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Towards climate resilient municipal water supply in Bangkok: A collaborative risk informed analysis

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A R T I C L E I N F O

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A B S T R A C T

Typical top-down approaches to climate change adaptation in the water sector rely on climate models to inform the adaptation design. In view of the inherent uncertainty associated with these models, this study uses a combined top-down and bottom-up approach called Collaborative Risk Informed Decision Analysis (CRIDA). Using the case of the Metropolitan Waterworks Authority, Bangkok, this study demonstrates the application of the approach, which includes (a) identifying critical thresholds that impact the system's performance, (b) unearthing the system vulnerabilities through a stress test (scenario analysis), and (c) identifying feasible adaptation interventions. Through a stakeholder consultation process, it was found that streamflow, salinity, and turbidity are the key performance metrics of the water supply system. A series of stress tests to the system was conducted by adjusting input variables assuming a wide range of possible future climatic conditions. Frequency curves of the various input variables were developed to facilitate stakeholders' planning for impending risks and for improving the overall robustness of the water supply system. Based on the stress test results and past studies of the study area, the raw water source of the Metropolitan Waterworks Authority is expected to be more saline in the future with more frequent and severe low flow conditions, for which a number of adaptation actions were formulated and proposed. It is suggested to develop adaptation pathways that can address a range of expected impacts of future climatic conditions on the Bangkok water supply system. The methodology presented is useful for study areas where a model of the system is unavailable, and data limitation is a challenge.

1. Introduction

Climate change is an imminent global threat, and water is the primary medium through which its impacts will be manifested. Literature abounds with examples of regions across the globe already bearing the brunt of these impacts in the form of extreme events such as floods (e.g. Sassi et al., 2019), droughts (e.g. Craig et al., 2019), cyclones (e.g. Walsh et al., 2012), and Glacial Lake Outburst Flood or GLOF (e.g. Aggarwal et al., 2017), among others. Understanding and addressing the impacts of climate change in the water sector is, therefore, a fundamental step towards climate change adaptation. These impacts are usually assessed in a top-down fashion, starting with making estimates of future climate conditions (mostly temperature and rainfall) using Global Climate Models (GCMs).

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The inputs of these models are then fed into a systems model (depending upon the area of interest), based on which the system outputs are generated. The problem with this approach is that the purpose of climate models is to provide an indication of future climate, not serve as the basis for designing climate change adaptation solutions. This is because climate models use multiple assumptions, and when the outputs of these models are used to analyse a system, it leads to overall uncertainty in understanding a system's vulnerabilities (Garcia et al., 2014; Sunyer et al., 2012; Fowler et al., 2007; Clark et al., 2016). Uncertainty arises from different sources on varying scales throughout the process of climate projection. According to Wilby and Dessai (2010), the top-down approach increases the uncertainty with each stage of evaluation due to the increase in complexity and number of permutations.

Many climate change adaptation interventions (e.g. raising the height of a dam to reduce climate-induced flooding or arranging inter-basin transfers to mitigate water scarcity) usually require significant upfront funding. Decision makers may find it difficult to justify these costs given the degree of uncertainty associated with the climate change projections. There has, therefore, been a growing focus on other approaches for climate change adaptation that takes this uncertainty out of the equation as much as possible. One such approach emphasizes a bottom-up philosophy to design appropriate solutions. Bottom-up approaches consider site-specific risks from the perspectives of local stakeholders and system capacities, relying more on the social sciences than on natural sciences like Physics, which drive the climate modelling processes. Such approaches have been applied to case studies at various locations and of different scales: Zhang et al. (2018) used a bottom-up vulnerability assessment framework to evaluate the vulnerability of inter-basin water transfer and demonstrated its application in the South-to-North Water Transfer Project (SNWTP) in China; de Koning et al. (2019) demonstrated the usefulness of bottom-up drivers of behavioural change among communities to help mitigate flood risks; and Forino et al. (2018) presented a suite of bottom-up climate change mitigation initiatives taken by the Transition Newcastle community group in Australia.

While bottom-up approaches are flexible in application and facilitate localized analysis, they have often been critiqued for their lack of technicality, and may by themselves, be insufficient for understanding future climate conditions. Hence, a coupling of both approaches (top-down and bottom-up) has been suggested by several researchers (Girard et al., 2015; Brown et al., 2012). There are numerous examples of combined top-down and bottom-up approaches: Bhave et al. (2014) used hydrological modelling to assess the effects of stakeholder prioritized adaptation options for the Kangsabati River catchment in India; and Van Tra et al. (2018) adopted combined top-down and bottom-up climate change impact assessment to address the impacts of climate change on water shortage in the Vu Gia-Thu Bon River Basin, located in the central coastal zone of Vietnam.

The focus of the current paper is one such combined top-down and bottom-up approach called Collaborative Risk Informed Decision Analysis (CRIDA). CRIDA provides a collaborative process for risk-informed decision-making: effectively assessing, managing, and communicating risks to stakeholders and decision makers, including successfully avoided risks and residual risks that cannot be avoided, quantified, or isolated (Mendoza et al., 2018). The CRIDA process does not begin with climate models or a selection of future scenarios to be used in the planning and design of a project. Instead, it begins with the standard engineering procedures of identifying planning objectives and the problems that need to be solved, after which the planning team addresses how the uncertainties affect the choices of options and trade-offs.

The water supply system of Bangkok, the capital city of Thailand, was selected as the study site for this study. The Metropolitan

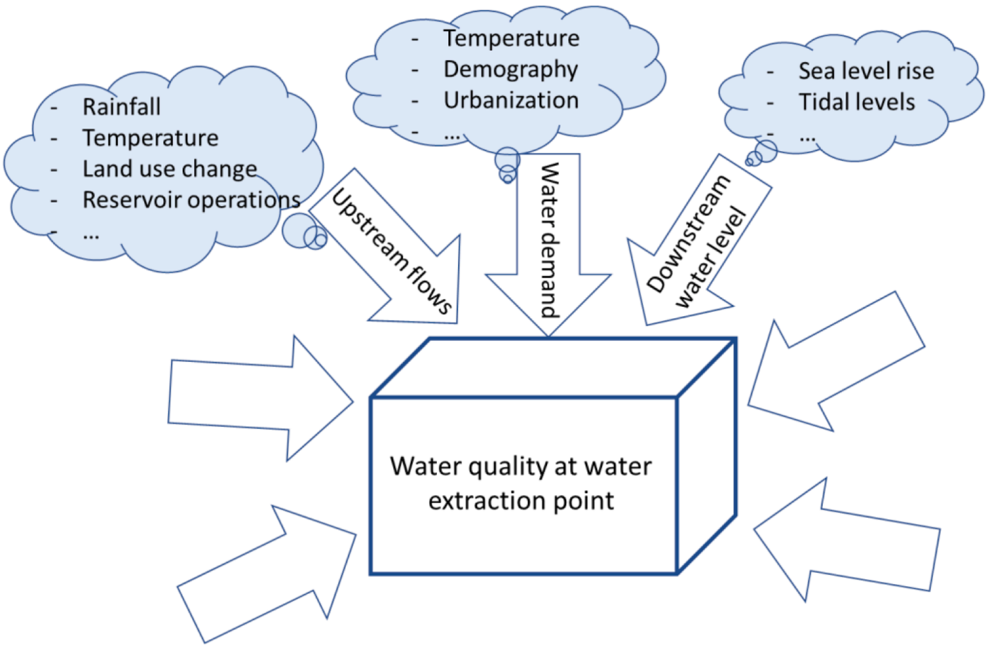

Fig. 1. Illustration of uncertainty present in a municipal water supply system of Bangkok. The variables in the block arrows directly affect the performance of the system, while the clouds represent other sources of uncertainty in the system.

Waterworks Authority (MWA) is the principal supplier of municipal water to Bangkok. Several factors, including climate change, natural disasters, government policies, and water resources management can affect the MWA's future operations (Metropolitan Waterworks Authority, 2017). Managing the water supply system involves meeting the demanded quantity while ensuring an acceptable quality of water. Municipal and industrial water usages receive the highest priority in water allocation; hence, these sectors do not usually face water shortage issues. The main problem faced by the MWA is water quality, which has to meet national drinking water standards even during periods of low river inflow, when water quality typically deteriorates. It is, therefore, essential to evaluate the potential challenges faced by the water supply system in Thailand to minimize disruptions to its operations.

