Risk Analysis of System Order for Water Infrastructure of Arid Regions

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Abstract—**Control and decision making of water supply systems influence economic, political, and social variables on several time horizons. Particularly in Central Asia, the international nature of water resources, large irrigation requirements, and depletion of surface water and aquifers in the arid region call for a systems-level framework to analyze disruptive scenarios and determine a schedule of risk countermeasures. This paper evaluates risk as the influence of scenarios on system order. Through scenario-based multi-criteria decision analysis, system initiatives are prioritized in the baseline and disruptive scenarios. The methods are applied to a case of water policies in Turkmenistan where twelve water policies are ordered according to six system criteria including social, situational, and economic factors. The system order is updated across each of seven disruptive scenarios relating to political, economic, technological, and societal trends and forecasts.**

Keywords—*systems engineering, policy analysis, water resources, Turkmenistan, scenario analysis, forecasting*

I. INTRODUCTION

Water resources management is a complex challenge facing Central Asia. With limited water supplies, growing populations and industries, and shared river systems, the need for efficient water policies and management is prevalent [1]. While each country has sovereignty over their own national water endowment, water flow patterns and quantities rely on inexact regional agreements [2]. The water resources challenges are as varied as they are complex, with examples including the dwindling of the Aral Sea, once the fourth largest in the world, to 10% of its original size and the depletion of the Amu Darya and Syr Darya rivers which provide a main water source for domestic and agricultural use in Central Asia [3].

Turkmenistan is located in the southern part of Central Asia. Many geographical factors complicate water resources management in the country including the fact that 80% of the country is covered by the Karakum Desert [4], all the rivers are international with the water resources formed outside of the country [5], and the region is arid with minimal rainfall and a higher percentage of solar days [4]. Approximately 88% of Turkmenistan's surface water resources stem from the Amu Darya River [6]. For this reason, changes in water level or water allocation along this important international river could be very disruptive. Water usage also varies greatly by season due to agricultural demand, which accounted for 92% of Turkmenistan's water resources use in 2021 [5].

This paper applies a systems-oriented approach to identifying the most disruptive scenarios for water policies in Turkmenistan. A risk register is developed which incorporates scenario-based multi-criteria decision analysis. The methods are applied for the case of water policies in Turkmenistan. Twelve water policies are assessed against six system criteria to develop a baseline system order of the water policies. Seven scenarios are identified which change the rank of the water policies, and the disruptiveness of the scenarios is quantified to aid in stakeholder decision making.

II. BACKGROUND

The five republics composing Central Asia, Kyrgyzstan, Tajikistan, Uzbekistan, Kazakhstan, and Turkmenistan, declared independence in 1991 [3]. Their independence has implications for water sharing due to the legacy of centralized water control in the region as internal water resources turned into international ones [7]. In 1992, the Interstate Commission for Water Coordination (ICWC) was established to allocate water sharing between the five republics [7]. In 1993, the International Fund for Saving the Aral Sea (IFAS) was established by the Central Asian states to develop and fund projects to improve the ecology of the Aral Sea [8]. These organizations along with many others seek to address the growing water resources complexities in the region.

In Turkmenistan specifically, there are many existing and ongoing water infrastructure projects. The Altyn Asyr Lake is a man-made reservoir in the Karakum Desert designed to reclaim runoff water from agriculture through a series of canals with additional energy projects nearby and construction of villages for fishing and farming [9]-[11]. The Karakum Canal is the longest canal in the world and provides water from the Amu

Darya River to the south of Turkmenistan including many agricultural areas and the capital of Ashgabat [12]. Much of the infrastructure is aging and energy intensive, causing about half of the water to be lost between withdrawal and final delivery [13]. The United Nations Development Programme (UNDP) supports projects seeking to improve infrastructure including adding liners to canals, installing more efficient water pumps, and switching to water-saving irrigation methods [13]. Drip irrigation, distributing water to slowly drip to plant roots instead of flooding fields or channels, in particular is promising as experiments have shown that this method can achieve higher efficiency and lower water consumption for cotton in Turkmenistan [14]. Another challenge facing the infrastructure is the siltation of reservoirs along the Amu Darya River caused by the buildup of sediment which reduces the capacity and water supply efficiency [15] in addition to increasing flood risks and reducing hydropower capabilities [16]. Beyond river water resources, Turkmenistan is also exploring desalination of water from the Caspian Sea to supply drinking water with a desalination plant already built in Ekerem, but the process is very expensive due to the high pressure required to filter water through reverse osmosis [17]-[18]. A map of Turkmenistan and the republics of Central Asia including selected water resources such as the Amu Darya River, Karakum Canal, Altyn Asyr Lake, and Caspian Sea are shown in Fig. 1.
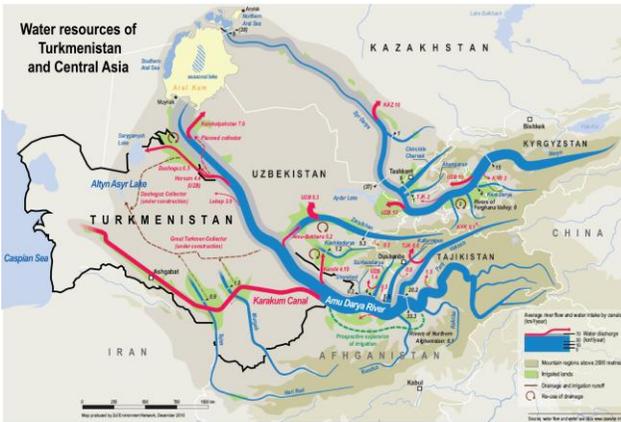

