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A Novel Idea for Groundwater Resource Management during Megadrought Events

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Abstract

Due to the effects of global climate change on duration, frequency and number of drought events, the occurrence of prolonged droughts, referred to as "megadroughts" (lasting for two decades or longer) will become more probable in the future. Thus, it is crucial for countries especially in arid and semi-arid regions of the world to develop appropriate preparedness plans for megadrought risk management. Since groundwater is the key water resource in these regions, it is important to reliably quantify the maximum sustainable extraction to ensure a sufficient groundwater reserve, i.e. the Strategic Groundwater Reserve, for a probable future megadrought event. For this purpose, a new concept of Probable Maximum Drought is proposed in this study, based on the concept of Probable Maximum Flood. As the spillways of large dams are designed based on the Probable Maximum Flood to minimize the probability of failure and the associated casualties and damages, the Probable Maximum Drought concept is proposed to estimate Strategic Groundwater Reserves to limit the consequences of prolonged droughts, including damage and threats to societal stability. This will allow water resources managers and policymakers to develop appropriate strategies to adapt and restrict development plans of a given region based on a sustainable megadrought risk management.

Keywords Probable maximum drought · Strategic groundwater reserve · Sustainable water resources management · Climate change

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1 Introduction

Drought is a “creeping phenomenon” (Wilhite 1993) which develops over time with diffuse and slowly spreading impacts, in contrast to other disasters such as floods (Cap-Net UNDP 2015). During the 1994–2014 period, drought events accounted for only 5% of all natural disaster events happening around the world, while affecting more than one billion people, which accounts for almost 25% of the world population, who were affected by all natural disasters (UNFPA 2015). The longevity and widespread spatial extent of drought events also cause the highest economic and environmental consequences among all natural disasters (Wilhite 2000). The increase in the human population along with the change in the standards of living has created many challenges around the world with respect to access to water with sufficient quality (Gleick 1993). In addition, the effects of climate change increase the intensity and frequency of drought events in many parts of the world (IPCC 2013), which, in turn, results in a significant reduction of water availability and accessibility during those drought events.

The impacts of climate change on drought and water availability have been studied by many researchers around the world (e.g., Dai et al. 2004; Sheffield and Wood 2008; Piao et al. 2010; Dai 2011; Ashraf Vaghefi et al. 2014; Trenberth et al. 2014; Diffenbaugh et al. 2015; Kelley et al. 2015; Mann and Gleick 2015; Nam et al. 2015). One of the most relevant findings of previous drought-related researches was that the extra heat added to the climatic system due to global warming has the potential to cause droughts to develop more quickly, more intensely, and longer-lasting (Trenberth et al. 2014). For example, the results of Sheffield and Wood (2008) suggest that the prevalence of the long-term droughts has tripled due to climate change. Hence, the economic and environmental consequences are likely to be exacerbated as compared to what was estimated by Wilhite (2000).

In recent years, the occurrence of prolonged drought events referred to as “multi-decadal droughts” or “megadroughts” (lasting for two decades or longer) has been a great concern for communities all around the world. Megadrought events can have immense destructive potential and put not only the ecosystem but also the societal stability at risk. This is illustrated by recent advances in Archeology and Paleoclimatology, which suggest that megadroughts may have played a critical role in the collapse of several highly developed civilizations, including the Classic Maya empire in Central America (250–950 CE; Peterson and Haug (2005)) or the Neo-Assyrian empire in today’s Iraq (912–609 BCE; Sinha et al. (2019)). Nowadays, many societies worldwide are considered to be developing in a more or less sustainable way and are thus considered stable. Therefore, the limited occurrence of megadroughts (Coats and Mankin 2016) may have led to an underestimation of the societal risk associated with such events; due to the fact that megadrought events are rare, and the extent of their damages to the ex-generation may have been forgotten by the current or next generation. This, however, may render the notion of societal stability to be highly deceptive since societies may in fact not be resilient against these natural hazards at all (Cook et al. 2007). Therefore, it is of great importance to better understand and quantify the future probability of occurrence as well as the potential impacts of megadroughts (Coats et al. 2015).