As illustrated in Fig. 1, the water quality at the intake point of the utility is determined by several variables (the block arrows), examples include the demand, the river flow from the upstream and the water level from the downstream, which could subject the system to problems such as saltwater intrusion, if, it is near the sea. Each variable is accompanied by a non-exhaustive cloud of uncertainty, and the assumptions involved in the projection of each variable could compound or magnify the overall uncertainty while evaluating the system for future adaptation responses.

Given the complexity of the system and the inherent uncertainties involved, a modified planning process is introduced to develop an understanding of climate change-related critical thresholds of the MWA, the water utility of Bangkok. Adhering to the principles of the CRIDA framework, these critical thresholds are estimates from the perspective of its stakeholders and should then form the basis for climate change adaptation interventions that the utility could undertake. The contribution of this research is two-fold; 1) a modified CRIDA framework to identify climate risks for localized planning and adaptive solutions, and 2) a practical case study to demonstrate the use of the approach in managing a municipal water supply system in Bangkok, Thailand.

2. Study area and data

2.1. Study area

The Chao Phraya River Basin (Fig. 2) is the largest and the most important basin in Thailand. It consists of eight sub-basins and covers an area of approximately 158,587 km^2 (approximately 32% of Thailand). The basin can be divided into the upper part (the Ping, Wang, Yom, and Nan basins) and the lower part (the Chao Phraya, Sekae Krang, Pasak, and Tha Chin basins). The water in the Chao Phraya Basin is used for four main purposes (with the proportion of the total water demand expressed in parentheses) comprising agriculture (73%), drinking water consumption (4%), industries (5%), and environment, including managing saltwater intrusion (18%) (The Crown Property Bureau, 2012). The order of water use priority in the Chao Phraya, beginning with the highest, is: municipal and industry, environmental conservation, agriculture, and inland waterway navigation (Takeda et al., 2016). The Bhumibol (capacity: 13.5 billion m^3) and Sirikrit (capacity: 9.5 billion m^3) multipurpose dams are the two main reservoirs in the basin. Dry season flows are primarily controlled by these two dams located on the Ping and Nan rivers respectively.

The MWA receives water from two raw water sources, the Chao Phraya River and the Mae Klong River, and is responsible for supplying municipal water to Bangkok and two nearby provinces, Nonthaburi and Samutprakan. Four water treatment plants under

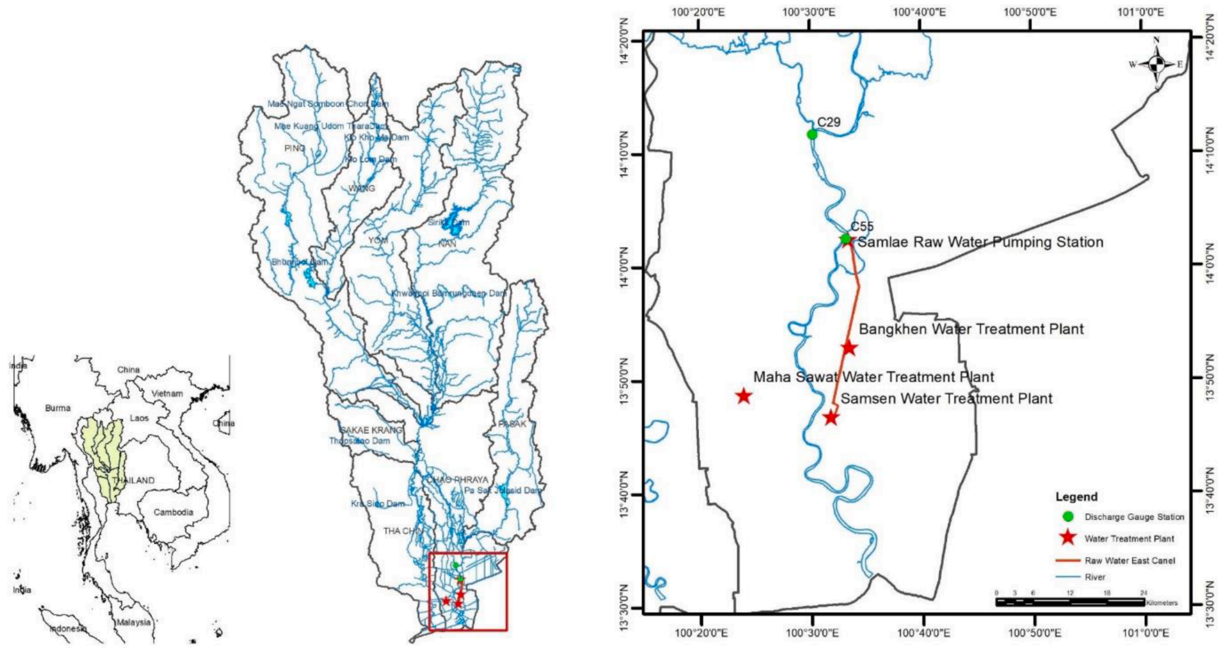

Fig. 2. Map of Thailand, the Chao Phraya River Basin, and the study area.

the operation of MWA provided 2064 MCM of water in 2017 for distribution and sale. The Samlae intake station (station C55 in Fig. 2), 96 km away from the Gulf of Thailand, pumps raw water from the Chao Phraya River to supply to the Bang Khen, Samsen, and Thon Buri water treatment plants for distribution to the East side of the MWA service area, and the Ta Muang water intake collects raw water from the Mae Klong River to supply to the Mahasawat water treatment plant for distribution to the West side of the MWA service area (Metropolitan Waterworks Authority, 2017). The Bangkhen treatment plant, with the maximum capacity of 4.4 million m^3/day, supplies water to most parts of Bangkok and is the primary point of interest in this study. The raw water is transported by open canals from the intake points to the water treatment plants.

Given the proximity of the water intake point to the Gulf of Thailand, one of the issues experienced by the MWA is the backwater effect due to tides, leading to saltwater intrusion problems, especially during the dry season when there is reduced flow from the upstream. To minimise the effects of salinity, there has to be sufficient flow from the upstream to manage the inflow of saline water. The river flow is closely monitored at the Bangsai station (C29) and salinity is measured at the Samlae intake point (C55).

2.2. Observed data

Data for river flow at C29, salinity at C55, and turbidity at C55 were collected from the MWA and the Royal Irrigation Department (RID). Table 1 lists the data collected and used in the study.

Challenges were faced in terms of data availability for river flow and salinity. For river flow, since new telemetry systems were only installed in 2009, consistent data were obtained only from the newly installed stations. For both river flow and salinity, data for several months are missing due to the catastrophic flood in Thailand in 2011. The observed data for a common period of availability from 2009 to 2010 and from 2012 to 2015 were used in the study.

3. Methodology

3.1. CRIDA framework

The CRIDA framework (Mendoza et al., 2018) was developed with the aim of supporting site-specific water resources planning and management decisions while minimizing risks arising from uncertainty. The framework involves stakeholders in the decision-making process right from the beginning to ensure that needs specific to the system are addressed. The complete planning cycle involves five steps: establishing the decision context wherein stakeholders can identify and define the critical thresholds of the performance of the system (i.e., define the limits that can break the system); assessing bottom-up vulnerability (which involves incrementally stressing the system until the breaking point to understand the vulnerabilities inherent to the system); formulating robust actions (to reduce the vulnerabilities detected through the previous step); evaluating alternatives (to arrive at holistic plans and projects); and institutionalizing decisions (to set the stage for implementation).

The first three steps of the framework are detailed in Fig. 3, with the blue, green and orange boxes representing each step respectively. The performance indicators, critical thresholds and system stressors are identified in Step 1. The stress test is conducted in Step 2, wherein a model would usually be used to relate the system stressors to the performance metrics, and these stressors will be varied as inputs to the model to stress the system until it fails the critical thresholds (defined in Step 1). Adaptation pathways are then developed based on analyzing the plausibility of system failure. While the CRIDA framework is highly customizable for site-specific studies, its application to our study was limited by data availability and the lack of a model to relate the system performance to its stressors. This study is thus carried out using a modified framework as detailed in the next section.

