uncontrollable input. The sensitivity criteria could help quantify its impact on the performance of the reservoir system in terms of the RRV. The ten years of inflow were classified into 6 different scenarios listed in Table 1. The 1st and 6th scenario, with $18.48 \times 10^6\, m^3$ and $7.64 \times 10^6\, m^3$ have the largest and smallest average annual inflow, respectively.

4. Results and discussion

The stiffness and sensitivity criteria for the Aidoghmoush reservoir were modeled with Eqs. (15) through (22). The reliability, resiliency, and weighted vulnerability served as objective functions (OFs) to calculate an operating policy for the reservoir. The reservoir storage, which is a continuous variable, was herein discretized by 5 MCM (million cubic meter) intervals. The OFs were optimized for each of the defined inflow scenarios. The weighted vulnerability (υ_w) was normalized prior to comparing it with reliability and resiliency. Specifically, the weighted vulnerability values of each inflow scenario were divided by the maximum υ_w of each scenario. This confined the weighted vulnerability to the range between 0% and 100%, and rendered it a dimensionless performance criterion. The calculated performance criteria are shown in Figs. 2 through 4.

For each chart depicted in Figs. 2–4 (18 charts in total), a simple linear regression was fitted to the curves. The stiffness criterion for active storage was calculated for all six inflow scenarios with Eq. (15). The results are summarized in Tables 2–4.

The results listed in Tables 2–4 were used to calculate the sensitivity criterion of the Aidoghmoush reservoir with Eq. (16). The average stiffness criterion was calculated for each of the six inflow scenarios and used as the performance criteria for the reservoir's active storage. The results are listed in Table 5.

This study's results indicate the reliability has the highest value of stiffness and sensitivity criteria due to changes in active storage in the Aidoghmoush reservoir. The weighted vulnerability exhibited the lowest values of stiffness. The resiliency's sensitivity displayed the lowest value. These results indicate that although stiffness and sensitivity are related to one another that does not necessarily imply. They behave equally under similar circumstances.

5. Summary and conclusions

This study introduced and demonstrated a method to quantify the effect of system input on the performance of water resources systems. To do so, the input data sets were categorized into two different classes, namely, controllable and uncontrollable variable. Stiffness criteria were proposed to quantify the magnitude of controllable variables' impacts on the performance of reservoirs. However, uncontrollable inputs may have additional influence on the performance of water resources systems. Thus, sensitivity criteria were introduced to measure the potential impact of such variables on the performances of water resources. Additionally, a modified vulnerability called weighted vulnerability was introduced, whereby a nonparametric distribution served as weight to include all failure events to measure the vulnerability of a system. The Aidoghmoush reservoir was chosen as a case study and its performance was assessed by changes in inflow and reservoir capacity. Stiffness (of reservoir capacity) and sensitivity (of reservoir inflow) criteria were calculated to quantify the impacts of inflow and active storage on system performance.

The values of the stiffness criteria due to changes in the reservoir capacity were in order of decreasing magnitude ascribed to reliability, weighted vulnerability, and resiliency. This indicates the system change associated with a change in the reservoir capacity would be experienced in order of decreasing magnitude by the resiliency, weighted vulnerability, and reliability. In other words, reliability was proven to be stiff and therefore difficult to be influenced via changes in the

Table 1
Reservoir inflow scenarios.

	Scenarios					
	1st Scenario	2nd Scenario	3rd Scenario	4th Scenario	5th Scenario	6th Scenario
Timeline	1991–1995	1992–1996	1993–1997	1994–1998	1995–1999	1996–2000
Average annual inflow ($\times 10^6$ m^3)	18.48	18.45	16.03	14.69	10.34	7.64

