Assessment of System Order Risk and Resilience with Modeled Societal and Hydrologic Variables

Gigi Pavur, M.IEEE
Dept. of Civil and Environmental Engineering
University of Virginia
Charlottesville, VA USA
gp3vd@virginia.edu

Megan C. Marcellin, M.IEEE
Dept. of Systems and Information Engineering
University of Virginia
Charlottesville, VA USA
mcm5ft@virginia.edu

Davis C. Loose, M.IEEE
Dept. of Systems and Information Engineering
University of Virginia
Charlottesville, VA USA
dcl6d@virginia.edu

Megan E. Gunn, M.IEEE
Dept. of Systems and Information Engineering
University of Virginia
Charlottesville, VA USA
meg9hq@virginia.edu

Matthew C. Gunn M.IEEE
Dept. of Systems and Information Engineering
University of Virginia
Charlottesville, VA USA
mcg3er@virginia.edu

Benjamin D. Trump
Engineer Research & Development Center
US Army Corps of Engineers
Concord, MA USA
Benjamin.D.Trump@usace.army.mil

Igor Linkov
Engineer Research & Development Center
US Army Corps of Engineers
Concord, MA USA
Igor.Linkov@usace.army.mil

Venkataraman Lakshmi, SM.IEEE
Dept. of Civil and Environmental Engineering
University of Virginia
Charlottesville, VA USA
vlakshmi@virginia.edu

James H. Lambert, F.IEEE
Dept. of Systems and Information Engineering
University of Virginia
Charlottesville, VA USA
lambert@virginia.edu

***Abstract* — Uncertainty of hydrologic conditions in the near future (within thirty years) challenges economic development in complex regions of Central Asia. This study models risk and resilience in terms of disruption to system order using multiple criteria of impacts to society and hydrology. Models of low, moderate, and extreme variables are compared for their impacts. Sub-basins of the greatest and least disruption to system order are identified on regional maps. A demonstration of Turkmenistan at the sub-basin level is provided. Results and methodology of this analysis support efforts to improve understanding of regional risk and resilience considering modeled scenarios of future societal and environmental conditions.**

Keywords — Risk management, multicriteria analysis, scenario-based preferences, decision analysis

I. Introduction

Globally, sustainable development efforts are challenged by uncertainty of environmental metrics [1-3]. Uncertainty of flood and drought intensity, frequency, and duration can exacerbate challenges to sectors of economy, food, water, energy, and health [1-3].

The Coupled Model Intercomparison Project Phase 6 (CMIP6) addresses these challenges [1-2, 4-5]. This global collaboration compares and assesses General Circulation Models (GCMs) of historic, present, and future hydrologic conditions. A notable component of CMIP6 is consideration of Shared Socio-economic Pathways (SSPs). These provide modeled scenarios of near future conditions, such as present to thirty years. The SSPs vary from conservative (SSP126), moderate (SSP245), and extreme (SSP585) scenarios of future conditions of temperature and precipitation [1-2, 4-6].

This study aims to improve understanding of risk and resilience when considering multidisciplinary factors of society and future hydrology. It is among the first to use high-resolution modeled data in a *risk register* of basins. A demonstration is provided for Turkmenistan, a region of Central Asia facing uncertainty of hydrologic conditions in the next three decades [7].

The methodology is as follows: First, social and hydrologic criteria are ordered from highest to lowest importance. Second, a baseline scenario is defined using only social criteria. Third, scenarios of combined society and hydrologic criteria are created across three SSPs (SSP126, SSP245, and SSP585) for three models. Fourth, factor weights for criteria are updated using a swing weight technique [8-10]. Fifth, the disruption of system order between the baseline and the scenarios is used to calculate risk [8-13]. Sixth, disruption is quantified using normalized sum of differences in order [14-21]. Scenarios of greatest and least disruption are identified. Seventh, basin order and risk are spatially mapped for scenarios of interest. Lastly, basins of the greatest increase and decrease in order across scenarios are mapped.

