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Development of a framework for assessing climate risk in water supply and its computation for the Districts of Maharashtra, India

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ABSTRACT

The paper discusses the development of a composite index for assessing the risks faced by rural communities because of disruptions in water supply caused by natural hazards such as droughts, floods, and landslides. The various parameters considered for developing the three dimensions of the risk index, namely, hazard, exposure, and vulnerability, the rationale for choosing those parameters, and the manner in which these parameters influence them are discussed. The index uses 29 variables: five for hazard, 15 for exposure, and the remaining nine for vulnerability. The variables are natural, physical, socioeconomic, and institutional or policy-related. The quantitative criteria for assigning values for various parameters and the analytical procedure for computing the sub-indices and the final risk index are also discussed. The paper also presents the results of a mapping of climate-induced risk to water supply in 35 districts of the state of Maharashtra in western India, done using district level data on the various parameters concerned, and identifying the district where water supply systems are highly prone to climate-induced risks.

Key words: Climate-induced risk, Exposure, Maharashtra, Natural hazards, Rural water supply, Vulnerability

HIGHLIGHTS

- The paper discusses the development of an analytical framework or tool for assessing climate-induced risks faced by rural communities in the state of Maharashtra.
- Three dimensions of the risk, namely, hazard, exposure, and vulnerability, are considered.
- The climate-induced risk in water supply caused by natural hazards such as droughts, floods, and landslides is analyzed and mapped for all the 35 districts of Maharashtra.

1. INTRODUCTION

Climate risk is a composite of hazard, exposure, and vulnerability (WMO, 2009). The degree of risk in water supply induced by climate variability and change depends on a variety of natural, physical, social, economic, cultural, environmental, and institutional factors (Kumar *et al.*, 2021). For building climate-resilient water supply systems in any locality, understanding the various factors influencing the climate risks and the local contexts in relation to these factors are extremely important (source: based on UNICEF & GWP 2014; UNICEF, 2016; Kumar *et al.*, 2021).

Many regions of a country also face extreme climatic events, especially droughts and abnormally wet years. Some of these natural hazards can and do cause damage to rural water supply infrastructure. Some of the hazards also impact on the source water in terms of quantity and quality. For any type of climate-induced hazard, the degree or magnitude changes from region to region within the country (Niranjan *et al.*, 2021). That said, the exposure of the water supply systems to these climate-induced hazards depends on the extent of dependence of the system to the affected water bodies. Given the vast variation in the types of water supply systems (Kumar *et al.*, 2021), the exposure of the water supply schemes to the hazards will vary significantly across space. Depending on how vulnerable the community is to the disruptions in water supply services caused by the hazard, they face public health risks due to interruptions in water supply or contamination of the water supplied to them.

The paper discusses the development of an analytical framework or tool for assessing the risks faced by rural communities due to their vulnerability to disruptions in water supply caused by natural hazards such as droughts, floods, and landslides. The various parameters considered for developing the three dimensions of the risk index (namely, hazard, exposure, and vulnerability), the rationale for choosing those parameters, and the manner in which they influence the relevant dimensions of risk are discussed. The quantitative criteria for assigning values for various parameters and the analytical procedure for computing the sub-indices and the final risk index are also discussed. The paper finally presents the results of a mapping of climate-induced risk in water supply in the districts of Maharashtra, a state in western India, done using district level data for the various parameters concerned.

2. REVIEW OF INTERNATIONAL LITERATURE ON ASSESSING CLIMATE-INDUCED RISKS IN WATER SUPPLY

Attempts to assess the water-related impact of climate hazards on the performance of water supply schemes are very limited. A study by Yung *et al.* (2011) assessed the impacts of population growth and varying climate on the performance of a municipal water supply system using a hybrid simulation model. The simulation model takes in climatic variables and water consumption patterns derived from historical records and projects future water demands under different assumptions. The model estimated the effects of water efficiency management programmes (WEMPs) and system expansion on improving the supply to the city of Ayr in the district of Waterloo in Canada. The study found that rapid population growth would substantially increase the risk of water shortage of the system, where system improvements such as WEMPs or an increase in system capacity will alleviate some of the pressure.

The impact of future change in climate on the water supply system was assessed by considering the following: (1) the possible outcomes of changing monthly maximum temperature and monthly precipitation magnitudes; and (2) the frequency of precipitation events for the monthly precipitation values projected by the general circulation models. The simulation results suggest that a rise in temperature and a change in precipitation magnitude would negatively impact the performance of the system. The results also suggest that a reduction in precipitation may adversely affect system performance. Conversely, an increase in precipitation may lessen the impacts of a warmer climate. Further modifying the frequency of precipitation events seems to amplify the effects of an increase or decrease of precipitation magnitude.

Another study by Nastiti *et al.* (2018) assessed potential risks induced by climate change on clean water supply in South Tangerang, a city in Indonesia, which built on a 2016 study by the city government. The climate risk assessment of 2016 had indicated that several areas are potentially exposed to a high risk of climate change. Survey and in-depth interview with communities and sectoral officers suggested that the risk to clean water supply in the city was on the rise. The study adopted a method in which some of the vulnerability indicators were modified. The results of the study demonstrated that many wards in South Tangerang would be exposed to high climate risks of clean water supply. By 2021, about 54% of the wards would be exposed from high to very high risk of clean water supply. These results signify the tangible need of adaptation actions, to prevent the worsening impacts of climate on clean water supply.

Calow *et al.* (2015) had conducted a study of risks in rural water supply associated with changes in climate covering the whole of Ethiopia, on a medium term. Basing its predictions on the climate change predictions for Ethiopia by McSweeney *et al.* (2010), the study suggests that despite the uncertainty and knowledge gaps in the predictions of climate change for Ethiopia, there is a growing body of evidence documenting the range of possible impacts of changing climate on water systems and services. The study had summarized those impacts in relation to the spring and hand dug well technologies, for the risks arising from intense rainfall events and prolonged dry periods.

In terms of intense rainfall-induced hazard for springs, the study predicted seasonal or drought-related reductions in spring yield or complete drying up of springs, and seasonal or drought-related reduction in water quality due to less dilution of pollutants. In terms of impacts of these hazards, it predicted an increase in public health risk due to water quality deterioration, which may be rapid but short or long term. In the case of hand dug wells, the study predicted increased contamination of groundwater and lateral flows in soils as the hazards. In terms of impact, it predicted the following: (a) water quality deterioration may be rapid but short term or, in the event of contamination of the surrounding aquifers, long term; and (b) damage to infrastructure, e.g., from landslides, gullies, and flooding.

In terms of prolonged drought-induced hazards for springs, the study predicted the following: (a) seasonal or drought-related reductions in spring yield or complete drying up of springs; and (b) seasonal or drought-related reduction in water quality due to less dilution of pollutants. With regard to the impact, it predicted the following: (a) seasonal or drought-related shortages – insufficient water to meet the demand; (b) public health risk from water rationing/cutbacks or use of alternative (unsafe) sources; and (c) public health risk from deteriorating water quality at the end of a dry season or drought. The following were the predicted impacts for dug wells: (a) seasonal or drought-related shortages; (b) public health risk from water rationing/cutbacks, or use of alternative (unsafe) sources; and (c) public health risk from deteriorating water quality at the end of a dry season or drought.

Based on the review of the limited published literature available, it can be stated that the studies looking at the impacts of climate-induced water-related hazards on water supply systems are not comprehensive, as they fail to look at the three dimensions of risk, i.e., 'hazard', 'exposure' and 'vulnerability', systematically. The assessments of risk are based on predictions of 'hazard' obtained from climate change models. While predicting the risks, the studies have considered only a few of the factors determining the exposure of water supply systems to climate hazards and vulnerability of the communities to the disruptions in services caused by those hazards. Overall, a framework for risk assessment is missing in the analysis, and the assessments bank too much on speculations. As a result, it is difficult to identify the measures for risk reduction.

3. DEVELOPMENT OF COMPOSITE INDEX FOR ASSESSING CLIMATE-INDUCED RISK IN WATER SUPPLY

For the development of the index to assess climate-induced risk to water supply, the factors influencing the three different dimensions of risk, i.e., hazard, exposure, and vulnerability, in the rural water supply sector are identified and grouped as natural, physical, socioeconomic, and institutional factors. These factors and the relevant variables were identified from the literature review, expert knowledge, and understanding of the study regions.