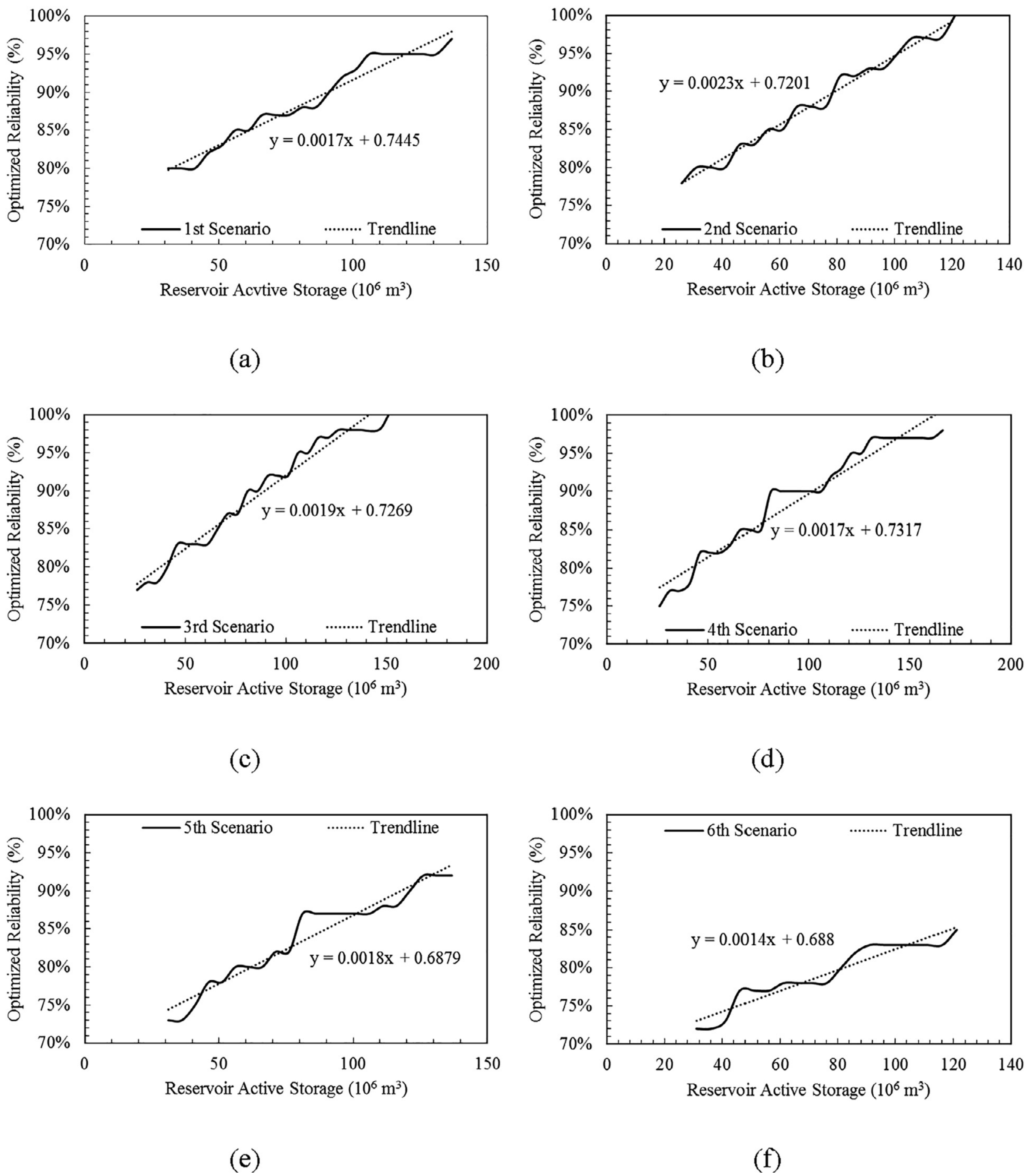

Fig. 2. Reservoir active capacity (x) and optimized reliability (y) charts for six different inflow scenarios, (a) 1st scenario, (b) 2nd scenario, (c) 3rd scenario, (d) 4th scenario, (e) 5th scenario, and (f) 6th scenario.