II. Data

This section describes the population and hydrologic projections data used in the demonstration. All data are pre-processed by spatially resampling to the sub-basin level. The sub-basins are defined by the Level 05 HydroBASINS product [22]. The HydroBASINS data is available in 2026 at: https://www.hydrosheds.org/products/hydrobasins.

Population data was derived from the Oak Ridge National Laboratory LandScan Global [23]. The 2023 population data (i.e., the most recently available data at the time of analysis) was used for the demonstration. LandScan Global data are available in 2026 at: https://landscan.ornl.gov.

Modeled hydrologic data from 2024 – 2055 were obtained from NASA (NEX-GDDP-CMIP6) [24]. This dataset downscales CMIP6 to a higher spatial resolution of 0.25° x 0.25°, which is sufficient for this demonstration at the Level 05 HydroBASINS resolution [24]. The hydrology variables selected for this demonstration are precipitation and air temperature. The NEX-GDDP-CMIP6 is available in 2026 at: https://doi.org/10.7917/OFSG3345.

Three SSPs were used in the demonstration, specifically SSP126, SSP245, and SSP585. Three models were selected for the demonstration based on previous research by Zareian et al., 2024 that assessed model performance in Turkmenistan and western Asia [25]. The selected models include BBC-CSM2-MR developed by the China Meteorological Administration, IPSL-CM6A-LR developed by the Institute Pierre-Simon Laplace, and HadGEM3-GC31-LL developed by the Meteorological Office Hadley Centre [25].

III. METHODOLOGY

This section describes the methodology in several parts as follows. The framework of the model includes the following elements:

1) $S_c = \{c_1, \ldots, c_j\}$: the set of *j* criteria,
2) $S_n = \{S_o, \ldots, S_n\}$: the set of *n* scenarios containing one or more criteria, with S_0 representing the baseline scenario,
3) $b_i = \{b_1, \ldots, b_i\}$: the set of *i* basins,
4) w_j: the weight assigned to criterion c_j in scenario s_n.

Table I summarizes the social and hydrologic criteria used for the demonstration. The SSP and model information are indicated for each hydrologic criterion.

$$S_n(b_i) = 100 * \sum_{j=1}^{k} w_j c_{ij} \quad (1)$$

$$where\ 0 \le w_j \le 1\ \forall j \in J\ and \sum_{j \in J} w_j = 1$$

First, the criteria are ordered using Eq. 1. A descending sorting order is used for the population density and air temperature criteria (i.e., basins of the greatest population density or the warmest air temperature are considered as the highest priority). An ascending sorting order is used for the precipitation data (i.e., basins of the least precipitation are considered as the highest priority).

Second, the social data (i.e., the population density criteria) is used to define the baseline order. This represents the system before disruptions due to consideration of the modeled hydrologic conditions.

TABLE I. SAMPLE OF CRITERIA, SSP, AND MODEL INFORMATION USED IN THE DEMONSTRATION TO MODEL DISRUPTION OF SYSTEM ORDER

Criterion			**Index**
Variable	**SSP**	**Model**	
Population density in 2023 ($pop.$)	N/A	LandScan	c_1
Average annual precipitation from 2024 – 2055 ($pr.$)	SSP126	BBC-CSM2-MR	c_2
		IPSL-CM6A-LR	c_3
		HadGEM3-GC31-LL	c_4
	SSP245	BBC-CSM2-MR	c_5
		IPSL-CM6A-LR	c_6
		HadGEM3-GC31-LL	c_7
	SSP585	BBC-CSM2-MR	c_8
		IPSL-CM6A-LR	c_9
		HadGEM3-GC31-LL	c_{10}
Average annual air temperature from 2024 – 2055 ($tas.$)	SSP126	BBC-CSM2-MR	c_{11}
		IPSL-CM6A-LR	c_{12}
		HadGEM3-GC31-LL	c_{13}
	SSP245	BBC-CSM2-MR	c_{14}
		IPSL-CM6A-LR	c_{15}
		HadGEM3-GC31-LL	c_{16}
	SSP585	BBC-CSM2-MR	c_{17}
		IPSL-CM6A-LR	c_{18}
		HadGEM3-GC31-LL	c_{19}

Third, scenarios are defined to consider criteria of both society (i.e., population density) and hydrology (i.e., modeled precipitation and air temperature from 2024-2055). Table II summarizes the scenarios and contributing criteria. Scenario *s.00*, population density, represents the baseline order.