The ways in which the different variables can influence climate-induced hazard, exposure, and vulnerability are discussed in the subsequent sub-sections. A summary of the discussion is also presented in Table 1.

3.1. Factors influencing climate-induced hazard in water supply

Occurrence of natural hazards such as droughts, floods, landslides, and cyclone are mainly influenced by natural factors. These include rainfall and its variability, flood proneness, aridity, and overall renewable water availability. Rainfall above the normal limit usually reduces the probability of drought occurrence and helps in relieving water scarcity, and vice versa. As pointed out by Maliva & Missimer (2012), areas that receive low annual rainfall are at greater risk of having frequent droughts. In India, inter-annual variability in rainfall is found to be higher in regions with lower magnitude of (mean) annual rainfall (Sharma, 2012). Hence, such regions are likely to experience droughts more frequently compared to those with lower variability (Kumar *et al.*, 2006, 2008).

Further, given the nature of the relationship between rainfall and runoff in semi-arid and arid tropical regions, the impact of meteorological droughts in terms of hydrological stress in areas experiencing low (mean) annual rainfall is greater compared to their counterparts receiving higher (mean) annual rainfall, for the same intensity of drought (in terms of the standard precipitation index (SPI); Source: based on James *et al.* (2015) and Deshpande *et al.*, (2016)).

Flood-prone areas are at a greater risk of recurring floods due to excessively high rainfall (Brouwer *et al.*, 2007). Heavy rainfalls in the area can have adverse effects on surface water quality and groundwater, which can contaminate water supply (Brouwer *et al.*, 2007; Zimmerman *et al.*, 2008). Another factor that influences water scarcity (during droughts) is the overall availability of annual renewable water in a region (Rijsberman, 2006). Renewable water availability of more than 1,700 m^3/capita/year is considered secure (Falkenmark *et al.*, 1989).

3.2. Factors influencing community's exposure to hazards

A community's exposure to any hazard is influenced by several factors. Natural factors include occurrence of cyclones, depth to water table, climate, and groundwater stock. Cyclones can cause strong winds that can damage power lines, thereby disrupting water supply. Groundwater at shallow depth will be susceptible to biological contamination during floods. High groundwater stock can play a vital role in buffering the effects of the risks posed during droughts (Calow *et al.* 2010). In areas with cold climate, exposure of a community to the risks posed during a bad rainfall year will be low as overall water requirements will be less (Kabir *et al.*, 2016a, 2016b). Areas with humid climate have a greater chance of outbreak of waterborne diseases during floods (Githeko *et al.* 2000).

There are several physical factors influencing community exposure to hazards and they include characteristics of the water sources, age of the water supply systems, provision of buffer storage of water in reservoirs per capita, proportion of households (HHs) covered by tap water supply, resource depletion due to over-exploitation, flood control measures such as dams, and water pumping facilities. A perennial water source would significantly reduce community exposure to droughts. Further, an aging water supply system is at a greater risk of damage and disruption during floods and cyclones. Adequate provision of buffer water storage in reservoirs is another important factor that can reduce exposure to water scarcity conditions during droughts (Kumar, 2010; McCartney & Smakhtin, 2010; Kumar *et al.*, 2016). However, the chances of occurrence of such practices would depend a lot on the frequency of the occurrence and intensity of droughts.

Similarly, HHs' access to tap water supply will help in counteracting prolonged exposure to climate-induced risks (WHO, 2002; Montgomery & Elimelech, 2007; Hunter *et al.*, 2010). Further, flood control measures such as embankments, dykes, dams, and water pumping infrastructure will help in reducing severity of floods. Pumping stations and transformers kept in low-lying areas also increase the exposure to flood hazards.

Table 1 | Factors influencing climate-induced risk.

Sub-index (factors)	Variable (indicators)	Rationale	Impact on severity of risk (negative or positive)[a]
Hazard sub-index			
Natural	Rainfall	In high rainfall areas, the drought impacts on hydrology will be less as compared to low rainfall areas and vice versa in low rainfall areas	Negative
	Rainfall variability	In areas of high rainfall variability, the frequency of occurrence of severe droughts will be higher	Positive
	Aridity	Impact of droughts in areas having high aridity in terms of hydrological changes will be more as compared to areas of low aridity	Positive
	Annual renewable water availability	Renewable water availability of more than 1,700 m^3/capita/year is considered as secure	Negative
	Flood proneness	'Flood-prone' areas are more susceptible to hazards associated with high rainfall	Positive
Exposure sub-index			
Natural	Depth to ground water table	Groundwater at shallow depth will be susceptible to biological contamination during floods	Negative
	Temperature and humidity	In areas with cold and humid climate, there is high chance of water and food contamination due to unhygienic conditions and spreading of insect vectors	Positive
	Groundwater stock	Act as buffer during droughts. Normally available in the alluvial areas, and as valley fills along rivers	Negative
	Occurrence of cyclone with high-speed winds along the coastal districts	Cyclones with high-speed winds may damage the water supply system (WST) or affect the power supply thus interrupting the supply of water from electrically operated WSS	Positive
Physical	Characteristics of natural water resources	Perennial water source would significantly reduce community exposure to droughts	Negative
	Condition of the water supply systems	Old water supply systems are more susceptible to disruption and damage during floods and cyclones	Negative
	Provision of buffer storage of water in reservoirs per capita	Reduces exposure to water scarcity conditions during droughts	Negative
	Proportion of HHs covered by tap water supply	Reduces chances of contamination of water during collection and storage	Negative
	Flood control measures such as embankments, dykes, dams, and water pumping facilities	Reduces severity of floods	Negative

(*Continued.*)

Table 1 | Continued

Sub-index (factors)	Variable (indicators)	Rationale	Impact on severity of risk (negative or positive)[a]
	Availability of skilled labour for immediate repair and maintenance of water supply system	Non-availability of skilled labour for immediate repair of WSS may cause interruptions in water supply	Negative
Socioeconomic	Proportion of people living in low-lying areas	Relatively more exposed to flood hazards	Positive
	Proportion of people having access to water supply source within the dwelling premises	Less exposure to risk posed by droughts or floods	Negative
Institutional and policy	Disaster risk reduction measures available, preparedness and ability to respond	Helps community to prepare better for any adverse eventuality	Negative
	Existence of policy to hire private tankers for emergency water supply	Help community to face water stress induced by droughts	Negative
	Provision for tanker water supply in rural areas in terms of number of tankers	Increases community's ability to tide over the crisis caused by reduced water supply from public systems	Negative
Vulnerability sub-index			
Socioeconomic	Population density	High population density increases vulnerability	Positive
	Proportion of people living under poverty	Vulnerability will be high for those who lack wherewithal to have access to alternate sources of water including purchased water	Positive
	Proportion of people who are unhealthy	Undernourishment in general and malnourishment, especially among children, make community more vulnerable	Positive
	Access to primary health services	Good access to primary health facilities make community less vulnerable	Negative
	Percentage of children under the age of 5 with stunting (Height-for-age)	Physical growth of children (under the age of 5), an indicator of the nutritional well-being of the population, influences vulnerability to diseases	Negative
	Proportion of aged population (above 65 years)	Proportion of aged people in the community increases the vulnerability to hazards	Positive
Institutions and policy	Ability to provide relief and rehabilitation measures for floods and cyclones (number of agencies, including Government, private, and NGOs)	Improve community adaptive capacity	Negative
	Social ingenuity and cohesion	Improves community adaptive capacity and resilience	Negative
	Adequate number of primary and other health infrastructure	Decreases community vulnerability to diseases	Negative

[a]'Positive' sign suggests that if the value of the variable increases, the effect on the particular dimension of risk (i.e., hazard or exposure or vulnerability) will be higher. Conversely, 'negative' sign suggests that if the value of the variable increases, the effect on the particular dimension of risk will be lower.

Socioeconomic factors in the context include the proportion of people living in low-lying areas, and the proportion of people having access to water supply source within the dwelling premise. Low-lying areas, due to their topographical disadvantage, will be more prone to floods (Patz & Kovats, 2002). Nevertheless, people having access to water supply within their premises will have less exposure to risk posed by droughts or floods, owing to the fact that there will be lesser chance of water contamination that normally happens during collection, conveyance, and storage, if the source is available (WHO, 2002).