Fig. 1. Water resources of the arid region of analysis for the disruption of system order. Adapted from [7].

Many organizations are helping to address water resources management in Turkmenistan through funding projects, defining goals, and encouraging regional cooperation. The United Nations (UN) established a 2030 agenda with development goals including one on water sanitation and management [19]. The UN is also involved in a current programmatic intervention to address water management in Turkmenistan to improve resilience [20]. Other projects have launched water metering systems for the Karakum Canal to measure water flow and provide data for accurate water allocations [21]. The Central Asia Regional Economic Cooperation (CAREC) Program focuses on agriculture and water as one of its main operational clusters and promotes discussion on water management issues [22]-[23]. The Global Environment Facility (GEF) has multiple ongoing projects in Turkmenistan on improving water use efficiency, applying new

irrigation technology, and monitoring water reclamation [24]-[25]. IFAS has also created a 2023 agreement between Central Asian states committing to further strengthen regional water cooperation and introduce resource-saving technologies [26]. The ICWC also has helped support the Fourth Aral Sea Basin Program from 2020-2030 with projects focusing on the integrated use of water resources [27]-[28].

III. METHODS

This paper describes a multi-criteria decision analysis to model risk as the disruption of system order adapted from [29]-[32]. Stakeholder perspectives are considered to develop system criteria that will be used to measure and rank the effectiveness of the initiatives which are components of the system. The initiatives are identified through stakeholder elicitation and literature review. The initiatives are then assessed for each of the criteria in order to determine the baseline prioritization. Scenarios, such as trends, changes, and new developments, that could disrupt the system are then identified. The change in criteria importance for each scenario is then quantified in order to determine changes in initiative rankings and to determine the disruptiveness of each scenario.

The method is developed through the creation of three sets. The first set is the system criteria, $C = \{c_1, c_2, ..., c_m\}$ which represents the objectives of the system. These criteria are determined through stakeholder consultation and available reports. Each criterion is assigned a relative weight in the baseline scenario, w_{jb}, which represents the criterion's relative importance to stakeholders in the baseline scenario. The six criteria used for the water policies case in Turkmenistan are identified in Table I and are given equal weight in the analysis.

TABLE I.   CRITERIA FOR DETERMINING SYSTEM ORDER OF WATER INFRASTRUCTURE

Index	Criteria	Sub-criteria
c.01	Operational Longevity	Water resilience
		Fuel use management
		Resource quality resilience
c.02	Adaptability	Timeframe
		Local support
		Regional negotiation
c.03	Mitigation	Address soil salination
		Improve water availability
		Reduce agriculture waste
c.04	Affordability	Cost
		Outside investment
		Potential savings
c.05	Quality of Life	Potable water
		Reduce resource degradation
		Promote regional collaboration
c.06	Economic Development	Attract foreign investment
		Create jobs
		Improve revenue streams

The second set contains policies and projects that address the water conditions in Turkmenistan, denoted as the set of

initiatives $X = \{x_1, x_2, \dots, x_n\}$. The initiatives are developed from stakeholder elicitation as well as a literature review of current policies and associated projects. Table II describes each of the twelve initiatives used for the water policies case in Turkmenistan that are briefly described in the Background section.