At least one-third of the global population along with the production of more than 4% of the world’s food supplies depend on groundwater resources (Richts and Vrba 2016). In arid areas, due to the high probability of drought occurrence (Vrba and Renaud 2016) and falling mean annual precipitation below 75% of its long term average (Cap-Net UNDP 2015), groundwater is often the main source of water. In such regions, groundwater provides water for more than

60% of the population (Richts and Vrba 2016) or is at least an essential supplement to other freshwater resources for agriculture, industry and domestic consumptions (Morris et al. 2003; Giordano 2009; Gleeson et al. 2012; Vrba and Renaud 2016). While groundwater is considered to be a vital resource for water and food security, policymakers and water resources managers are often not aware of the importance of groundwater's role in sustainable development and the necessity of its protection (Richts and Vrba 2016). A comprehensive understanding of the importance of groundwater is thus the key element to avoid over-drafting which results in groundwater decline, in order to ensure sustainable use of these resources (Famiglietti 2014; Dalin et al. 2017; Rodell et al. 2018).

Langride (2009) emphasized that while there are some water shortage contingency plans, such as desalination, inter-basin water transfer, and increased water use efficiency in order to provide sufficient water for burgeoning demands, implementing these strategies can lead to increasing future water requirements, hardening of "demand-side conservation strategies" and increasing vulnerability to water shortages during severe drought events in the future. He suggested that in order to sustainably manage the risk of the probable future megadroughts, it is important to approach the problem with alternative strategies that could both enhance water supply and reduce vulnerability to drought. Such proactive strategies rather than traditional reactive strategies will most likely need to involve reserving and setting aside parts of the groundwater in an aquifer for extraction exclusively during megadrought events (Langridge and Daniels 2017), which is typically referred to as "Strategic Groundwater Reserve" (SGR). This strategic reserve is a crucial "emergency" water source during severe megadroughts, particularly in arid and semi-arid continental environments that are characterized by groundwater overexploitation and have no access to alternative strategies such as seawater desalination.

Due to overexploitation, many river basins worldwide have experienced a significant groundwater depletion over the last decades and have not recovered even in wet years (Rodell et al. 2018). Since groundwater extraction is the key strategy to meet water demands in these basins, the gradually progressing groundwater depletion either until now or in the future reduces the Strategic Groundwater Reserve (SGR). During the megadrought events, this matter has the potential to cause considerable water shortages and associated social conflict. Thus, developing a management approach is crucial to reduce groundwater overdraft, recover groundwater levels and sustain drought reserve (Langridge and Daniels 2017). Maintaining an accessible Strategic Groundwater Reserve (SGR) may help to mitigate the risk of megadrought events (Yu et al. 2018). However, the overarching question is how much groundwater extraction is sustainable in order to ensure a reliable Strategic Groundwater Reserve (SGR) for future megadrought risk management plans. Due to uncertainties arising from future changes in land use, population and climate, this remains a challenging question to answer (Langridge and Daniels 2017; van Engelenburg et al. 2018). Accordingly, the objective of this paper is to propose a novel concept, the Probable Maximum Drought (PMD), to provide sufficient information to meaningfully estimate the required Strategic Groundwater Reserve (SGR) in arid, groundwater-dependent regions of the world. This new concept which is here proposed for the first time in the scientific literature can be utilized as an effective strategy in order to manage the groundwater in a sustainable and operational manner and to consent a consistent and reliable megadrought risk management.