Institutional and policy factors also play an important role in regulating community exposure to climate-induced risks in water supply. Policy to hire private tankers for emergency water supply in rural areas and increase in number of such tankers being made available will help a community to face water stress induced by droughts. Further, provision of disaster risk reduction measures such as flood and cyclone warning, drought prediction, and evacuation measures will help a community to prepare better for any adverse eventuality (Pollner *et al.*, 2010).

3.3. Factors influencing community vulnerability to hazards

A community's vulnerability to disruptions in water supply resulting from hazards is mainly socioeconomic and institutional in nature. Climate is the single-most important natural factor that influences in the context. For instance, cold climate and humidity increase flood-related health risks such as diarrhoea caused by bacteriological contamination of water and food (Haines *et al.*, 2006; Githeko *et al.* 2000). Inadequate personal and community hygiene resulting from water shortages can result in diseases such as diarrhoea (Esrey *et al.*, 1985; Howard & Bartram, 2005). But in hot, arid, and semi-arid climates, breeding of water-related insect vectors that can cause such diseases would be less (Hunter, 2003). Hot and arid areas are more prone to drought-related health risks such as dehydration (Haines *et al.*, 2006).

Population density is a key socioeconomic variable that affects community vulnerability to the health risks associated with climate-related hazards. More densely populated areas have greater faecal loadings within the environment, and these are associated with greater vulnerability to infectious disease (Woodward *et al.*, 2000).

The burden of waterborne diseases is often closely linked to poverty (Fass, 1993; Stephens *et al.*, 1997) and malnutrition. The poor tend to be more vulnerable to diseases and have least access to basic services (WHO & UNICEF, 2000). This could be due to the high proportion of the poor lacking the wherewithal to have access to alternate sources of water, and hence being generally unhealthy. There is greater prevalence of undernourishment in general and malnourishment among children of poor families. Nevertheless, better access to primary health services will make them less vulnerable. People with malnutrition are more vulnerable to waterborne diseases.

Age is also an important factor affecting the vulnerability of the population to health problems caused by disruptions in water supply services in terms of quantity and quality of the supplied water. Aged people are more vulnerable to diseases, including waterborne diseases. Communities with a higher proportion of people in the old age category can be highly prone to disease risks, even if they score high on social and economic development indicators such as health and per capita income. A study carried out by the Institute for Resource Analysis and Policy (IRAP) explaining the inter-state variations in COVID-19 infections and COVID-19 deaths in India showed high influence of aged population (expressed in terms of the percentage population above the age of 60) on both the dependent variables (Kumar *et al.*, 2023).

Institutional and policy factors such as availability of greater number of institutions with ability to provide relief and rehabilitation measures to people affected during floods and cyclones (including government, private, and NGOs) in terms of required equipment and budgetary allocations and preparedness improve community adaptive capacity against climate-induced vulnerabilities. Similarly, the presence of an adequate number of public health infrastructure decreases population vulnerability to the severity of diseases caused during hazards (Haines *et al.*, 2006). Finally, social ingenuity also matters in its adapting to natural disasters and reducing the vulnerability. Social ingenuity is the ability to reimagine relationships between people and organizations, and how they communicate, partner, and value each other (Homer-Dixon, 2001). Social cohesion, the extent of connectedness and solidarity among groups in a society is a characteristic of homogeneous communities, and helps in adaptation, building resilience, and vulnerability reduction (IRAP, GSDA & UNICEF, 2013).

3.4. Climate-induced risk in water supply

Table 1 identifies the various factors that influence the climate-induced water-related hazards, exposure of the water supply systems to these hazards, and vulnerability of the communities to the disruptions in water supply caused by the hazard, and also the different variables that define them. They were identified through a systematic search of the scientific literature that deals with climate hazards related to water, the impacts of such hazards on the water supply systems in terms of quantity and quality of water available from the sources and the systems, the vulnerability of the communities to problems associated with the lack of water for domestic needs, and the factors that determine the degree of these hazards, exposure, and vulnerability. A total of six factors are identified as key to influencing climate risk in water supply, through their effect on hazard or exposure or vulnerability. They are as follows: only natural factors influence the degree of a hazard; natural, physical, socioeconomic, and institutional and policy factors influence the degree of exposure of the water supply system to the hazard; and socioeconomic and institutional and policy factors influence a community's vulnerability. In total, there are four variables (all natural) influencing the hazards; 15 variables (four natural, six physical, two socioeconomic, and three institutional and policy related) influencing exposure; and eight variables (five socioeconomic and three institutional and policy related) influencing vulnerability. Table 2 discusses the quantitative criteria used for assigning values to different variables.

The composite index has three sub-indices (one for hazard, one for exposure, and one for vulnerability). Each sub-index is given equal weightage, but comprises different numbers of variables (indicators) whose numerical values (scores) together characterize the value of the attribute represented by the sub-index. To begin with, a maximum score of '3' will be assigned to any variable in the case of the worst situation, and the minimum score of '1' will be assigned to the variable for the best situation. For obtaining the numerical value of each sub-index, scores for different indicators will be added up and divided by the highest value possible for that sub-index for normalizing. For instance, a sub-index that has five independent variables (indicators) can have a maximum possible computed value of 15 (i.e., 5×3). This means the highest normalized value possible for any sub-index will be 1.0. The composite climate risk index for water supply will be computed by multiplying the values of the three sub-indices, namely, hazard, exposure, and vulnerability. If the value of a hazard sub-index is 0.67, that of exposure is 0.50, and that of vulnerability is 0.33, then the value of the risk will be 0.11 ($0.67 \times 0.50 \times 0.33 = 0.11$).

4. CLIMATE-INDUCED RISKS TO RURAL WATER SYSTEMS IN MAHARASHTRA

The state of Maharashtra is prone to several climate hazards. They include cyclones, landslides, droughts, and floods (State Disaster Management Authority (SDMA) 2016). While the coastal region is hit by cyclones, large inland areas of the Marathwada and Vidarbha regions are hit by periodic (meteorological) droughts that often become severe with serious hydrological and socioeconomic impacts (Deshpande *et al.*, 2016; Kabir *et al.*, 2016b). The areas in the Western Ghats region that have steep slopes and that experience very high rainfall and intense showers are subject to frequent landslides. The west-flowing rivers originating from the Western Ghats also experience flash floods affecting the coastal plains. All these natural hazards have serious implications

Table 2 | Quantitative criteria for assigning values for different variables.

Sub-index (factors)	Variable (indicators)	Impact on severity of risk (negative or positive)	Score: 1 = Low	2 = Moderate	3 = High	Score given	Remarks
A. Hazard Sub-Index							
Natural	Rainfall	Negative	Average annual rainfall greater than or equal to 1,000 mm	Average annual rainfall between 500 and 1,000 mm	Average annual rainfall less than or equal to 500 mm		The hazard is drought
	Rainfall variability	Positive	Coefficient of variation in rainfall is less than 17%	Coefficient of variation in rainfall is equal to/between 17 and 40%	Coefficient of variation in rainfall is greater than 40%		As per guidelines of IMD
	Aridity	Positive	Humid to sub-humid	Semi-arid	Arid to hyper-arid		Per guide lines of IMD
	Annual renewable water availability	Negative	Renewable water availability of more than or equal to 1,700 m^3/capita/year	Renewable water availability of between 1,000 and 1,700 m^3/capita/year	Renewable water availability of less than equal to 1,000 m^3/capita/year		
	Flood proneness	Positive	Probability of occurrence of flood less than 10%	Probability of occurrence of flood is between 10 and 33%	Probability of occurrence of flood greater than 33%		
B. Exposure sub-index							
Natural	Depth to ground water table	Negative	Depth to ground water table is greater than or equal to 30 m	Depth to ground water table is 5–30 m	Depth to ground water table is less than or equal to 5 m		The exposure is in the form of bacteriological contamination

(*Continued.*)