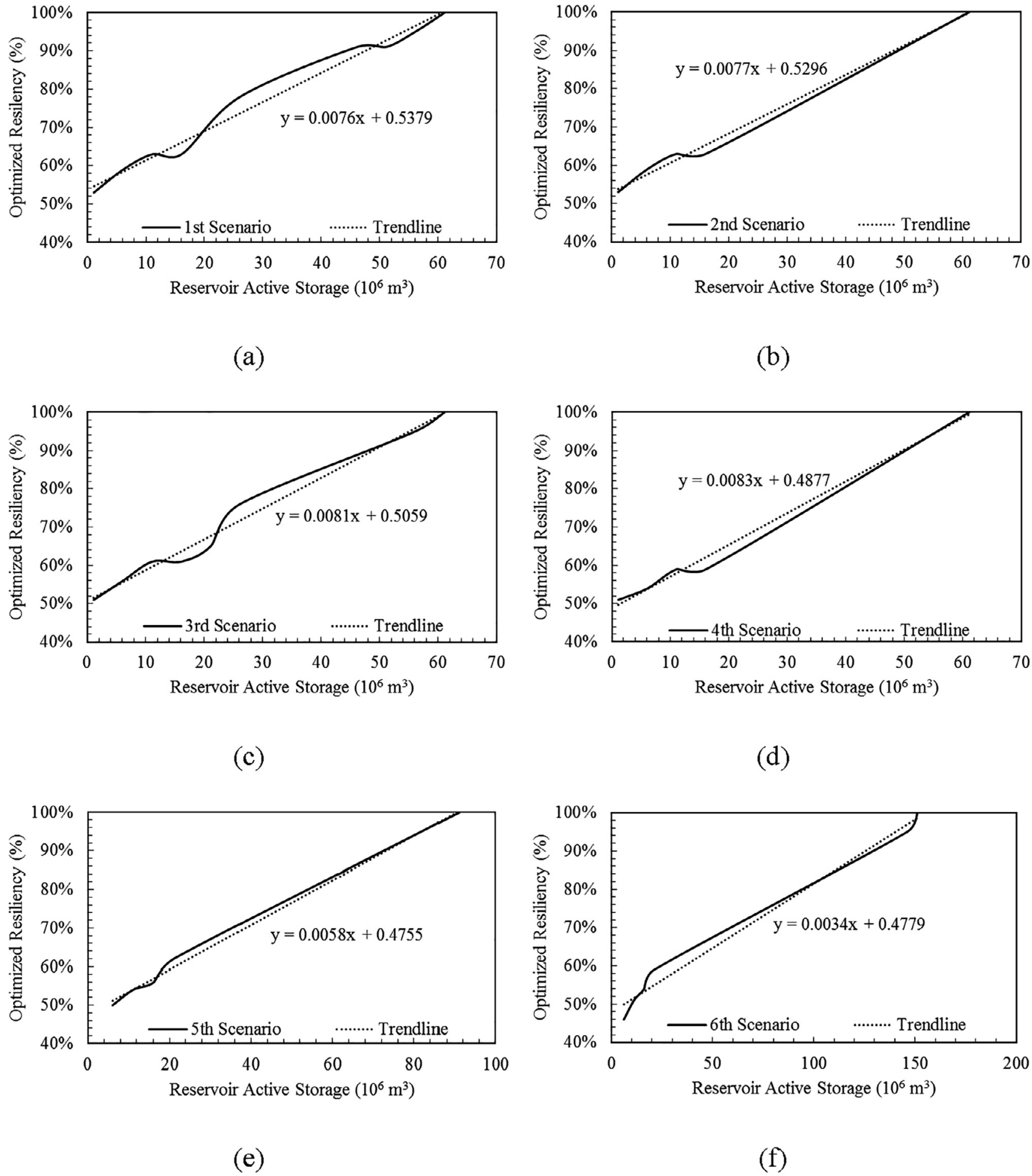

Fig. 3. Reservoir active storage (x) and optimized resiliency (y) charts for six different inflow scenarios, (a) 1st scenario, (b) 2nd scenario, (c) 3rd scenario, (d) 4th scenario, (e) 5th scenario, and (f) 6th scenario.

controllable input (the reservoir's active storage). Resiliency, on the other hand, had the lowest value of stiffness criteria, and it is more prone to be controlled and managed by changing the controllable input. A lower value of the stiffness is preferred by planners and managers of water systems because this implies smaller changes in the controllable inputs, less effort, and, thus, lower costs involved in system control.

This study demonstrated the stiffness and sensitivity criteria can be used individually to analyze the performance of the system, or they may be combined to predict the system's performance in the foreseeable future. The Aidoghmoush reservoir was chosen as a case study to demonstrate the proposed analytical framework. The performance assessment results showed the reliability criteria had the highest value of the stiffness criterion, making it difficult to modify by manipulating the controllable input, and had the highest value of the sensitivity criterion, making it more likely to be influenced by the uncontrollable inputs. This means the reliability of the system will be more affected by natural phenomena, such as drought events, for instance, rather than by other performance criterion of the water system. This signals such system