3.2. Modified CRIDA framework

This study focuses on the same three steps using a slightly modified version of the CRIDA framework. In Fig. 3, the steps of the modified framework are outlined in red dashed lines and follow the red arrows. The main modification occurs in the second step, where the cycle bypasses the requirement of a system model to establish performance through analyzing historical data and developing future scenarios. The stress test was carried out using the defined thresholds to evaluate performance metrics and understand the type of climatic regime that can cause the critical thresholds to be breached. This shifts the focus of the stress test from the cause of the problem (the stressor), to the performance indicator, where the potential effects on the system in a more stressed environment is studied. Reasonable adaptation actions are then evaluated based on the plausibility of occurrence of the future test scenarios.

The methodology presented is useful for study areas where a model of the water resources system is unavailable, and data availability is a challenge. While one could adopt a simple model to relate stressors and performance indicators, a simplistic

Table 1
Summary of data used in the study.

Variable	Station	Resolution	Data availability	Source
River flow	C29	Daily	1 Jan 2009–31 Dec 2015 (Missing: 16 Feb – 31 Mar 2011)	RID
Salinity	C55	Daily	1 Jan 2007–31 Dec 2015 (Missing: 20 Oct – 19 Dec 2011)	MWA
Turbidity	C55	Daily	1 Jan 2009–31 Dec 2015	MWA

RID: Royal Irrigation Department; MWA: Metropolitan Waterworks Authority.

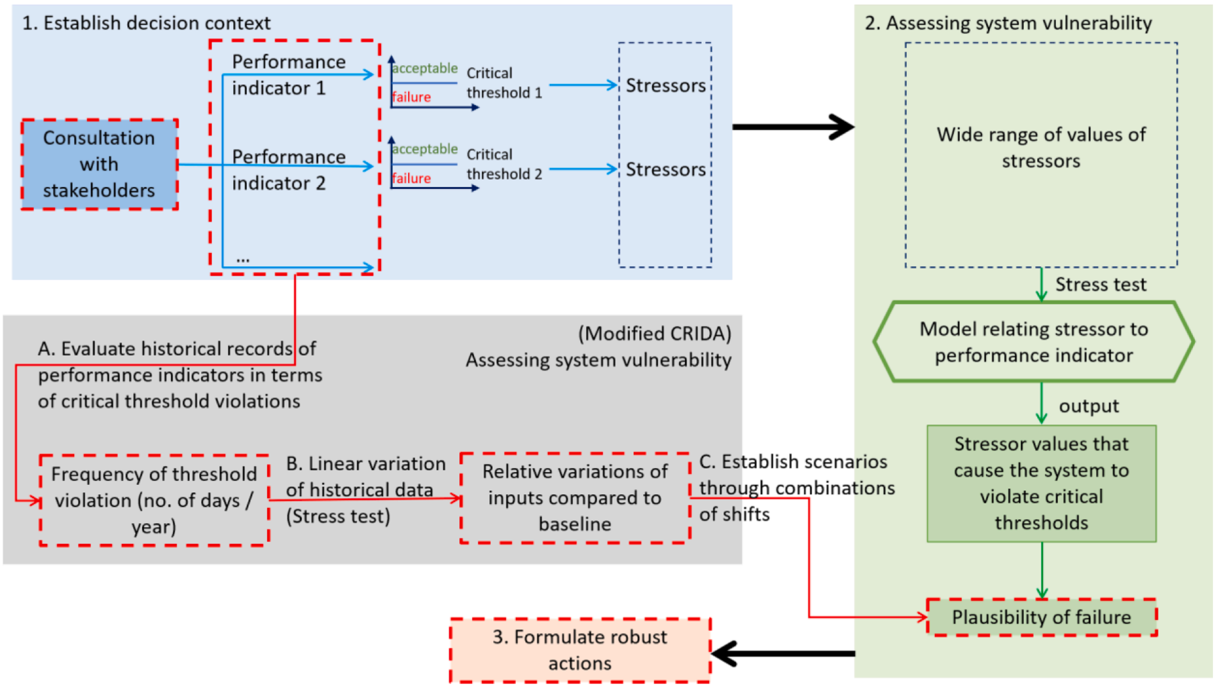

Fig. 3. Methodology of the study in comparison to the CRIDA framework. The blue box, green box, and orange box detail the first three steps of CRIDA respectively. The modified planning steps are placed within the gray box, outlined with red dashed lines and follow the red arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mathematical relationship between the performance metrics will undermine the complexity of the system and not be representative of the actual physical processes. Unless the model produces a really good fit, which can be explained with natural processes, focus should be placed on understanding the main patterns of the system performance and their critical thresholds instead. The measurable performance metrics of a system are direct or indirect results of multiple factors (Fig. 1), thus by analysing a wide range of outcomes in terms of scenarios, all stressors of the system are taken into account.

3.2.1. Establishing the decision context

This step marks the beginning of the planning process (Step 1 in Fig. 3), setting the stage for site-specific assessments in the vulnerability domain.

The staff members of the MWA were identified as the stakeholders in this study due to their familiarity with the operations of the water supply system. Thirty representatives from four MWA departments (the Water Quality Department, the Raw Water Transmission System Department, the Water Resources & Environment Department, and the Bangkhen Water Treatment Plant Department) attended an interactive open-ended interview session conducted at the MWA office.

Through the interviews, the respondents participated in rigorous discussions, expressed personal views, and arrived at a consensus on the main problems and issues faced by the system, the key constraints in the planning process, and the objectives the system had to fulfil. Additionally, they were asked to provide inputs on indicators of the system's performance and critical thresholds by specifying the tipping points beyond which the system is/would be unable to carry out normal operations based on performance levels (also defined as system failure). During the discussion session, they were also asked to provide their ideas with respect to possible interventions in the context of climate change.

3.2.2. Assessing system vulnerability

3.2.2.1. Analysis of system performance. The second step of the planning cycle involves performing site-specific analysis based on information obtained from stakeholders in the previous step. The key information used for the entire analysis include (i) the performance metrics (indicators of the system's performance) and (ii) their critical thresholds. The main modification to the CRIDA framework occurs in this step. Instead of identifying variables that affect the system performance and relating them to the actual performance, the analysis begins by studying the historical performance of the system. This is done through first plotting the time series of the variables with the defined thresholds to understand historical system failure occurrences and to gather a visual idea of the relationships between the different variables. Next, the inherent system variability was explored through an analysis of seasonal variability in different years. This allows us to understand whether the system is more prone to certain types of failure during different times of the year. Further, large fluctuations indicate that the system is already highly susceptible to the effects of climate variability, calling for more urgent actions to be taken. The frequency of system failure (in percent and average number of days per year) was analysed to evaluate the regularity with which actions would have to be taken by the utility. To better illustrate the actions as a response to the system state, an action matrix for each performance metric was created, wherein the data points were partitioned into regions based on the severity of system failure, and the relevant actions that the utility needs to take to push the system back into an acceptable state. The distinct segregation between the points gives an insight into the vulnerability of the utility at current adaptation levels.

3.2.2.2. Stress test. The crux of the CRIDA framework lies in the stress test, which is conducted to assess climate risk. Since the performance of the system in the past has been understood, the next step involves incrementally stressing the system to its breaking point. In this study, the focus lies in how often the critical thresholds are violated under different scenarios – which were developed by assuming that the distribution of all stressors remained constant between historical and future data. The stress test was conducted based on the historical data in three steps. First, extreme performances in terms of the number of violations in each year were determined for each performance metric. Next, the historical data of the individual metrics were arbitrarily varied until the number of violations at least surpasses the identified historical extremes, setting the boundaries for the stress test. This ensures that the system is exposed to conditions at least as severe as the historical extremes. Last, system failure due to a combination of variations in the performance metrics were explored through frequency curves – created by incrementally varying the observed data and identifying the number of days the system fails the defined thresholds in a given year. This exposed the system to a wide range of future variations as it took into account all the possible stressors of the system that can lead to any variation in any of the concerned variables. Such tests allow stakeholders to estimate the severity of failures should situations become adverse and provide an insight into the formulation of relevant adaptive approaches and measures.