TABLE II. SAMPLE OF SCENARIOS AND CRITERIA IN DEMONSTRATION TO MODEL DISRUPTION OF SYSTEM ORDER

Scenario	**Criteria**
s.00: baseline, pop.	c_1
s.01: pop. + pr.$_{SSP126}$ *+ tas.*$_{SSP126}$ *(BBC-CSM2-MR)*	c_1, c_2, c_{11}
s.02: pop. + pr.$_{SSP245}$ *+ tas.*$_{SSP245}$ *(BBC-CSM2-MR)*	c_1, c_5, c_{14}

s.03: pop. + pr.$_{SSP585}$ + tas.$_{SSP585}$ (BBC-CSM2-MR)	c_1, c_8, c_{17}
s.04: pop. + pr.$_{SSP126}$ + tas.$_{SSP126}$ (IPSL-CM6A-LR)	c_1, c_3, c_{12}
s.05: pop. + pr.$_{SSP245}$ + tas.$_{SSP245}$ (IPSL-CM6A-LR)	c_1, c_6, c_{15}
s.06: pop. + pr.$_{SSP585}$ + tas.$_{SSP585}$ (IPSL-CM6A-LR)	c_1, c_9, c_{18}
s.07: pop. + pr.$_{SSP126}$ + tas.$_{SSP126}$ (HADGEM3-GC31-LL)	c_1, c_4, c_{13}
s.08: pop. + pr.$_{SSP245}$ + tas.$_{SSP245}$ (HADGEM3-GC31-LL)	c_1, c_7, c_{16}
s.09: pop. + pr.$_{SSP585}$ + tas.$_{SSP585}$ (HADGEM3-GC31-LL)	c_1, c_{10}, c_{19}

Fourth, the swing-weight technique is used to update the scenario factor weights. To ensure that social and hydrology criteria are equally considered within a scenario, the sum of weights for the hydrology criteria is 0.5 across all scenarios.

Fifth, risk (R_n) at the basin level is calculated as the difference in basin order between the scenario order and the baseline order using Eq. 2. An increase in basin order results in a positive R_n value. A decrease in basin order results in a negative R_n value.

$$R_n(b_i) = S_0(b_i) - S_n(b_i) \quad (2)$$

Sixth, the normalized sum of squares of differences in order is calculated to identify the most and least disruptive scenarios. Eq. 3 and Eq. 4 are used to quantify risk as the influence of each scenario to the system order [8-10, 14-21].

$$x(S_n) = \sum_i^N \left(S_0(b_i) - S_n(b_i)\right)^2 \quad (3)$$

$$X(S_n) = \frac{x(S_n) - x(S)_{min.}}{x(S)_{max.} - x(S)_{min.}} \quad (4)$$

Lastly, spatial plots are used to improve understanding of the location and distribution of basin-level priority and risk. Thus, scenario basin order and risk and spatially plotted. Basins of the greatest increase and decrease in order across the scenarios are identified and further examined.

IV. Sample of Results of demonstration

This section describes a sample of results for the demonstration examining societal and hydrologic criteria in Turkmenistan from 2024-2055. The study area is defined by 27-sub-basins that either intersect or are contained by the Turkmenistan national boundary.

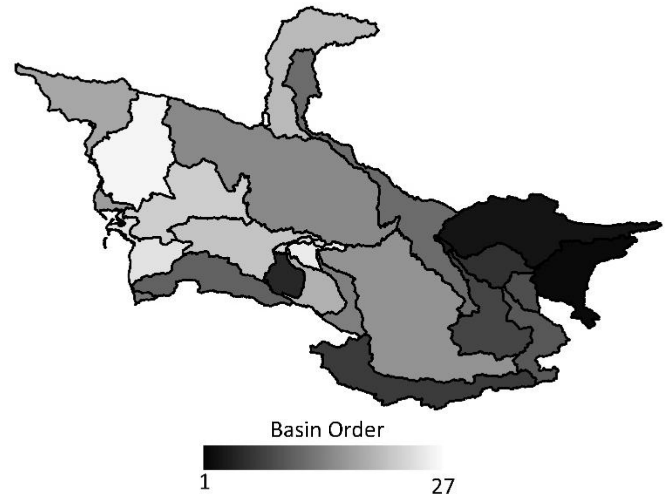

Figure 1: The basin order for scenario s.00: population density. This represents the baseline order in the demonstration.