Table 2 | Continued

Sub-index (factors)	Variable (indicators)	Impact on severity of risk (negative or positive)	Score			Score given	Remarks
			1 = Low	2 = Moderate	3 = High		
	Temperature and humidity	Positive	Temperature ranging between 30 and 35 °C and humidity ranging from 30 ± 5 to 50 ± 3%	Temperature ranging between 27 and 30 °C and Humidity ranging 30 ± 5 to 50 ± 3%	Temperature ranging between 23 and 27 °C and humidity ranging from 60 ± 8% to 80 ± 6% most favourable condition for unhygienic conditions		
	Groundwater stock	Negative	Groundwater stock is five times more than the annual recharge	Groundwater stock is two times more than the annual recharge	Groundwater stock is equal to or less than the annual recharge		Per guidelines of Central Ground Water Board (CGWB)
	Occurrence of cyclone with high-speed winds	Positive	No cyclones with high-speed winds		Cyclones with high-speed winds		
Physical	Characteristics of natural water resources	Negative	Perennial water source with low inter-annual variability (e.g., river)	Perennial source with high inter-annual variability (coefficient of variation in the annual flows)	Seasonal water sources (ephemeral rivers, lakes, ponds, etc.)		
	Condition of the water supply system	Negative	New water supply pipeline systems (less than 5 years)	Medium aged water supply pipeline systems (between 5 and 15 years)	Old aged water supply pipeline systems (more than 15 years)		
	Provision of buffer storage of water in reservoirs per capita	Negative	Provision of buffer storage in a reservoir minimum 36 m^3/capita/year	Provision of buffer storage in a reservoir between 15 m^3/capita/year	Provision of buffer storage in a reservoir less than 9 m^3/capita/year		
	Proportion of HHs covered by tap water supply	Negative	More than 75% of HHs are covered by tap water supply	40–60% of HHs are covered by tap water supply	Less than or equal to 40% of HHs are covered by tap water supply		

(*Continued.*)

Table 2 | Continued

Sub-index (factors)	Variable (indicators)	Impact on severity of risk (negative or positive)	Score 1 = Low	2 = Moderate	3 = High	Score given	Remarks
	Flood control measures such as embankments, dykes, dams, and water pumping facilities	Negative	Flood control measures available	Significant damage reported due to floods despite the availability of flood control measures	No flood control measures available		
	Availability of skilled labour for immediate repair and maintenance of water supply system	Negative	Available		Not available		
Socioeconomic	Proportion of people living in low-lying areas	Positive	Less than or equal to 25% of people living in low-lying areas	25–50% of people living in low-lying areas	Greater than or equal to 50% of people living in low-lying areas		
	Proportion of people having access to water supply source within the dwelling premises	Negative	More than 75% of people have access to water supply source within the dwelling premises	40–75% of people having access to water supply source within the dwelling premises	Less than 25% of people having access to water supply source within the dwelling premises		
Institutional and policy	Disaster risk reduction measures available	Negative	Disaster risk reduction force available within a radius of 100 km	Disaster reduction force available within a radius of 100–500 km radius	Disaster risk reduction force available outside 500 km radius		

(*Continued.*)

Table 2 | Continued

Sub-index (factors)	Variable (indicators)	Impact on severity of risk (negative or positive)	Score			Score given	Remarks
			1 = Low	2 = Moderate	3 = High		
	Existence of policy to hire private tankers for emergency water supply	Negative	Policy exists to hire private tankers for emergency water supply		No policy exists to hire private tankers for emergency water supply		
	Provision for tanker water supply in rural areas in terms of number of tankers	Negative	More than 1 tanker for 20 HHs	1 tanker for 20–50 HHs	Less than 1 tanker for 50 HHs		
C. Vulnerability sub-index							
Socioeconomic	Population density	Positive	Population density less than 200 persons/km^2	Population density in the range of 200–500 persons/km^2	More than 500 persons/km^2		
	Proportion of people living under poverty	Positive	Less than equal to 25% of people living under poverty	25–60% of people living under poverty	Greater than 60% of people living under poverty		
	Access to primary health services	Negative	More than 60% people having access to primary health services	25–60% of people having access to primary health services	Less than 25% of people having access to primary health services		
	Proportion of people who are unhealthy	Positive	Infant mortality rate less than or equal to 12.0 (per 1,000 people)	Infant mortality rate between 12.0 and 60.0 (per 1,000 people)	Infant mortality rate greater than 60.0 (per 1,000 people)		

(*Continued.*)

Table 2 | Continued

Sub-index (factors)	Variable (indicators)	Impact on severity of risk (negative or positive)	Score: 1 = Low	2 = Moderate	3 = High	Score given	Remarks
	Percentage of children under the age of 5 with stunting (low height-for-age ratio)	Negative	Average height of children below the age of 5 as a % of the median is 95–110	Average height of children below the age of 5 as a % of the median is 85 to 89	Average height of children below the age of 5 as a % of the median is less than 85		
	Proportion of people above the age of 65 years	Positive	Proportion of aged population <5%	Proportion of aged population 5–8%	Proportion of aged pop. Above 8%		
Institutions and policy	Ability to provide relief and rehabilitation measures for floods and cyclones (no. of agencies, including government, private, and NGOs)	Negative	More than one NGO for 1,000 people	One NGO for 1,000–2,000 people	Less than one NGO for 2,000 people		
	Social ingenuity and cohesion	Negative	Settled and homogenous communities, exposed to natural disasters	Settled, but heterogeneous communities exposed to natural disasters	Settled, but heterogeneous communities not exposed to natural disasters		
	Adequate number of primary and other health infrastructure	Negative	One sub-health centre covered 3,000–5,000 of rural population	One sub-health centre covered 6,000–8,000 of rural population	One sub-health centre covered more than 8,000 of rural population		

for the performance of rural water supply systems through their adverse impacts on the quantity and quality of source water, the water supply infrastructure, and the community's ability to access water supply sources. They affect the functioning of water supply schemes through the damage they cause to power supply systems.

The previous works on climate-induced water supply risks have mainly focused on droughts in Marathwada and Vidarbha regions and their impact on water supply in cities and rural areas (Ganguly *et al.*, 2021). There is hardly any work that analyses the impacts of cyclones, landslides, and floods on quantity and quality of water in the sources that are tapped for water supply, and the water supply infrastructure.

The state displays high heterogeneity with regard to the following: (i) the physical factors, namely, topography, climate, soils, geology, geohydrology, and hydrology that influence the degree of the water-related 'hazards' that occur from climatic phenomenon (such as cyclonic winds, heavy rainfall, meteorological droughts, and peak flood discharge in rivers); (ii) the socioeconomic factors that, along with some of the physical factors, influence the exposure of the water supply systems; and (iii) the combination of socioeconomic, institutional, and policy factors that influence the vulnerability of the communities to the disruptions in water supply caused by the hazards. The state has excessively high rainfall regions and low rainfall regions; it has mountainous areas, plateau areas, and coastal plains; it has cold and humid areas as well as hot and arid areas; it has hard rock areas as well as alluvial patches; it has socioeconomic highly advanced regions (Konkan region) as well as very backward, tribal areas (State Disaster Management Authority (SDMA), 2016; Ganguly *et al.*, 2021).

Risk is a complex interplay of hazard, exposure, and vulnerability. Under a scenario that exists in the state as explained above, it is important to systematically map climate-induced risk in water supply for different areas of the state by considering the potential variations in the degree of hazard, degree of exposure, and degree of vulnerability across space, to identify regions that are highly prone to risk. This will require a robust framework. The composite index developed for assessing climate-induced water supply risk discussed earlier can be used for this.

Maharashtra witnessed one of the most severe droughts in its history in 2013. It was considered as the region's worst drought in 40 years. The Union government allocated almost half of its disaster budget to relief effort. The Government's Empowered Group of Ministers provided INR 1,207 crore for relief, including 2,136 water tankers to supply water to 1,663 villages. However, due to the increased numbers of starving livestock, a further INR 1,160 crore was allocated to the agricultural sector for scarcity mitigation, and for supplying water and fodder.

During the drought of 2015, which badly hit the Marathwada region, drinking water for the city of Latur had to be transported through rail wagons from the Western Ghats region. The Marathwada region has no buffer storage in their reservoirs. The cost of transporting a unit volume of water was far higher than the cost of desalination. In the past, such drastic measures had to be resorted to only during the worst drought of 1985–1987 in the Saurashtra peninsula of Gujarat in western India (Kumar, 2018). As shown by a recent field study, many villages in that state, which could not obtain good-quality water from surface reservoirs either through piped water supply schemes or by tankers, had to use poor-quality groundwater for drinking, cooking, and other domestic uses (Udmale *et al.*, 2018).