TABLE II. INITIATIVES FOR IMPROVING WATER INFRASTRUCTURE SYSTEMS

Index	Initiative
x.01	Altyn Asyr Lake
x.02	Desalination
x.03	UN Development Goals
x.04	Water Metering
x.05	Desilting of Reservoirs
x.06	UN Programmatic Intervention
x.07	CAREC Projects
x.08	UNDP Infrastructure Projects
x.09	GEF Projects
x.10	Drip Irrigation
x.11	ICWC Projects
x.12	IFAS 2023 Agreement

Additional initiatives representing other water policies and associated projects can be assessed in future work as new policies are developed or the impact of current policies is better understood.

Each of the system components is then scored against all of the system criteria in order to establish a baseline system order. This process begins with the criteria-initiative assessment where each initiative is given a score for how well it achieves each criterion: 'very well,' 'well,' 'somewhat,' or 'not at all.'

The four classifications correspond to a numerical score a_{ij} for initiative x_i in relation to criterion c_j. In the criteria-initiative assessment, each initiative is scored according to its stated goals. For each criterion, three binary sub-criteria were developed as shown in Table I. Each sub-criterion is structured so that a score of one represents a positive achievement of the sub-criterion while a score of zero represents that the initiatives do not address the sub-criterion. The sum of the sub-criterion scores for each initiative is then mapped to the overall score for each criterion.

The criteria-initiative assessment is shown symbolically in Table III: a filled circle represents 'very well,' a half-filled circle indicates 'well,' an empty circle denotes 'somewhat,' and a dash signifies 'not at all.' The assessment scores are determined through a literature review of current policies and projects.

The next step to calculate the baseline system order is to determine the baseline scores for each initiative. An additive value form is used, following the convention of [29], [33]. The scores are calculated as a weighted sum of each of the criteria-initiative assessment scores as shown in (1) with the baseline score for initiative x_i denoted $V(x_i)_b$:

$$V(x_i)_b = \sum_{j=1}^{m} w_{jb} a_{ij}, \forall x_i \epsilon X. \tag{1}$$

If $V(x_p)_b > V(x_q)_b$, then initiative x_p is ranked higher in the baseline system order than x_q. The baseline system order is then obtained from sorting the baseline scores for each initiative in descending order. Next, the disruption of various scenarios on the system objectives is assessed.

The third set represents possible changes within the system including threats and opportunities for improvement and is denoted as the set of scenarios $S = \{s_1, s_2, \dots, s_p\}$. Table IV describes the seven scenarios included in the water policies case for Turkmenistan. Stakeholder disposition changes could include changes in international cooperation, policy fluctuation, or regional relations. The natural hazards scenario incorporates droughts, desertification, pandemics, or other natural disasters.

TABLE III. CRITERIA-INITIATIVE ASSESSMENT FOR WATER INFRASTRUCTURE SYSTEMS

	x.01 - Altyn Asyr Lake	x.02 - Desalination	x.03 - UN Development Goals	x.04 - Water Metering	x.05 - Desilting of Reservoirs	x.06 - UN Programmatic Intervention	x.07 - CAREC Projects	x.08 – UNDP Infrastructure Project	x.09 - GEF Projects	x.10 - Drip Irrigation	x.11 - ICWC Projects	x.12 - IFAS 2023 Agreement
c.01 - Operational Longevity	●	—	●	○	○	◐	○	◐	◐	○	◐	○
c.02 - Adaptability	◐	◐	●	○	○	◐	◐	○	—	◐	◐	◐
c.03 - Mitigation	◐	○	◐	○	○	○	○	◐	○	○	●	○
c.04 - Affordability	—	—	○	◐	○	◐	◐	◐	○	○	○	○
c.05 - Quality of Life	—	○	●	○	○	○	○	○	○	○	●	●
c.06 - Economic Development	●	○	○	○	●	○	○	●	◐	●	○	○

Economic changes consist of changes in main industries, markets, supply chains, and jobs. Digitization could include the creation and adoption of new technologies across industries. The infrastructure enhancements may include improved dams, canals, and water treatment facilities. The condition changes scenario represents changes in temperature, weather, water levels of reservoirs, or river flow. Population shifts could include changes in population as well as the population distribution and density across Turkmenistan.