Fig. 1 shows the spatial plot of *s.00*, the population density basin order, and represents the baseline basin order. Basins of the greatest population density (i.e., the greatest priority) are depicted in black with a value equal to or near one. Generally, the highest order basins are in the northeastern region. The basin containing Ashgabat, the capital of Turkmenistan, additionally ranks highly in the baseline scenario. Basins of the lowest population density (i.e., the lowest priority) are depicted in white with a value equal to or near 27. The lowest priority basin in the baseline scenario is in the northwestern region and contains the large, highly saline waterbody, Garabogazköl [26-27].

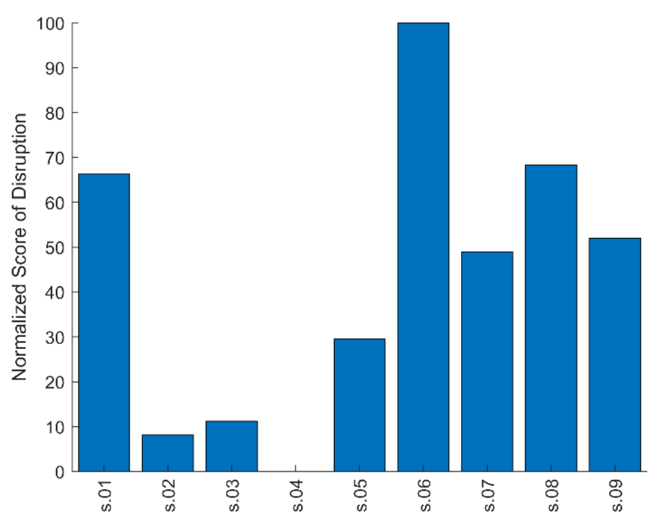

Figure 2: Normalized score of disruption for each scenario, s.01 – s.09 in the demonstration

Fig. 2 shows the normalized score of disruption for scenarios *s.01 – s.09* in the demonstration. The least disruptive scenario is *s.04*, population density and modeled hydrologic data for precipitation and air temperature in SSP126 using IPSL-CM6A-LR. The most disruptive scenario is *s.06*, population density and modeled precipitation and air temperature in

SSP585 using model IPSL-CM6A-LR. It is important to note that the observed pattern of SSP126 being the least disruptive scenario and SSP585 being the most disruptive scenario was not the case for the other two models. Thus, the models do not agree on which SSP is most disruptive to system order.

Spatial plots of basin order and risk are examined to improve understanding of the most and least disruptive scenarios. Fig. 3A shows the basin order spatial plot of the least disruptive scenario, *s.04*. Fig. 3B shows the basin order spatial plot of the most disruptive scenario, *s.06*. In both scenarios, the basin order shows a similar spatial distribution with higher priority in the northern portions of the study area and high priority in the central basin containing Ashgabat. To better understand the relative increases and decreases in basin order compared to the baseline scenario, the spatial distribution of risk is examined.