Maharashtra is largely prone to floods. While some floods are caused by the occurrence of excessively high rainfall combined with the unique topography (like in the Konkan region), there are many man-made reasons for the occurrence of floods. Most floods in Maharashtra are flash floods due to poor drainage systems. Very few floods, like the one that occurred in the Konkan region in 1983, are natural due to heavy rains. The floods of 2005 and 2006 have shown that almost all the districts in the state are vulnerable to floods (State Disaster Management Authority (SDMA) 2016)).

The coastal areas of the state are risk prone to cyclones. The state has a coastal belt of over 700 km. Thus, the Konkan region including Mumbai becomes prone to cyclones. There are many marine fishing villages/hamlets with fishing boats engaged in fishing in this coastal belt that are exposed to the effects of cyclones. In the Arabian Sea, severe cyclonic storms have been recorded in the past affecting the Maharashtra–Goa coast. The coastal city of Mumbai has faced many cyclone threats in the recent past. It has faced peripheral impact in 1982, 1988, and October 1996, and has been hit by cyclones in 1948 and June 1996. The most recent cyclone to hit the state was *Phyan* (2009), which had affected the coastal districts in the state (State Disaster Management Authority (SDMA) 2016).

5. FACTORS INFLUENCING CLIMATE-INDUCED WATER SUPPLY RISKS IN RURAL MAHARASHTRA

5.1. Rainfall, its variability, temperature, humidity, and aridity

The mean of average annual rainfall of the districts in the state varied from the highest of 3,504.58 mm in Raigarh to the lowest of 604.7 mm in Ahmednagar district for the years 1901–2021. The mean annual rainfall for all the districts is shown in the following. Inter-annual variability in rainfall (expressed in terms of coefficient of variation) of the districts ranged from the highest of 32.51 in Jalna to the lowest of 17.88 in Raigarh.

The highest and lowest temperatures are recorded as 33.8 and 20.6°C in the Akola and Satara Districts, respectively. The humidity is highest in Raigarh and Sindhudurg Districts with 76%. It is lowest in Dhule District with 44.05%.

Almost all the districts of the state come under the semi-arid region category. The number of districts falling under the 'semi-arid region' category is 24 out of the 34 districts of Maharashtra, while three districts fall under the 'arid region' category, and the rest under the 'humid region' category.

5.2. Annual renewable water availability

The annual renewable water availability for districts in the state varied from the highest of 8,344.7 m^3/capita in the Gadchiroli District to the lowest of 520.9 m^3/capita in the Thane District.

5.3. Flood proneness

There is a moderate possibility of occurrence of floods in almost all the districts of Maharashtra with the highest probability of 20.66% in Pune and the lowest of 8.26% in Jalna.

5.4. Depth to groundwater table and groundwater stock

The depth to groundwater table was found to be highest in the Hingoli District with an average value of 12.99 m below ground level (b.g.l.) and lowest in the Raigarh District with an average value of 4.12 m b.g.l.

Nearly 90% of the state's geographical area is underlain by hard rock formations that are characterized by very limited static groundwater resources (or groundwater stock). The unconsolidated and semi-consolidated formations generally have static groundwater. The groundwater stock in the state is largest in Ahmednagar District (1,198.81 MCM) and it is lowest in Mumbai (53.65 MCM).

5.5. Occurrence of cyclone with high-speed winds

The probability of occurrence of cyclone with high-speed winds is highest in all the five coastal districts of Maharashtra, namely, Mumbai, Raigarh, Ratnagiri, Sindhudurg, and Thane.

5.6. Characteristics of natural water resources

There are 18 districts that have perennial water resources with high inter-annual variability, 13 districts that have perennial water resources with low inter-annual variability, and three districts that have seasonal water resources. The three districts with seasonal water resources are Ahmednagar, Bid, and Gondia.

5.7. Condition of the water supply system

Most of the districts in the state have water supply systems aged less than five years except five districts that have moderately aged water supply systems, namely, Bid, Chandrapur, Nandurbar, Parbhani, and Thane.

5.8. Provision of buffer storage of water in reservoirs per capita

The provision of buffer storage per capita is highest in Satara District with 1,221.8 m^3/capita and lowest in four districts, namely, Bhandara, Jalna, Latur, and Parbhani districts with no buffer storage.

5.9. Proportion of HHs covered by tap water supply

The proportion of HHs covered by tap water supply as on 18 November 2022 is highest in Jalgaon District with 100% and lowest in Nandurbar District with 35.54%.

5.10. Flood control measures such as embankments, dykes, dams, and water pumping facilities

Flood control measures are present in 25 districts and significant damage has been reported due to floods in six districts despite the availability of flood control measures. There are no flood control measures available in Amravati, Buldhana, and Washim Districts. Bhandara district has the highest number of flood control measures with a total of 548 embankments and 21 dams.

5.11. Proportion of people living in low-lying areas

Almost 90% of the districts have no to less than 25% of people living in low-lying areas, whereas Nanded has the highest percentage of people (89%) living in low-lying areas.

5.12. Proportion of people having access to water supply source within the dwelling premise

Mumbai has 100% of people with access to a water supply source within their dwelling premises. Sindhudurg has the lowest of 73.2% of people having access to a water supply source within their dwelling premises.

5.13. Disaster risk reduction measures available

There are 24 districts that have disaster risk research and rescue teams within the radius of 100 km. The remaining 10 districts have disaster risk and rescue teams within the radius of 100–500 km.

5.14. Existence of policy to hire private tankers for emergency water supply

Almost all the districts have an existing policy to hire private water tankers during emergencies for drinking water supply except four districts, namely, Bhandara, Gadchiroli, Gondia, and Mumbai.

5.15. Provision for tanker water supply in rural areas in terms of number of tankers

There is provision for tanker water supply in rural areas with more than one tanker for 20 HHs in Aurangabad and Bid Districts, whereas one tanker for 20–50 HHs is available in Jalna and Ahmednagar Districts. All the other districts have less than one tanker for water supply in rural areas.

5.16. Population density

The district of Mumbai, which includes the Mumbai metro, has the highest population density of 20,316 persons/km^2 and Gadchiroli has the lowest population density with 74 persons/km^2.

5.17. Proportion of people living under the poverty line

Nandurbar District has the highest proportion of people living under the poverty line with 52.12% and Mumbai has the lowest proportion of 4.12% of people living under the poverty line.

5.18. Access to primary health services

Less than 25% of the population of all the districts in the state, except Mumbai, have access to primary health services.

5.19. Proportion of people who are unhealthy (use infant mortality per 1000 live births)

Gondia District has the highest infant mortality rate of 66 and Ratnagiri District has the lowest infant mortality rate of 27.

5.20. Percentage of children under the age of 5 with stunting

Nandurbar has the highest of 45.8% of children under the age of 5 with stunting and Satara district has the lowest of 20.2% of children under the age of 5 with stunting.

5.21. Proportion of aged population (above 65 years)

All the districts in the state have more than 8% of people above the age of 65 years, except two districts, namely, Nandurbar and Thane.

5.22. Ability to provide relief and rehabilitation measures for floods and cyclones

Here we considered the number of NGOs that are engaged in relief and rehabilitation works during natural calamities. None of the districts in the state have more than one NGO per 2,000 persons to provide relief and rehabilitation measures for floods and cyclones.

5.23. Social ingenuity and cohesion

There are four districts in the state with settled and homogenous communities exposed to natural disasters, and 15 districts each in the settled but heterogeneous communities exposed to natural disasters and the settled but heterogeneous communities not exposed to natural disasters.

5.24. Adequate number of primary and other health infrastructure

There is only one health sub-centre covering more than 8,000 people in Sindhudurg District indicating that it has an inadequate number of primary and other health infrastructure. In other districts, there is one health sub-centre covering less than 8,000 people.

6. MAPPING OF WATER SUPPLY RISKS IN RURAL MAHARASHTRA

Data pertaining to the different variables considered in the assessment of climate risk in water supply were collected from a wide range of secondary sources of the state government of Maharashtra and the central agencies (such as the India-Water Resource Information System (India-WRIS) and the Indian Meteorological Department (IMD)) and deduced for each one of the districts of the state.