3.2.2.3. Plausibility of variability changes. Having identified the system goals and vulnerabilities, the plausibility of the system metrics being varied was investigated. In this step, top-down approaches were integrated in the analysis as studies on future climate projected at the study area of interest were explored. As mentioned in Section 1, this forms the technical aspects of the analysis as results from climate models are compared against the stress test results to inform the likelihood of variations in the performance metrics in the future.

3.2.3. Formulating actions

With the plausible future conditions in mind, adaptation actions have to be formulated to address the identified climate risks. When identifying adaptation measures, it is important to consider decision variables individually and in combination, as they may be interrelated. For example, the worst-case plausible scenario can be expressed and explored through an action matrix to determine the intervention required. While possible solutions to the existing problems were raised during the stakeholder meeting, it is important to evaluate each decision to justify the necessity of actions and the urgency of their implementation.

4. Results and discussion

4.1. Decision variables and thresholds

Two main water quality issues were identified during the stakeholder meeting. The following decision variables and thresholds form the basis of conducting our analysis:

a) Salinity problems can occur when station C29 measures a river flow below 80 m^3/s.
b) At the Samlae pumping station (station C55), salinity level of>0.25 g/L would cause the treatment plant to reduce operations, and a more severe level of 0.50 g/L would trigger critical plant operation plans.
c) At the Samlae pumping station (station C55), a turbidity level of>200NTU would increase the cost and duration of water processing.

The performance metrics identified include the river flow at station C29, and salinity and turbidity levels at station C55. The locations of these stations are shown in Fig. 2. High salinity affects the taste of water for drinking and may impact electrical conductivity-based industrial operations, while high turbidity increases retention time and operation costs as more chemicals are required to treat the raw water.

Conventional water treatment plants are unable to treat salinity. Instead, the MWA counters the problem by asking dam operators to release water from the upstream to dilute salinity. The release request is made when the flow at station C29 is less than 80 m^3/s. However, the release is subject to upstream water availability. It is important to note that the flow of 80 m^3/s is only an indication that the salinity at the water extraction point might be high since sufficient flow from the upstream is not available to counter salt-water intrusion from the Gulf of Thailand.

Salinity levels are monitored at the pumping station, which are the actual indicator of the system performance, and the data generated at this point prompts the appropriate action that needs to be taken by the MWA. When salinity values are>0.25 g/L, the MWA slows down its operations by retaining water in the canal for a longer period to prevent saline water from entering the Bang Khen water treatment plant. At a more critical salinity value of 0.50 g/L, consumers would have to be warned about the high salinity levels in the water and the duration for which the problem will persist. Consumers would be advised to reduce their water usage during such critical periods to maintain lower salinity levels in their water storage tanks.

The specific goals of the utility are, thus, to alleviate the salinity problems at the intake point during the dry season, and the turbidity problems during the wet season.

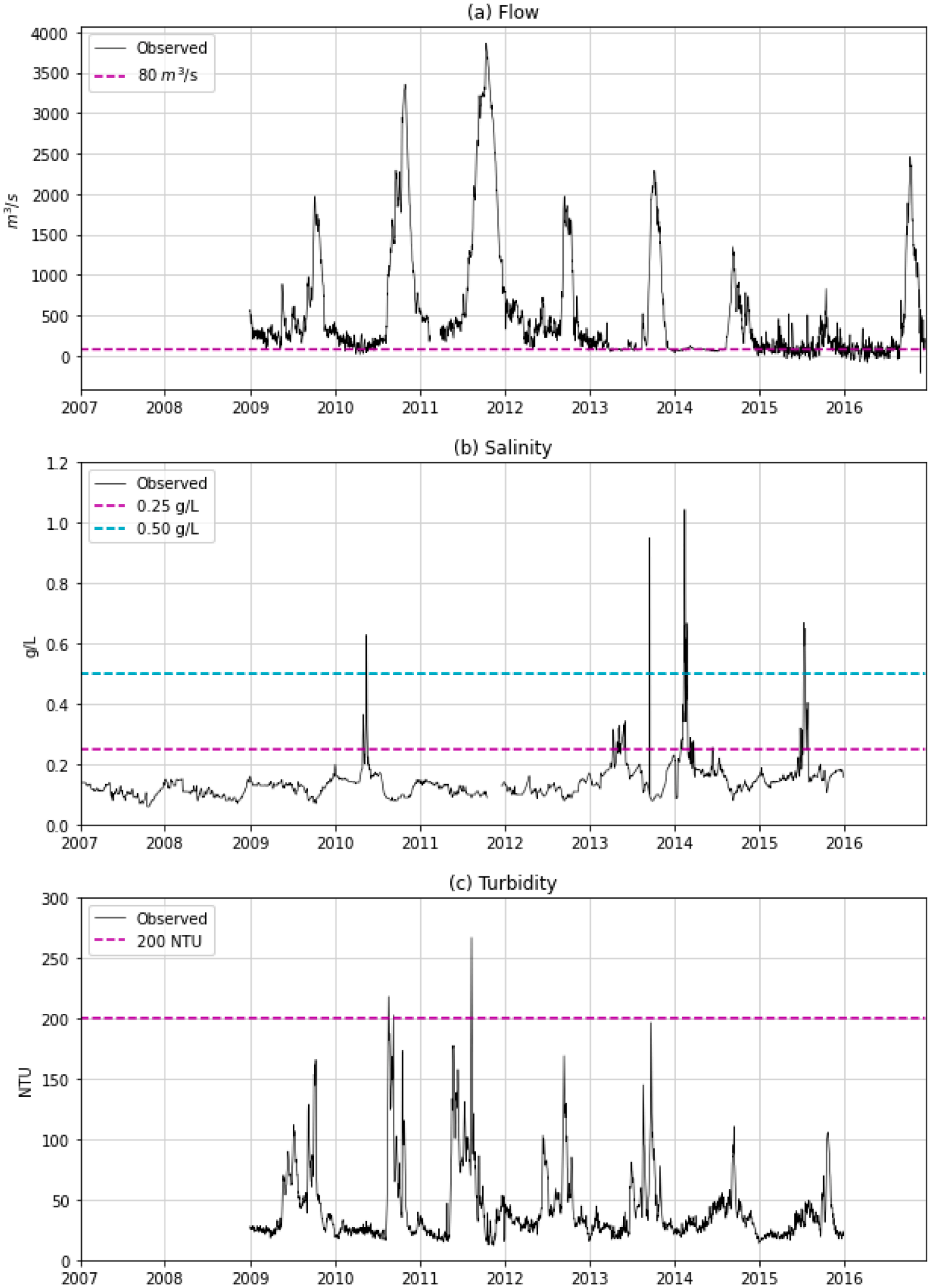

Fig. 4. Average daily (a) flow at station C29, (b) salinity at station C55, and (c) turbidity at station C55. The dashed lines indicate the threshold(s) defined for each variable.

4.2. Assessing system vulnerability

4.2.1. Analysis of system performance

Fig. 4 plots daily average observed flow, salinity, and turbidity in the system with the respective defined threshold of each variable. A comparison of the profiles of the time series illustrates the interactions between the variables. In general, the three failure modes did not occur simultaneously, the system experienced high turbidity and low salinity only during periods of high flows, while high salinity mostly occurred when the streamflow was about 100 m^3/s. This suggests that the failure due to salinity/turbidity are mutually exclusive, but are linked to the flows.

The discharge profile at station C29 (Fig. 4(a)) follows a general seasonal pattern with increasing values towards the monsoon season during the second half of the year. High flows were recorded during the last quarter of the years 2010 and 2011, with the peak flow of 3860 m^3/s being observed in 2011, the year that Thailand experienced a massive flood. Low flows were observed between 2014 and 2016, which were drier years. Station C29 recorded flows below 80 m^3/s for 16.9% of the time, an average of 62 days per year.