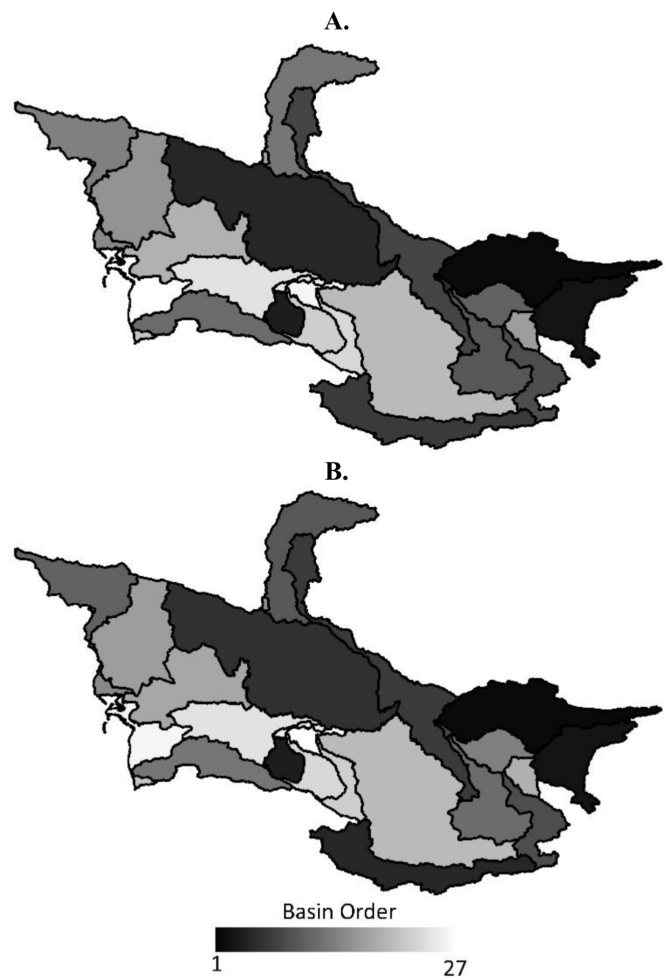

Figure 3: Spatial plots of basin order for the following scenarios: (A) the least disruptive scenario, s.04, and (B) the most disruptive scenario, s.06.

Fig. 4 shows the spatial plots of risk for the most and least disruptive scenarios. Basins are depicted in blue if the given basin decreased in order compared to the baseline scenario. Similarly, basins are depicted in red if the given basin increased in order compared to the baseline scenario. Fig. 4A shows the spatial risk plot for the least disruptive scenario, *s.04*. Fig. 4B shows the spatial risk plot for the most disruptive scenario, *s.06.* Generally, basins in the northern and northwestern regions increase in priority while basins in the southern region decrease in priority for both scenarios.

To improve understanding of the location of basins with the greatest disruption to system order, the top three basins of greatest increase and decrease in basin order are mapped. Fig. 5 shows the three basins of greatest increase in order are clustered in the northern region (depicted in red). The three basins of greatest increase and decrease in basin order are mapped. Fig. 5 shows the three basins of greatest increase in order are clustered in the northern region (depicted in red). The three basins of greatest decrease in order are divided between the southern region and the northeastern region (depicted in blue).