TABLE IV. SCENARIOS FOR WATER INFRASTRUCTURE SYSTEMS

Index	Scenario
s.01	Stakeholder Disposition Changes
s.02	Natural Hazards
s.03	Economic Changes
s.04	Digitization
s.05	Infrastructure Enhancements
s.06	Condition Changes
s.07	Population Shifts

The impact of each scenario on the relative importance of each criterion is then determined. A five-point Likert scale is used with the options 'decreases,' 'decreases somewhat,' 'neutral,' 'increases somewhat,' and 'increases.' The impacts are then mapped to a normalized weight w_{jk} for criterion c_j under scenario s_k so that the effects of 'decrease' and 'increase' are inversely proportional as are 'decreases somewhat' and 'increases somewhat'. The scenario criteria weights are then applied to the initiative rankings by modifying (1). The score for each initiative x_i in scenario s_k is denoted $V(x_i)_k$ and calculated according to (2):

$$V(x_i)_k = \sum_{j=1}^{m} w_{jk} a_{ij} , \forall x_i \epsilon X, s_k \epsilon S. \qquad (2)$$

The relative reweighting of criteria for each scenario allows stakeholders to make judgments of relative criteria importance based on insight and experience without the requirement to make an additional criteria-initiative assessment for each scenario [33]. The criteria-scenario assessment is shown in Table V, where the five-point Likert scale is denoted symbolically with upward arrows representing an increase and downward arrows representing a decrease. Solid arrows represent a stronger impact than empty arrows, and dashes are neutral.

To capture the change in system order, each scenario is also given a scenario disruptiveness score which quantifies risk by calculating the total level of disruption to the system order. The disruptiveness of scenario s_k is denoted $D(s_k)$ and is calculated using the change from baseline scores for each initiative in the scenario. The scores are calculated using (3) before normalizing for comparison:

$$D(s_k) = \sum_{i=1}^{n} (R(x_i)_b - R(x_i)_k)^2. \qquad (3)$$

TABLE V. CRITERIA-SCENARIO ASSESSMENT FOR CHANGES IN CRITERIA IMPORTANCE UNDER POTENTIALLY DISRUPTIVE SCENARIOS

	s.01 – Stakeholder Disposition Changes	s.02 – Natural Hazards	s.03 – Economic Changes	s.04 – Digitization	s.05 – Infrastructure Enhancements	s.06 – Condition Changes	s.07 – Population Shift
c.01 – Operational Longevity	▽	△	▲	—	—	▲	▽
c.02 - Adaptability	—	△	△	—	▲	▲	▲
c.03 - Mitigation	—	△	—	—	△	△	▲
c.04 - Affordability	△	▼	▽	△	△	▽	▽
c.05 - Quality of Life	▲	▲	—	—	—	△	▲
c.06 - Economic Development	▽	▽	▲	▲	△	▲	—

IV. RESULTS AND DISCUSSION

The system order results are shown in Fig. 2. The initiatives are sorted according to their baseline system order which is shown by the black bar, with the highest priority initiatives at the top left. The red bar shows how far each initiative can decrease in ranking under the disruptive scenarios. The blue bar indicates how far the initiative can increase in ranking under the disruptive scenarios. For example, initiative $x.08$ is ranked third in the baseline scenario, but its ranking can increase to first or decrease to fifth depending on the disruptive scenarios. The UN Development Goals for clean water and sanitation is ranked highest in the baseline system order followed by ICWC projects, the UNDP infrastructure project, and the Altyn Asyr Lake. Due
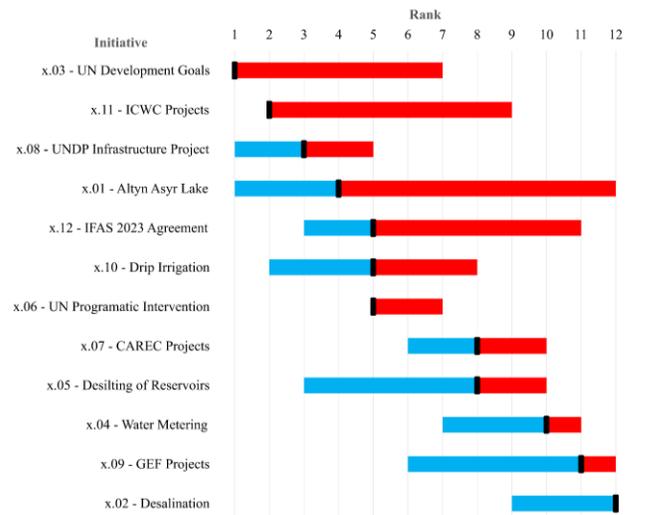

Fig. 2. Disruption of system order of water infrastructure initiatives by several scenarios, with red and blue indicating decreases and increases in the rank of an initiative, respectively.

to the scenarios, there is a relatively high variability of the system order with the system order scores having an average range of 5.66 across the seven different scenarios. The Altyn Asyr Lake has the highest variability in system order as it is ranked first in some scenarios and last in others. Many reports are also uncertain of the impact of the Altyn Asyr Lake with concerns about water degradation, evaporation, and seepage [9] while other reports emphasize its importance to Turkmenistan and Central Asia [10].