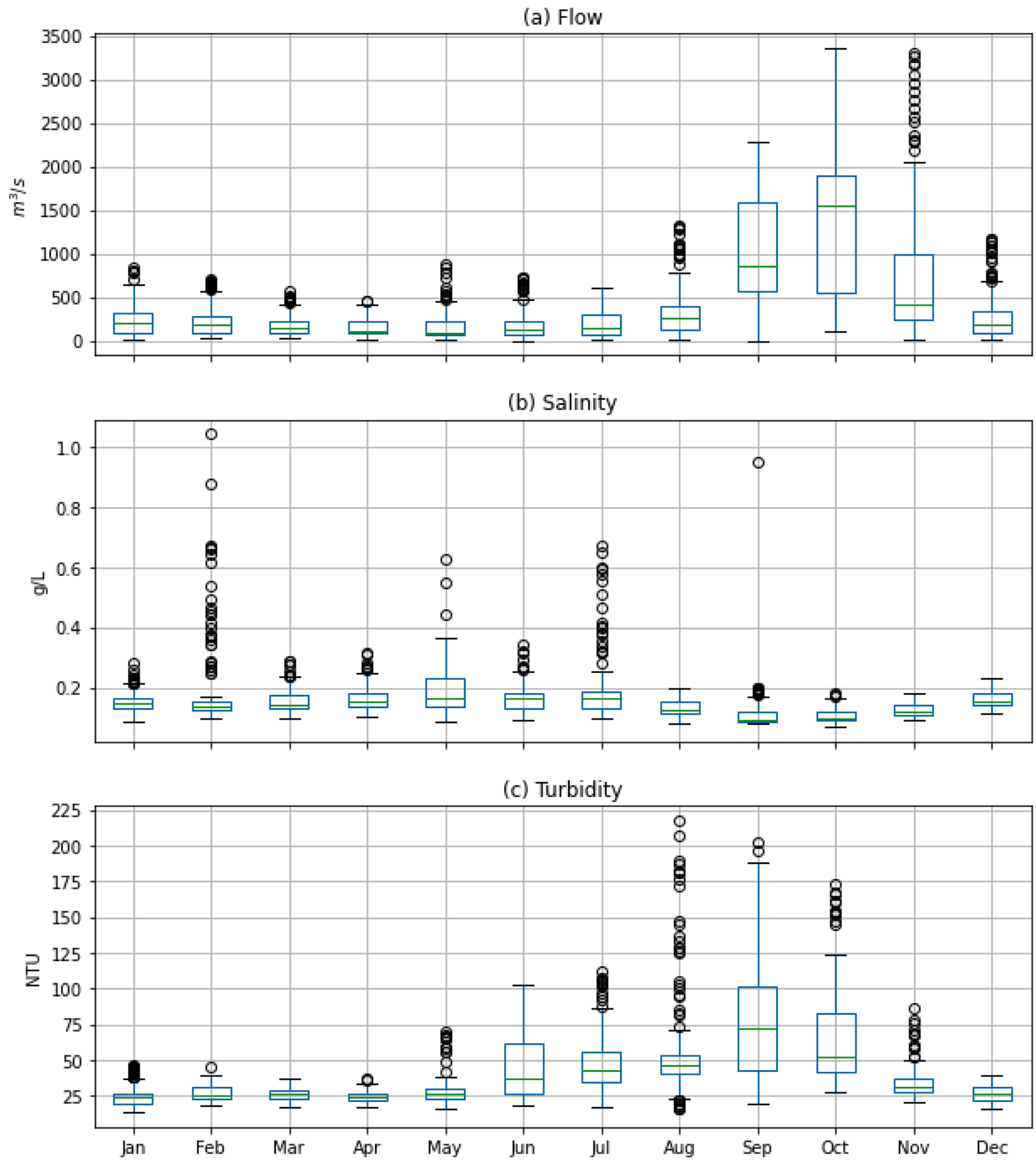

Fig. 5. Comparison of seasonal variability of (a) flow, (b) salinity, and (c) turbidity.

Majority of the flow values lie between 100 and 1000 m^3/s, and only for about 10% of the time, the flow exceeds 1000 m^3/s. This indicates that there are potentially 60 days per year on average when the water supply system experiences disruptions and requires remedial action in the form of additional water being released from the upstream by the responsible authorities.

For salinity, two threshold values were identified by stakeholders, one at a value>0.25 g/L and another at 0.50 g/L. From Fig. 4(b), it is evident that most of the observed data had salinity values below 0.25 g/L, which indicates that the system is in an acceptable condition most of the time. It was found that the system had salinity above 0.25 g/L for 5.34% of the time, which converts to an average of 19 days per year while salinity values rose above 0.50 g/L for 0.82% of the time, an average of 3 days per year. The days with spikes in salinity (prominently 1 g/L in 2014 and 0.95 g/L in 2013) correspond to days with successive low flows.

From Fig. 4(c), failure due to turbidity appears to be less of a problem as recorded values are below 50 NTU most of the time. Only in the years 2010 and 2011 was turbidity above the threshold, which coincides with the periods of high flows (Fig. 4(a)). The highest turbidity was recorded in 2011 (270 NTU), because of higher amounts of sediments in the flood water. Based on the available historical records, the prominent failure periods are in August 2011 recording four days exceedance of the threshold, and August 2010 with three days exceedance.

The statistical distributions of the monthly flow, salinity, and turbidity are compared in Fig. 5. These plots clearly reflect the inherent variability of the system. Fig. 5(a) suggests that the water supply system in Bangkok is highly susceptible to the effects of climate variability. Although seasonal patterns are pronounced, with dry conditions during the beginning of the year and wet conditions in the second half of the year, large variations are observed between different years. During dry years such as 2014, the flow values peaked at only one-fifth that of 2010. Notably, high flow rates have larger interquartile ranges, indicating greater dispersion of data around the median compared to drier periods.

In Fig. 5(b), the median salinity of every month falls below 0.25 g/L with a small spread in the interquartile range. The excessively large salinity values are observed only between January and July, corresponding to low flow conditions. This can be attributed to the onset of El Niño in Thailand, and insufficient release from the upstream reservoirs because of low water storage and diversion of water for agricultural purposes upstream of the intake point (Kordach et al., 2017).

The turbidity illustrated in Fig. 5(c) follows a similar pattern to flows (Fig. 5(a)). Large values recorded in August and September occurred in 2010, the year with high flows preceding the flood event in 2011. The peak in turbidity at C55 occurs earlier than the flow