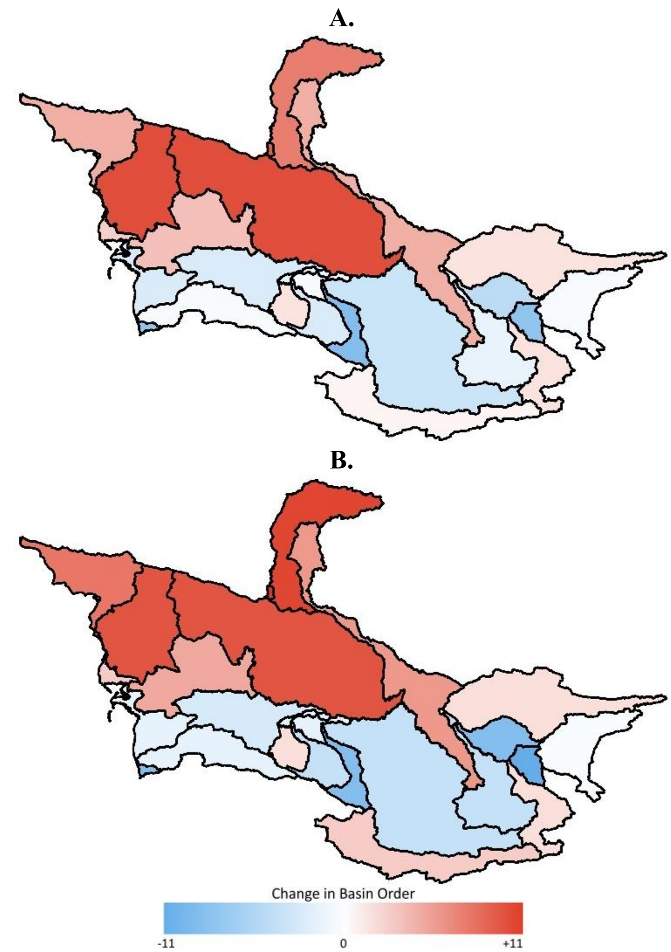

Figure 4: Spatial plots of the basin-level disruption to system order for the following scenarios: (A) the least disruptive scenario, s.04, and (B) the most disruptive scenario, s.06.

To improve understanding of the location of basins with the greatest disruption to system order, the top three basins of greatest increase and decrease in basin order are mapped. Fig. 5 shows the three basins of greatest increase in order are clustered in the northern region (depicted in red). The three

basins of greatest decrease in order are divided between the southern region and the northeastern region (depicted in blue).

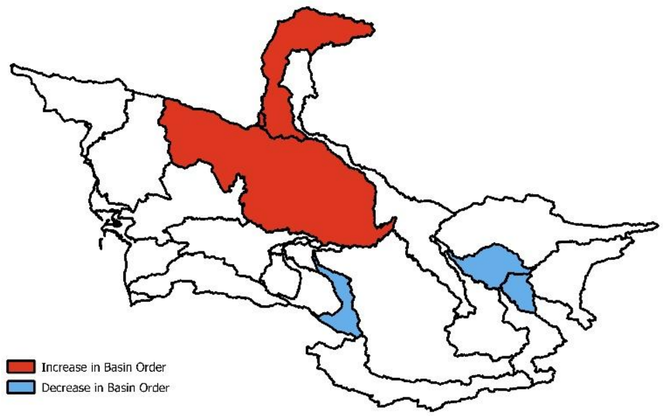

Figure 5: Spatial plot of the top three basins with greatest increase (red) and greatest decrease (blue) in basin order.

V. Discussion

A demonstration of the methodology is provided for sub-basins of Turkmenistan. Priorities of society (i.e., population density) and the environment (i.e., hydrologic projections) are combined in a *risk register* of basins. Quantification of disruption and spatial plots give insight into basin-level risk and resilience for the region considering current population distributions and modeled hydrology data from 2024-2055.

The most and least disruptive scenarios are identified. This showed notably similar spatial patterns of northern basins generally increasing in basin order and southern basins decreasing in basin order. This suggests that regardless of the level of disruption, the scenarios concur with regions that increase and decrease in priority. However, the most and least disruptive scenarios of this demonstration were derived from the same model, IPSL-CM6A-LR. Thus, further analysis is recommended to understand the system disruption nuances across different models.

It is important to note this study is limited by consideration of only two hydrologic variables at an annual temporal resolution. Future work can utilize additional modeled variables available in CMIP6 at sub-annual, seasonal, and monthly timescales. Additionally, the model can be further improved by incorporating multidisciplinary datasets representing priorities of public policy, public health, economic development, etc.

VI. Conclusions

This study demonstrates a methodology to quantify risk as the disruption of system order considering the combined sustainable development priorities of populations and modeled hydrologic conditions. This demonstration is among the first to use high-resolution projections in a *risk register* of basins.

Three scenarios were considered to improve understanding of system disruptions considering low, moderate, and extreme scenarios of modeled hydrologic conditions over a horizon of 30 years. The basins of greatest disruption (increase and decrease in order) were identified and mapped to further examine the spatial patterns of disruption.

This study serves as a framework to support future risk analysis of hydrologic projections considering multidisciplinary criteria. Results of the study and demonstration can be used to support economic development efforts aimed to decrease basin-level risk and increase resilience to uncertainty of society and hydrology.

Acknowledgments

This research was supported by the United States Army Corps of Engineers and the Commonwealth Center for Advanced Logistics Systems.

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