The normative criteria already defined were used to assign values for each one of the variables, and normalized as 1, 2, and 3. Based on these values, the final assessment of hazard, exposure, and vulnerability was done, and further normalized to bring the value of each sub-index in the range of 0.0 and 1.0.

The computation shows that the value of the hazard ranges from a lowest of 0.46 for Jalna to a highest of 0.67 in four districts, namely, Ahmednagar, Dhule, Nashik, and Pune. The second highest value of hazard (0.60) was found in the case of 18 districts. The lowest value of hazard was in the case of Ratnagiri and Sindhudurg (0.47). The results are presented in Figure 1.

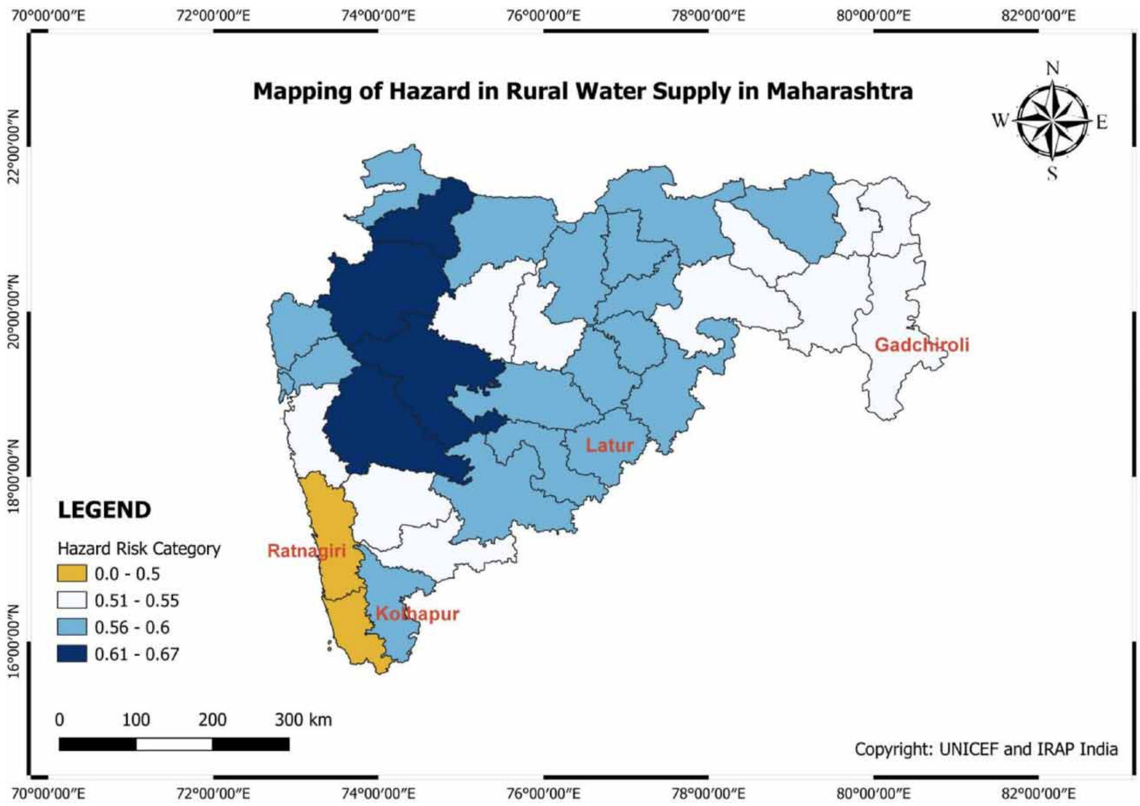

Fig. 1 | Mapping of hazard in rural water supply in Maharashtra.

With regard to exposure of the WASH systems, it was found to be highest for Mumbai, with a value of 0.72. The second highest value of exposure found was for Bid District with a value of 0.67. The lowest exposure was in the case of Jalna District with a value of 0.46. The variation in the degree of exposure among districts is higher than that of hazard. The results are presented in Figure 2.

With regard to vulnerability of the communities, six of the districts were found to have the highest value, i.e., 0.81. The districts are Thane, Palghar, Gondia, Nanded, Buldhana, Hingoli, Dhule, and Jalna. The vulnerability was found to be lowest in the case of Mumbai (0.63), which faces the highest degree of hazard. The second lowest vulnerability was found in the case of three districts, namely, Gadchiroli, Chandrapur, and Sindhudurg. In the case of vulnerability, the variation in the values among districts (0.81–0.63) is much lower as compared to hazard and exposure. The vulnerability values are generally quite high for most districts. The results are presented in Figure 3.

The final risk in water supply (Figure 4) induced by climate ranged from the lowest of 0.16 in the case of Sindhudurg to the highest of 0.31 for Bid. The second highest value of risk was for Nanded and Parbhani (0.30 each). Seven districts have high value of risk (0.27 and above). They are Thane (0.28), Palghar (0.29), Gondia (0.28), Ahmednagar, Amravati, Buldhana, Mumbai, and Pune (0.27 each). To make the rural water supply systems resilient, we need to focus on reducing the exposure of the systems to the hazards and vulnerability of the communities.

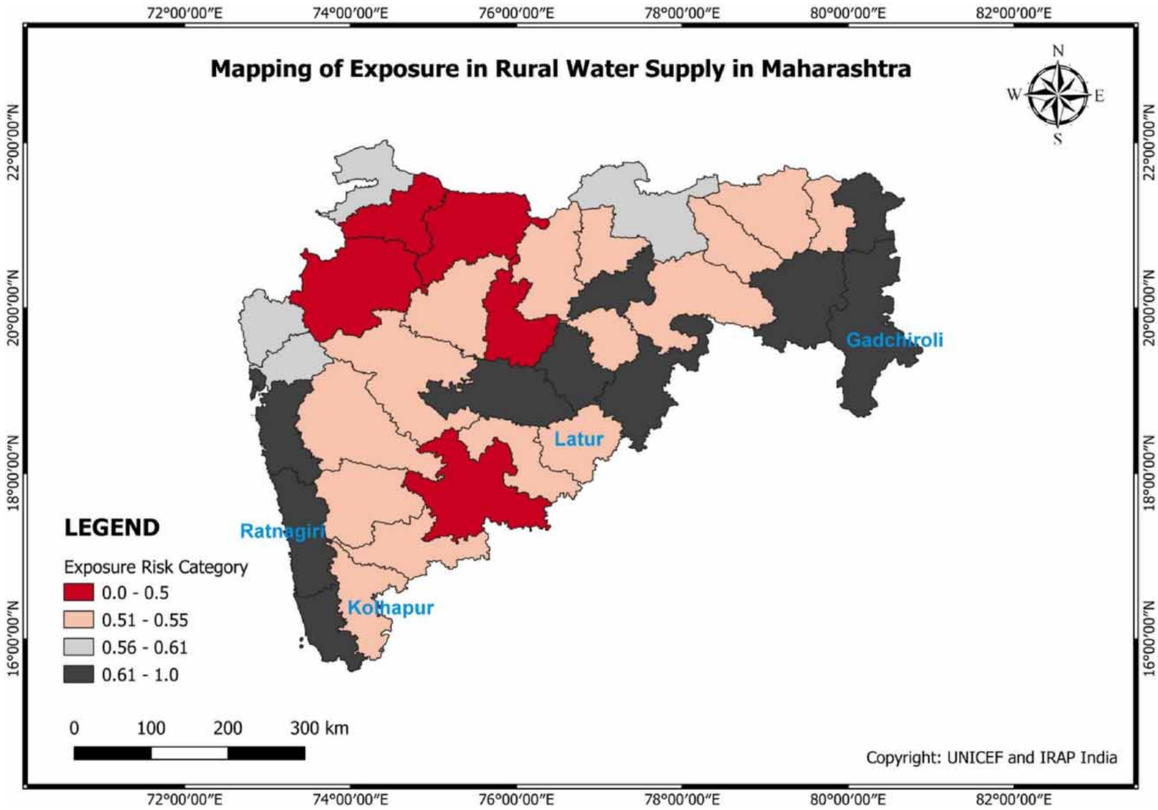

Fig. 2 | Mapping of exposure in rural water supply in Maharashtra.