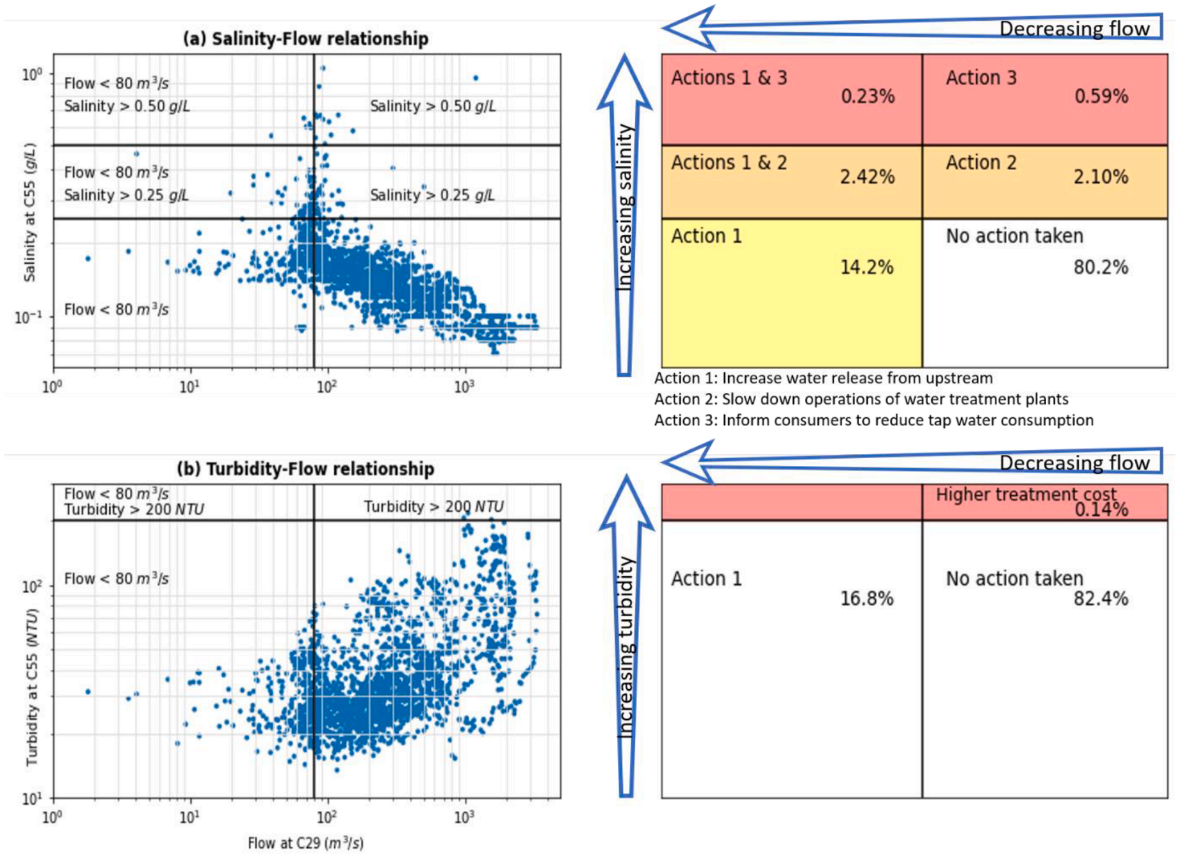

Fig. 6. Left panel: Scatter plots indicating the relationship between (a) flow and salinity, and (b) flow and turbidity. Right panel: the corresponding schematic of actions taken in each case. Action 1 is increased water release from upstream, Action 2 is slowing the treatment plant's operations, Action 3 is asking consumers to reduce tap water consumption to preserve the salinity levels in their storage tanks.

at C29 for most of the years, suggesting that the rise in flow rates were already bringing in organic matter to the water intake point. Possible sources of the organic matter include suspended solids from the river bed, runoff from river banks, etc.

The river flows at C29 and its influence on the water quality at the raw water intake point is evident. The system is prone to saltwater intrusion between January and July, and turbidity problems between August and October. While both issues do not occur simultaneously, the utility should be prepared to face both problems in the same year, and for more extreme failure conditions in face of climate extremes. It is hence important to gain insights of plausible future climate conditions to facilitate better planning and decision-making.

Fig. 6(a) and (b) illustrate the relationship between salinity and flow, and turbidity and flow, respectively. All defined threshold values are marked on the plots and each scatter plot is complemented by an action matrix to describe the responses from the utility for each failure scenario.

The salinity-flow relationship (Fig. 6(a)) seems to be stronger during periods of high flows as the points start to converge with lesser scattering, as compared to when the flows are low. When high flows are experienced, salinity would be low since a greater volume of water from the upstream pushes the saline water back to the Gulf. Conversely, when flow rates are low, the intake point is more susceptible to saline water from the Chao Phraya River mouth. The tidal effects are more pronounced as illustrated by the large scatter in Fig. 6(a) when flows at station C29 are less than 100 m^3/s. Without the countering effects from the upstream flows, tidal water can flow towards the Samlae pumping station, bringing in brackish water and potentially causing salinity levels to increase. This problem can be further exacerbated by climate change causing sea level rise at the river mouth and low flow upstream.

The system is within a healthy salinity range 94.6% of the time, with low flows experienced 14.2% of the time. The left of the action matrix in Fig. 6(a) corresponds to periods of low flow, such that intervention is required to increase the flow from upstream to dilute salinity. The orange and red regions on the left indicate failure due to both flow and salinity. Such failure occurs 2.65% of the time. Low flows are countered by upstream releases, which depend on the available water storages in the two main reservoirs. If after the alert, salinity still fails to stay below the prescribed threshold, the possibilities are one or more of the following: (i) insufficient storage in the reservoirs hence no release, (ii) insufficient release, or (iii) excessive water diversion for upstream users (mainly irrigation) between the reservoirs and raw water intake point for the MWA supply. The orange and red regions on the right side of the matrix correspond to acceptable flows but high salinity due to high tides. The streamflow is not enough to flush out the saltwater towards the Gulf of Thailand. Such a phenomenon was recorded between May and July in the years 2010, 2013, 2014, and 2015. This highlights the non-preemptive nature of saltwater intrusion during the summer months.

The scatter plot in Fig. 6(b) suggests a generally positive relationship between turbidity and flow. The system's failure due to high turbidity is experienced only in the top right quadrant (three days over six years of analysis), corresponding to the periods with high flow. Unlike salinity, turbidity can be treated with more chemicals and higher retention time in the tanks. It is unknown exactly how long more the treatment process will take and how much the additional chemicals would cost for the utility. Having more turbidity problems in the system will disrupt the operations and affect the budget of the utility. Despite the low failure rates in the past, it is essential to not overlook this potential problem that can be exacerbated by climate change too. High turbidity is a product of large upstream discharges, contributed by high rainfall events and soil moisture saturation, and made worse by sea level rise. According to Promchote et al. (2016), the rise in sea level also contributed to the 2011 flood as the phenomenon obstructed the natural drainage from the upstream water. The understanding of the possible effects on turbidity levels are thus important.

4.2.2. *Stress test*

The stress test in this study was conducted for the identified performance metrics of the system (river flow, salinity, and turbidity). The effects of future climatic conditions were incorporated by introducing scenarios of reduced/increased flow and turbidity from the upstream due to reduced/increased rainfall in the catchment areas and/or reduced/increased use of water in the upstream areas by agriculture, industries, and other water use sectors and reduced/increased salinity level from the downstream due to sea level alterations caused by climate variability and change.

Table 2

Stress test. (a) Number of days the system fails each defined threshold in each year. The highlighted values indicate the worst-performing year for each threshold; (b) Average number of days per year the system is expected to fail after varying each variable by −30% to + 50% for the years 2009–2010 and 2012–2015. The highlighted values are at least as large as the numbers in (a), indicating the boundaries for the stress test.

Critical thresholds	(a) No. of failure days in a year								
	2009	2010	2011	2012	2013	2014	2015	Average	
Flow < 80 m^3/s	1	24	–	1	74	134	136	62	
Salinity > 0.25 g/L	0	14	–	0	31	28	22	19	
Salinity > 0.50 g/L	0	2	–	0	1	8	6	3	
Turbidity > 200NTU	0	3	4	0	0	0	0	1	
Critical thresholds	(b) Variation in variable values (% change)								
	−30	−20	−10	0	+10	+20	+30	+40	+50
Flow < 80 m^3/s	112	100	85	62	44	32	24	20	17
Salinity > 0.25 g/L	7	10	14	19	24	35	45	69	96
Salinity > 0.50 g/L	1	2	3	3	4	5	5	7	8
Turbidity > 200 NTU	0	0	0	1	2	3	5	7	7

The challenge of the stress test is in deciding the boundaries of testing. Several studies have projected future climate and streamflow conditions in the Chao Phraya River Basin. The basin's streamflow in the future is expected to either increase or decrease depending on rainfall intensity and volume, suggesting potential flood and drought events (Sayama et al., 2015; Wichakul et al., 2015). This study