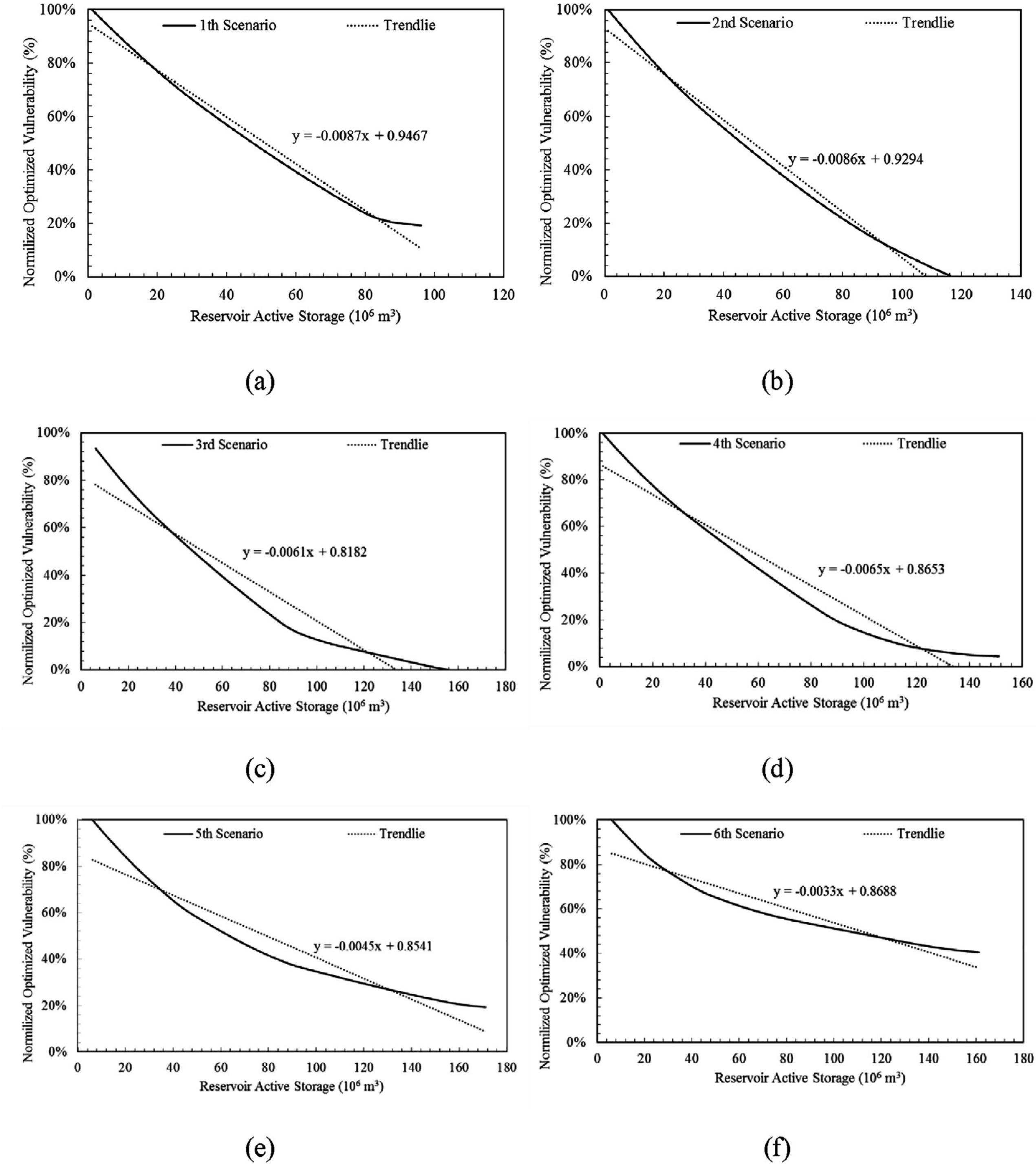

Fig. 4. Reservoir active storage (x) and normalized optimized weighted vulnerability (y) charts for six different inflow scenarios, (a) 1st scenario, (b) 2nd scenario, (c) 3rd scenario, (d) 4th scenario, (e) 5th scenario, and (f) 6th scenario.

Table 2
Stiffness criteria of reservoir's reliability due to changes in active storage.

Inflow scenario	$\beta_{1\max(\Delta S,\alpha)}$ ($1/10^6$ m^3)	$\varphi_{(\Delta S,\alpha)}$ ($1/10^6$ m^3)
1st	0.0017	588
2nd	0.0023	435
3rd	0.0019	526
4th	0.0017	588
5th	0.0018	556
6th	0.0014	714

Table 3
Stiffness criteria of reservoir's resiliency due to changes in active storage.

Inflow scenario	$\beta_{1\max(\Delta S,\gamma)}$ ($1/10^6$ m^3)	$\varphi_{(\Delta S,\gamma)}$ ($1/10^6$ m^3)
1st	0.0076	131
2nd	0.0077	130
3rd	0.0081	124
4th	0.0083	121
5th	0.0058	172
6th	0.0034	294

Table 4
Stiffness criterion of reservoir's weighted vulnerability due to changes in active storage.

Inflow scenario	$\beta_{1\max(\Delta S, \upsilon W)}$ (1/10^6 m^3)	$\phi_{(\Delta S, \upsilon W)}$ (1/10^6 m^3)
1st	−0.0087	115
2nd	−0.0086	116
3rd	−0.0063	159
4th	−0.0065	154
5th	−0.0045	222
6th	−0.0033	303

Table 5
Summary of stiffness and sensitivity criteria for Aidoghmoush reservoir.

	y		
	α	γ	υ_w
$\overline{\phi}_{(\Delta S,y)}$ (1/10^6 m^3)	568	162	178
$\Omega_{(\Delta S,y,I)}$ (1/10^6 m^3)^2	6976	3789	4388

Note: $\overline{\phi}_{(\Delta s,y)}$ = denotes the average of the stiffness criteria.

requires a careful operation, such as by hedging during the operation horizon. This type of operation, however, may be more achievable in a system with relatively low stiffness criteria, as such systems are more manageable by altering controllable input variables.

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