7. FACTORS CONTRIBUTING HIGH CLIMATE RISKS IN RURAL WATER SUPPLY IN CERTAIN REGIONS

The computation shows that the value of the 'hazard' ranges from the lowest of 0.46 for Jalna to the highest of 0.67 in four districts, namely, Ahmednagar, Dhule, Nashik, and Pune. With regard to exposure of the WASH systems, it was found to be highest for Mumbai, with a value of 0.72. The lowest exposure was in the case of Jalna district with a value of 0.46. The variation in the degree of exposure among districts is higher than that of hazard. With regard to vulnerability of the communities, eight of the districts were found to have the highest value, i.e., 0.81.

The districts are Thane, Palghar, Gondia, Nanded, Buldhana, Hingoli, Dhule, and Jalna. Vulnerability was found to be lowest in the case of Mumbai (0.63), which faces the highest degree of exposure to hazards. In the case of vulnerability, the variation in the values among districts (0.81–0.63) is much lower compared to hazards and exposure.

With regard to the water supply risk, a total of 11 districts had risk values equal to or above 0.27. They are Amravati, Ahmednagar, Bid, Buldhana, Gondia, Mumbai, Nanded, Palghar, Parbhani, Pune, and Thane. These are districts where rural communities are expected to face problems posed by disruptions in water supply services caused by hazards such as floods, droughts, cyclones, and landslides.

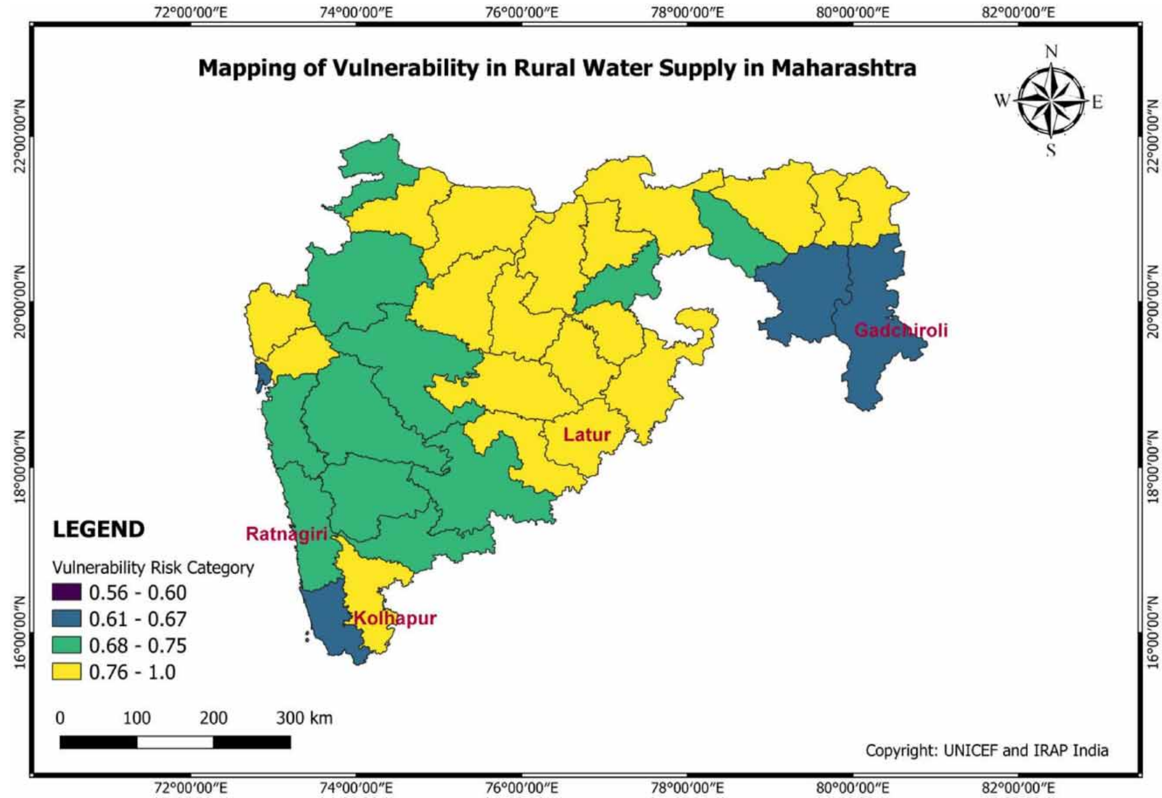

Fig. 3 | Mapping of vulnerability in rural water supply in Maharashtra.

The top 10 high districts that would face high water supply risk (with risk values equal to or more than 0.27) are Ahmednagar, Amravati, Bid, Buldhana, Gondia, Mumbai, Nanded,; Parbhani, Pune, and Thane. Most of the high-risk districts are in western Maharashtra, Aurangabad, and Nashik divisions. Table 3 lists the districts having high values of hazard, exposure, and vulnerability. In the case of hazard, only districts having a value equal to or more than 0.67 are chosen. In the case of exposure, all the districts having values equal to or more than 0.60 are chosen. In the case of vulnerability, the districts having values equal to or more than 0.81 are chosen.

The major source of risk for the Ahmednagar and Pune Districts, located in Aurangabad division, is the high degree of hazard (the value touching 0.67), contributed by overall water scarcity and high frequency of occurrence of meteorological droughts due to low high rainfall, high variability, and high aridity. The dependence on wells (bore wells and hand pumps) for rural water supply is very high in these divisions, despite the limited potential of the underground hard rock formations.

In the case of Bid, Mumbai, and Parbhani Districts, high risk is mainly contributed by high exposure of these districts (the value touching 0.60).

In the case of Buldhana, Gondia, and Thane, the high risk is mainly due to very high vulnerability of the communities in these districts. All three districts have vulnerability values touching 0.81. In the case of Nanded, high risk is contributed by both high exposure and high vulnerability. There is still one district (Amravati) that has high risks that is not explained by high degree of hazard, high exposure, or high vulnerability. The district experiences moderately high degree of hazard (0.60) and a high degree of vulnerability (0.78).

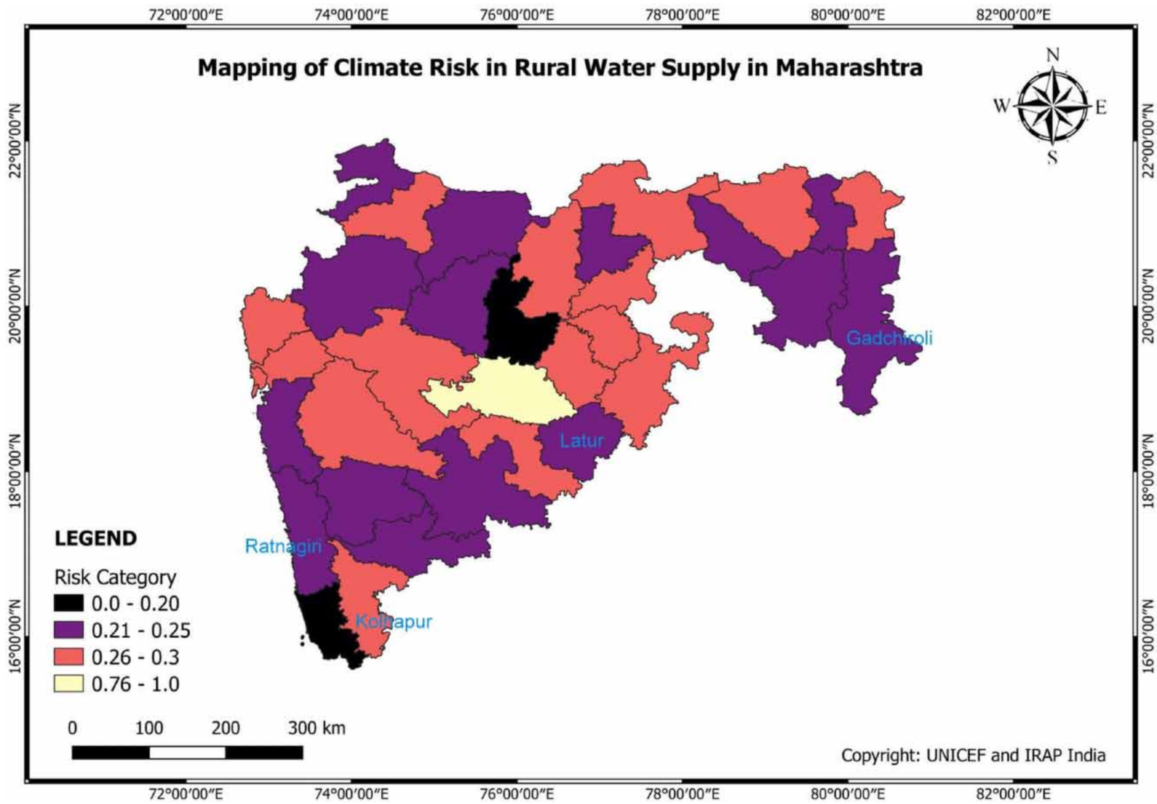

Fig. 4 | Mapping of climate risk in rural water supply in Maharashtra.