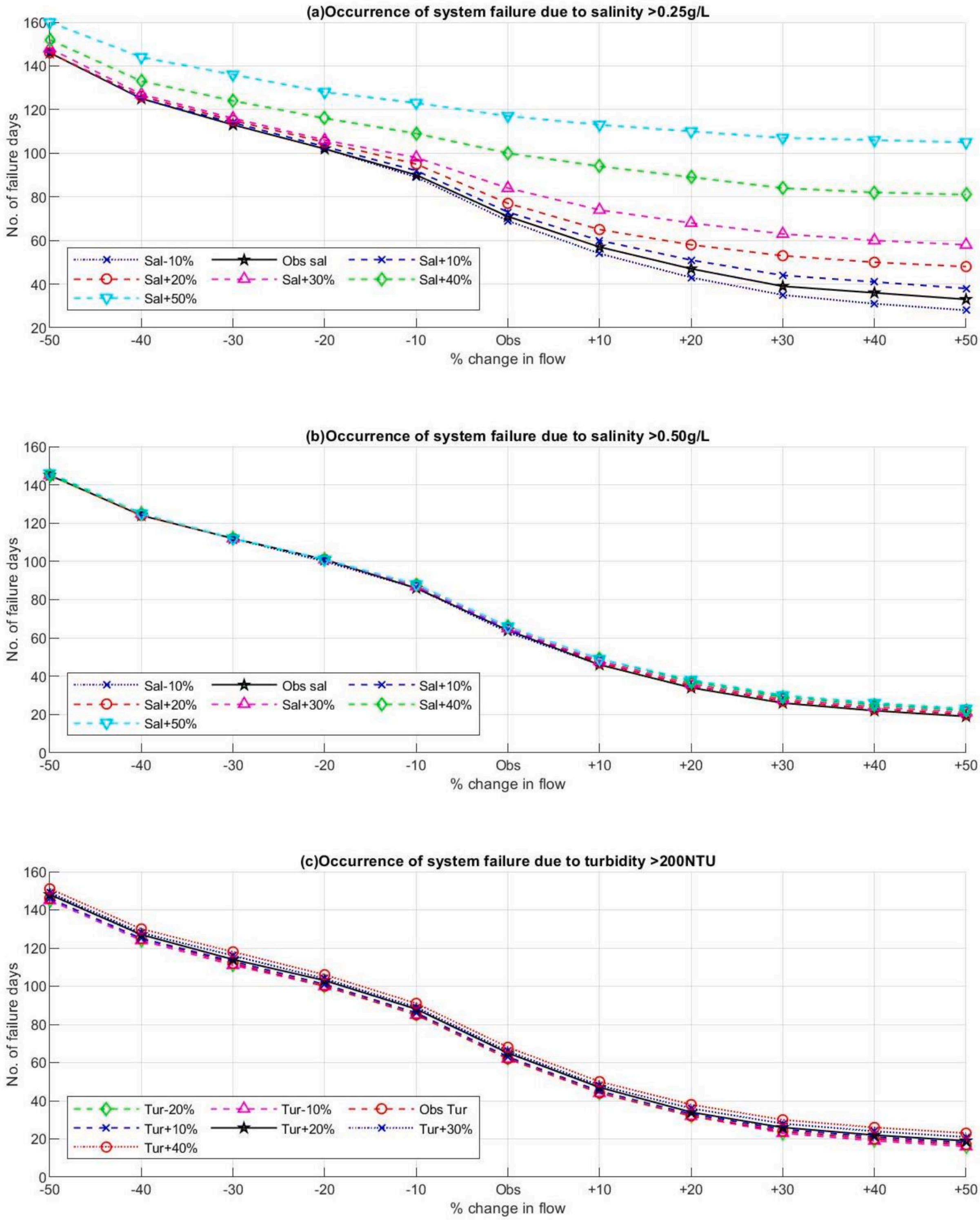

Fig. 7. Average number of days in a year when the system is expected to fail the threshold of (a) salinity > 0.25 g/L, (b) salinity > 0.50 g/L, and (c) turbidity > 200NTU after varying the frequency curves of the variables at 10% intervals.

has taken all available historical data, and assumed the distributions to be uniform. It is important to note that the system performance is ultimately defined by the water quality measured at the water intake point. The number of days the utility experienced system failure each year is shown in Table 2(a). As the years under investigation include both wet years and dry years, the extent of failure will form the basis of deciding the boundaries of the stress test. In other words, each variable will be varied until the average number of failure days in a year is at least as large as the values in Table 2(a). The system will be further stressed in the next part of the analysis when multiple variables are stressed at the same time.

Notably, the only two years with turbidity violations are 2010 and 2011, which are wet years. The effects of the flood are discounted in the average count with only one day of violation per year. This highlights the importance of the stress test, where the data should be varied until there are at least four days in a year that experience turbiidity above 200 NTU. The results of salinity further hightlights the complexity of the system and the effects of climate variability. The frequency of failure seems to suggest that 2013, 2014 and 2015 are dry years. Although year 2013 had the highest frequency of crossing the lower salinity threshold, there was only one occurrence of violating 0.50 g/L. This is in contrast to 2014 and 2015, both recording less violations of 0.25 g/L, but the utility had to respond to the high salinity violation with Action 3 (Fig. 5) for approximately a week in both years. With reference to Fig. 4(a), 2014 and 2015 indeed experienced lower flows than 2013. This exemplifies the role that the high tide at the river mouth plays in affecting the water quality at the intake point.

Based on Table 2(a), the observed data were incrementally stressed by increasing them linearly by up to 50%, when the higher salinity threshold was finally crossed with 8-days failure. The average number of days per year that the system is expected to fail the defined thresholds in each scenario was recorded (Table 2(b)). The lower salinity threshold goal was achieved after increasing by 20%, and for turbidity after increasing by 30%. To accommodate the effects of lower flows upstream, the variables were also decreased by up to 30%.

Results show that the changes in failure modes are more rapid when flows are reduced, as compared to the cases when flows are increased. As the flow is decreased, the number of failure days increases at a faster rate; whereas when the flow is increased, the number of failure days decreases at a slower rate. As expected, the number of days of failure increased (decreased) when flows are reduced (increased). This is similar to varying the thresholds by a certain percentage and evaluating the system performance in terms of number of days of failure.

For the salinity thresholds of 0.25 g/L and 0.50 g/L, when salinity values are increased, failure intensifies. However, the failure occurs at a faster rate with increase in the salinity level with the threshold of 0.25 g/L as compared to that of 0.50 g/L.

Upon comparing the results of failure due to flow at station C29 and salinity at station C55, it is evident that the flow threshold was crossed approximately three times as often as that of salinity. There were days when recorded flows were low, signalling the possibility of high salinity, but the recorded salinity was at the acceptable level, less than 0.25 g/L. This phenomenon could be due to low tide with minimal or no backwater effect and low flows from the upstream. Hence, the flow threshold of 80 m^3/s serves mostly as an indication for the precautionary measures to be taken.

Fig. 7 shows data that would allow MWA to understand the consequences of variations within any of the three decision variables (flow, salinity at 0.25 g/L and 0.50 g/L, and turbidity). This is the outcome from step C in Fig. 3. Each point on the plot represents the frequency of failure as a result of a combination of shifts.

Given the same salinity, an increase in flow will reduce the frequency of failure due to high salinity (downward trend in Fig. 7(a) and (b)) as more water is available to dilute the saline water from the downstream. Based on the results, it is not possible to entirely mitigate the problem of high salinity. With the current salinity levels, even if flow was increased by 50%, there will still be about 35 days of failure in a year. Having such drastic increases in flow will, on the other hand, make the system more susceptible to flooding and turbidity problems.

In events where the tide increases and sea level rises, an increase in salinity by 50% given the same flow conditions will cause the number of days with salinity above 0.25 g/L to almost double to 120 days a year. This corresponds to one-third of the year that raw water will be saline. If the condition is coupled with decreasing flow, the salinity problem is drastically exacerbated. In anticipation of high salinity and decreased flows, the water utility can discuss possible steps to minimize the frequency/seriousness of system failure with dam operators.

The frequency curves in Fig. 7(c) are parallel to each other, indicating that the system is more susceptible to failure due to changes in flows as opposed to varying the turbidity values directly. According to Göransson et al. (2013) and Delpla et al. (2009), high rainfall events will cause large discharges which will have greater impacts on turbidity and affect water treatment performance as well.

Table 3
Climate models used for projecting future climate in Chao Phraya and Gulf of Thailand.

Research	Model(s) used
Wichakul et al. (2015)	MRI-AGCM3.2S
Hunukumbura and Tachikawa (2012)	MRI-AGCM3.1S
Kure and Tebakari (2012)	MRI-AGCM3.1, MRI-AGCM3.2
Kotsuki et al. (2014)	CMIP5: CSIRO-Mk3.6, INM-CM4, MIROC5, CNRM-CM5, GFDL-ESM2M IPSL-CM5A-LR
Promchote et al. (2016)	CMIP5: CanESM2, CCSM4, CNRM-CM5, GFDL CM3, GFDL-ESM2, CSIRO Mk3.6.0, FGOALS, IPSL-CM5, NorESM1
Lacombe et al. (2012)	PRECIS (RCM)

4.2.3. Plausibility of variability changes

Evidence of climate change is prevalent as discussed extensively in the literature. Specifically, based on analysis of past observations, sea level rise in the Gulf of Thailand is evident (Saramul and Ezer, 2014), and is rising at a rate significantly faster than global average rates (Trisirisatayawong et al., 2011). This phenomenon is a huge concern as it affects the water quality at the intake point, making the system susceptible to salinity problems during the dry season and turbidity during the wet season. To understand the impacts of climate change, a variety of global and regional climate models have been employed to project future rainfall and discharge at the Chao Phraya, and rainfall and sea water level in the Gulf of Thailand (refer to Table 3). Although different models have different assumptions, all the studies converge on the idea of a changing climate resulting in greater variability in the studied variables.