The desalination projects, GEF projects, and water metering are ranked in the bottom three in the baseline system order. Additionally, these initiatives are not ranked above sixth in any of the disruptive scenarios. Desalination, while helpful for increasing freshwater supply, has numerous potential disadvantages including high energy requirements, brine by-product management, and overextraction of water from the Caspian Sea, which could threaten its health [16].

Certain initiatives, like the UNDP infrastructure project, drip irrigation, and CAREC projects have a baseline ranking that aligns with the center of the range of rankings under disruptive scenarios. These rankings suggest that the position of the initiatives within the system order remains relatively balanced between the different scenarios, increasing and decreasing in rank to an equal extent. Other initiatives like the UN Development Goals, ICWC projects, Altyn Asyr Lake, and IFAS 2023 agreement decrease in system order under certain scenarios far more than they increase. Conversely, desilting of reservoirs, water metering, GEF projects, and desalination can increase in system order far more than they can decrease.

The scenario disruptiveness scores are shown in Fig. 3. Digitization is the most disruptive scenario followed by stakeholder disposition and economic changes. Digitization has the opportunity to impact many different sectors as new technologies are adopted. This result is particularly significant as there are current projects focused on electronic document management and digital economy development in Turkmenistan seeking to improve business operating efficiency [34]. Due to the shared nature of water resources in Turkmenistan, changes in stakeholder disposition have far-reaching impacts on water resources management. Many organizations emphasize the need for regional cooperation for water management including the ICWC, IFAS, and CAREC Program [7]-[8], [22]-[23]. Economic changes, including shifts in agriculture and fuel sources, can grea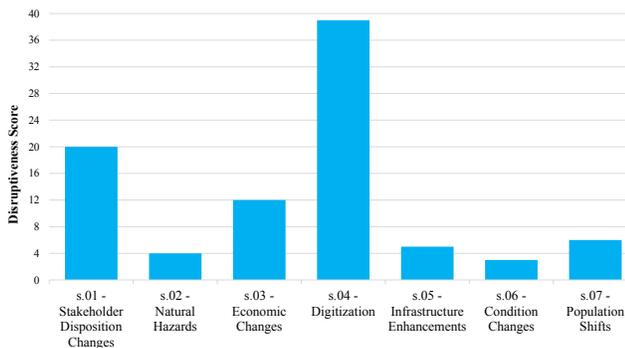tly change water demand and usage, especially with the large proportion of water used for agriculture in Turkmenistan [5]. Condition changes, natural hazards, infrastructure enhancements, and population shifts have the lowest disruptiveness scores of the scenarios considered. The disruptiveness scores provide insight into the possibly unforeseen impacts of certain scenarios on water policies. The scenario disruptiveness scores can also be used to inform stakeholder decisions on resilience and recovery measures to decrease the impact of the most disruptive scenarios.

V. CONCLUSIONS

This work demonstrates how scenario-based multi-criteria decision analysis can be applied to water policies. By addressing the current state of water policies in the baseline scenario, disruptive scenarios which will affect system priorities, thus changing the system order, can be identified. The methods define and quantify risk as the level of disruption to the system order of water policies. The work incorporates tools of systems analysis and risk analysis to provide insights for water policy, logistics, and infrastructure investment and planning including results on the highest ranked initiatives and most disruptive scenarios. Key results are summarized in Table VI.

TABLE VI.   SUMMARY OF KEY RESULTS OF MULTI-CRITERIA DECISION ANALYSIS FOR WATER INFRASTRUCTURE SYSTEMS

Result	Description
Most disruptive scenarios	s.04 Digitization, s.01 Stakeholder Disposition Changes, and s.03 Economic Changes were the most disruptive scenarios to the system order.
Highest ranked initiatives in the baseline	x.03 UN Development Goals, x.11 ICWC Projects, and x.08 UNDP Infrastrurcture Project were identified as the initiatives with the highest ranks in the baseline system order.
Lowest ranked initiatives in the baseline	x.02 Desalination, x.09 GEF Projects, and x.04 Water Metering had the lowest ranks in the baseline system order.
Initiative resilience	x.01 Altyn Asyr Lake had the highest variability in system order. x.06 UN Programmatic Intervention had the lowest variability.

The methods are applicable to regions experiencing water management and availability challenges. Future work will extend the methods to other regions in Central Asia and beyond. Additionally, hydrological data can be incorporated into the methodology to create a range of future scenarios, and sensitivity analysis can be done for uncertain or changing scores.

Fig. 3. Disruptiveness score for each scenario based on the sum of squared changes across all water infrastructure initiative rankings.

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