Table 3 | Listing of districts of Maharashtra having high values of hazard, exposure, and vulnerability.

Districts with high hazard (0.67 and above)	Ahmednagar, Dhule, Nashik, and Pune
Districts with high exposure (above 0.60)	Bid, Chandrapur, Gadchiroli, Gondia, Mumbai, Nanded, Parbhani, Raigarh, Ratnagiri, Sindhudurg, and Washim
Districts with high vulnerability (0.81 and above)	Buldhana, Dhule, Gondia, Hingoli, Jalna, Nanded, and Thane
Districts with high risk	Ahmednagar, Amravati, Bid, Buldhana, Gondia, Mumbai, Nanded, Parbhani, Pune, and Thane

One way to deal with the high 'exposure' is to switch to more dependable surface water–based systems or to create buffer storage in the local reservoirs that can be tapped during droughts and during the lean seasons. In Aurangabad division, switching to surface water-based schemes would require the importing of water from the water-abundant Konkan region. The imported surface water can also be stored in the reservoirs of the region during drought years when they are not full. The water stored in reservoirs can be used as buffer during droughts. In western Maharashtra, there is scope for building small reservoirs to create local surface storages using small dams for mini water supply schemes.

The access to good-quality surface water (which is free from minerals) from reservoirs for domestic uses and enhanced dependability of the supplies from such sources would also encourage rural HHs to go for piped water supply schemes with tap connection within the dwelling. This would further reduce the exposure of the communities to the disruptions in water supply caused by droughts and reduced rainfall.

8. CONCLUSIONS AND POLICY INFERENCES

The previous studies that looked at climate-induced water supply risks failed to look at the three dimensions of risk, i.e., 'hazard', 'exposure', and 'vulnerability', in a systematic way. The assessment of risk was based on predictions of 'hazard' obtained from the climate change models. The studies considered only a few of the factors determining the exposure of the water supply systems and vulnerability of the communities. Overall, the risk assessment lacked a framework and the assessments banked too much on speculations. More importantly, such impact assessments did not provide any clues on the risk reduction measures possible through reduction in exposure and vulnerability that remain within the socioeconomic and institutional and policy domains.

The risk assessment tool developed by us is a composite index, consisting of 29 variables, with the rationale for selecting them provided. This index is a refinement of the climate-induced Water, Sanitation, and Hygiene (WASH) risk index developed earlier (Kumar *et al.*, 2021). It looks at rural water supply alone, but takes into account different types of climate hazards such as landslide and cyclones in addition to droughts and floods.

It has three sub-indices, one for computing 'hazard', one for 'exposure', and another one for 'vulnerability'. The sub-index for 'hazard' uses five variables, all 'natural'. The sub-index for exposure uses 15 variables of which four are 'natural', six are physical, two are socioeconomic, and three are 'institutions and policies' related. The sub-index for vulnerability considers nine variables, of which six are 'socioeconomic' and three are related to institutions and policies. The quantitative criteria for assigning values to each one of these variables and the ways to normalize them were also discussed. All three sub-indices have equal weightages. The approach followed here opens up new avenues for risk mitigation possible through reduction in 'exposure' and 'vulnerability', in addition to those possible through hazard reduction.

For instance, in the case of hazards, nothing much can be done to reduce it as the values of the attributes such as rainfall, its variability, aridity, renewable water resources, and flood proneness cannot be altered through human interventions.

However, in the case of exposure, flood protection measures (building dams, vegetation barriers, and embankments) can be employed in areas affected by floods. Similarly, buffer storage of water can be created by building large and medium reservoirs to reduce the impacts in drought-prone areas if surplus runoff is available. Both the activities have to be planned and executed by the state Water Resources Department (WRD). Similarly, if only a small percentage of HHs have access to HH tap water connections, the poor families can be provided with HH tap connections by the state water supply agency to reduce the chances of water contamination during droughts and floods. Further, more tankers can be employed in the areas that are drought prone by the water supply department if the existing number is less than adequate. Also, disaster risk reduction measures can be employed by the State Disaster Management Authority, in areas exposed to cyclones and floods.

To reduce the vulnerability, more public health centres can be established by the state health department in districts where they are only a few. Similarly, in the disaster-prone districts where the communities are highly vulnerable, the ability of the district administration to provide relief and rehabilitation measures for floods and cyclones has to be enhanced. This is the responsibility of the SDMA.

It is important to note that the flood control reservoirs can also serve as drought proofing measures in years of relatively low rainfall by providing storage of freshwater. Also in the long-run, improved access to water supply will also impact on their health, education, and income (Kumar *et al.*, 2016) thereby also reducing the vulnerability of the families to the impacts of both floods and droughts. Hence they provide cross impacts (Source: based on Enzer (1972)).

Subsequently, a mapping of climate-induced water supply risk was carried out for all districts of the state of Maharashtra. The data pertaining to the different variables considered in the assessment of climate risk were collected from a wide range of secondary sources of the state government of Maharashtra and the central agencies and deduced for each one of the districts of the state. The outputs of the mapping exercise show that out of the 10 districts having high value of water supply risk, only in two it is due to high hazard, which is because of natural factors. In seven districts, the high risk is either due to high exposure or high vulnerability. In one district, it was because of the combined effect of high hazard and high vulnerability.

They are many districts in the state of Maharashtra where rural water supply schemes are prone to climate-induced risks. To be precise, a total of 11 districts had risk values equal to or above 0.27 – Amravati, Ahmednagar, Bid, Buldhana, Gondia, Mumbai, Nanded, Palghar, Parbhani, Pune, and Thane, which indicates moderately high risk. The hazards that cause these risks are droughts, riverine floods, cyclones, and landslides. Among all these, the most widespread impacts were from droughts given the hard rock geology, limited gravity irrigation from canals, very high dependence on groundwater for irrigation, and the heavy dependence on wells for rural water supply. Although the effect of cyclones and riverine floods are restricted to a few coastal villages, they often damage the water supply infrastructure.

To ensure drought resilience of the rural water supply schemes, it is important that care is taken while selecting the sources at the time of planning itself. The areas where climate-induced risks in water supply are high due to low rainfall, high aridity, and high magnitude of occurrence of droughts in the form of rainfall departure from normal values, also characterized by intensive groundwater irrigation, and therefore the drinking water bore wells face competition from irrigation. The droughts only compound the problems. The dependence on groundwater for building rural water supply schemes should be avoided in such areas. With regard to policy change, the high climate risk areas such as the one mentioned previously need to gradually shift to reservoir-based water supply schemes wherein the official agency can exercise control over water allocation.

The climate-induced risk mapping will help build the basis for climate finance or contingency funding by the states to allocate Operation and Maintenance (O & M) funds to sustain community-based water supply schemes. This would form the basis for differentiated funding in states where natural and socioeconomic conditions vary widely across space. Particularly in the case of Maharashtra, the risk mapping exercise will also help set a vision for transitioning from groundwater-based rural water supply schemes to surface water–based schemes, as well as protecting over-exploited aquifers. In addition, the various parameters considered for developing the indices will help us understand the critical variables to be considered when the state adopts an integrated water resources management programme or associated schemes instead of the climate-resilient WASH. The Jal Jeevan Mission, which aims to ensure functional HH tap water connections for every HH, is set to conclude in March 2025. The Mission focuses on single-village community-driven groundwater-based water supply schemes. Source strengthening and augmentation remain the key measures for ensuring sustainability. In states like Maharashtra, where the majority of rural water supply schemes are single-village schemes based on groundwater, these risk maps will help the government allocate resources and implement measures such as the conjunctive use of surface and groundwater, and asset protection, during extreme climate events.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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