Along the Chao Phraya River, the mean future flows are expected to increase: up to 5% at the daily scale (Wichakul et al., 2015), between 10 and 40% at the monthly scale (Kure and Tebakari, 2012), and>20% at the annual scale (Kotsuki et al., 2014). The extreme low flows are, however, projected to decrease (Wichakul et al., 2015) and could reduce by up to 40% (Hunukumbura and Tachikawa, 2012). At the Gulf of Thailand, Lacombe et al. (2012) projected an increase in annual precipitation due to higher intensity rainfall during the wet season. An increase in rainfall, coupled with other factors such as soil moisture saturation and sea level rise can lead to flooding events, potentially with an intensity similar to that experienced in 2011 (Promchote et al., 2016).

Both historical observations and future projections suggest the susceptibility of the water supply system to effects of climate change and potential failures due to high salinity and/or turbidity. For turbidity, lower flows would ease the problems such that the utility may not need to experience it at all. Conversely, high flow conditions with an intensity like 2011 would result in an event that the system has experienced before – in 2011, the utility recorded four days with turbidity above 200 NTU.

For salinity, Hoque et al. (2016) identified the Chao Phraya Delta as one of the coastal zones extremely vulnerable to salinization. Under the RCP 8.5 scenario in the year 2100, salinity intrusion distance is projected to increase with the salinity at Samlae falling between 0.99 and 1.70 g/L under the worst-case scenario (Wongsa, 2015). A salinity level of 1.70 g/L is a 60% increment from the highest recorded salinity in 2011 at 1.04 g/L. Further, it was found that the Gulf of Thailand will experience more severe sea level rise in the future, contributed by climate change and land subsidence effects (Jaroenongard et al., 2021). Such outcomes would cause complications in water supply as pumping would have to be stopped more frequently while still maintaining adequate water supply to consumers. Attempting to mitigate the problem by dilution from additional release upstream may lead to a cascade of issues including water storage and management of upstream reservoirs and socio-economic problems.

Based on the plausible future conditions, there is a high likelihood that the utility will face water shortage and salinity intrusion problems in the future, calling for interventions. Existing adaptation measures adopted by the MWA include maximizing water flow by restricting the farmers along the Chao Phraya from planting crops during the dry season (Kordach et al., 2017). This could, however, lead to other problems such as potential conflict with farmers and, in a worst-case scenario, a reduction in agricultural production due to shortage of water (longer dry spells) caused by climate change (Boonwichai et al., 2018).

4.3. Formulating actions

The final goal of the modified CRIDA framework is to identify climate risks for localized planning and adaptation solutions. Based on the analysis, water shortage and salinity intrusion problems will very likely intensify. Fig. 8 illustrates the extreme case where flow levels decrease by 40% (due to increased use of water upstream) and salinity increases by 60% (due to sea level rise and reduced flow from upstream). Evidently, the system performance becomes critical and the utility will need to deal with salinity problems for at least one-quarter of the year. This is disruptive to the operations of the utility and will affect the consumers as well. Such occurrences must be prevented as much as possible. Several potential solutions were discussed during the stakeholder interview sessions. One solution that the MWA was exploring includes transferring raw water from the Mae Klong river basin, where water availability is more than the

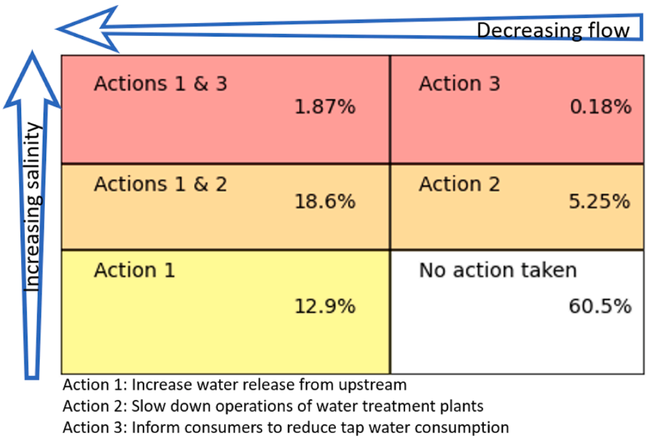

Fig. 8. Action matrix indicating the actions to be taken by the utility for failure due to flow and salinity. The case explored is that of flow level decreased by 40%, and salinity increased by 60%.

demand, to meet the demands of MWA service area. Other solutions that can be explored include shifting of the raw water intake upstream to reduce the effects of saltwater intrusion from the Gulf of Thailand and seawater desalination to provide an alternative water source for the utility to satisfy the demand.

For turbidity, the impacts on the operations of the utility would be that of longer water retention time and higher treatment costs to improve the water quality. Adaptation options to counter turbidity should be explored, but are not as urgent. Since such water quality issues are usually the results of high flows, proposed solutions will include those that can minimize the sediments from upstream, including enhanced soil conservation efforts in the upstream watersheds and controlled land use planning and management, and tighter policies and enforcement to prevent chemical discharges.

The proposed solutions include both operational and structural changes to the existing practices and water resources system. The sustainability of these solutions and their alternatives should be carefully evaluated, especially to justify the investments involved. For example, structural measures such as salinity barrier may be needed to control the effect of salinity which may require model-based analyses. Similarly, hydrological modelling of upstream watersheds to project river flows and a coupled hydrodynamic model downstream under climate change will help capture the complex dynamics of river flow, sea level rise and sedimentation. With all these tools available, several more iterations with the stakeholders are necessary for developing adaptation pathways given the best information available. These fall under steps four and five of the planning cycle, which are curently being researched and will be published in due course.

5. Conclusions and recommendations

This study presents a simple scenario-based approach to arrive at suitable climate change adaptation interventions in data-scarce situations. A site-specific assessment of climate change induced risks on municipal water supply in Bangkok was conducted using a modified CRIDA framework. The critical system performance metrics identified by the staff of the MWA during the stakeholder consultation session include streamflow, salinity, and turbidity. Climate change and climate variability effects were incorporated through scenario analysis. A series of stress tests was conducted by exposing the system to a wide range of future conditions. By varying the observed time series of data, the variability of the stressors was accounted for.

The developed frequency curves will allow the stakeholders to plan for impending risks, thereby improving the robustness of the water supply system. The approach used in this study provided the insights that the system is fairly robust to a wide range of plausible stressors given water allocation priorities. However, enhancing upstream releases to reduce the risk of high salinity or turbidity could result in conflicts with upstream use of water in agriculture. Based on the study's results, physical adaptation approaches can be explored if they can be shown to have more benefits than costs, contingent on the projected performance of the system.

A number of interesting conclusions can be drawn from the study. First, the identification of the critical thresholds by the stakeholders makes it easier for them to decide on appropriate interventions for climate change adaptation. Second, bringing climate change scenarios later into the analysis (through the stress test) helps identify the exact vulnerabilities of the system that need to be addressed. As seen in this study, it is not necessary to conduct a climate modelling (although this is recommended) for the stress test but scenario-based approaches can serve the purpose as well. It can be concluded that a similar approach will work well for smaller cities and systems where using climate models may not be very feasible or they bring in additional uncertainties due to downscaling global climate data at a smaller spatial scale. Third, this approach allows for incremental adaptation so that critical thresholds can be addressed in a phased manner. This aspect becomes quite useful when there are limited financial resources for the implementation of adaptation interventions. Water supply managers have the option to choose the scope and extent of the interventions required. Fourth, given that this approach has stakeholder consultation at the heart of the solution, there is a better chance of the sustained impact of the solution(s) to address the challenges of climate change.

The Bangkok water supply system is complex and its performance is dependent on the available river flow, salinity and turbidity. In anticipation of the potential impacts of climate change on the system, adaptation solutions that can be further explored include, for salinity, seawater desalination, shifting of the raw water intake upstream, or inter-basin transfers; and for turbidity, enhanced soil conservation efforts in the upstream watersheds, and tighter policies and enforcement to prevent chemical discharges. As such decisions require very large capital investments, more research needs to be conducted to further understand the system and address the feasibility of the adaptation options.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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