2 Strategic Groundwater Reserve (SGR)

Currently, the two concepts of "safe yield" (Lee 1915) and "sustainable yield" (Todd 1959) are standard methods for estimating the amount of groundwater that can be sustainably withdrawn from aquifers (Sophocleous 2000; Alley and Leake 2004; Gleeson et al. 2012; Rudestam and Langridge 2014). Yet, these concepts do not allow for any estimation of the Strategic Groundwater Reserve (SGR) for megadrought risk management. The safe yield is defined as: "the limit to the quantity of water which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve" (Lee 1915). As an initial thought, this definition does not consider the undesirable consequences of overutilization of groundwater resources over the surrounding areas for sustainable development (Sophocleous 2000), and therefore, in spite of this definition, some adverse consequences of overexploitation are still evident. Eventually, to prevent these adverse consequences, the concept of sustainable yield emerged which was defined as: "the amount of water which can [be] withdrawn (from a groundwater basin) annually without producing an undesirable result" (Todd 1959). This concept determines the allowable groundwater withdrawals to minimize the decline in the water level of aquifers and to ensure the long-term sustainability of groundwater systems (Sophocleous 2000; Alley and Leake 2004; Rudestam and Langridge 2014). More specifically, the sustainable yield is defined as the proportion of the recharge which can be extracted without short or long term adverse impacts on the ecosystems and human societies. Explicitly accounting for these two factors, the sustainable yield is considerably lower than the safe yield. While the concept of safe yield focuses on aquifers as value-neutral physical systems (Sophocleous 2000; Alley and Leake 2004), the sustainable yield addresses the resilience and combines the "adverse effects" and "sustainable groundwater management goals". However, the implementation of groundwater management based on sustainable yield still remains a problem, since the sustainable yield does not consider the occurrence of a megadrought event which is considered a "noise" within the wider context of a long-term trend. Sustainable yield leads to preparedness for gradual changes during a long term period. However, it does not lead to readiness for megadroughts which are considered to be rare events. Therefore, in some cases, while the sustainable yield is met, the Strategic Groundwater Reserve (SGR) may be at risk. In such cases, overexploitation of groundwater resources will lead to failure in future megadrought risk management preparedness plans. Therefore, it is essential to determine the sustainable use of groundwater in such a way to preserve a sufficient and reliable source of water, the Strategic Groundwater Reserve (SGR) for the occurrence of the Probable Maximum Drought (PMD). The concept of the Probable Maximum Drought (PMD), proposed in this study for the first time, is used as a strategy to manage the groundwater sustainably and to allow a reliable megadrought risk management. Table 1 illustrates a comparison between the three concepts of safe yield, sustainable yield and the Strategic Groundwater Reserve (SGR) for the Probable Maximum Drought (PMD).

3 Dimensioning the Strategic Groundwater Reserve (SGR)

Dimensioning the Strategic Groundwater Reserve (SGR) depends on the estimated risk of megadrought event and is defined based on the concept of the Probable Maximum Drought (PMD). The Strategic Groundwater Reserve (SGR) is defined as the reduction of renewable water (RW) compared to the average which can be defined as follows:

Table 1 The proposed concepts for sustainable groundwater management

Reference	The available shortcoming needs to be resolved	Proposed concept	Description
Lee (1915)	Dangerous depletion of the storage reserve, overexploitation leads to a decline in groundwater level and quality of an aquifer	Safe yield	"The limit to the quantity of water which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve."
Todd (1959)	Safe yield does not consider the undesirable consequences of overutilization of groundwater resources on surface water systems and on related groundwater-dependent ecosystems, leading to an unsustainable development	Sustainable yield	"The amount of water which can [be] withdrawn (from a groundwater basin) annually without producing an undesirable result."
This study	Sustainable yield does not consider the occurrence of a megadrought event which is a "noise" within a wider context of a long-term trend.	The Strategic Groundwater Reserve (SGR) for the Probable Maximum Drought (PMD)	The amount of water needed to be stored in the aquifer to ensure sufficient and sustainable water availability for future megadrought conditions.

$$\mathrm{SGR} = \sum_{j=1}^{d} \left(\overline{\mathrm{RW}} - \mathrm{RW}_j \right) \tag{1}$$

where $\overline{\mathrm{RW}}$ is the long-term mean annual renewable water, $\mathrm{RW_j}$ is the renewable water for water year of j ($j = 1$ is the first year of a megadrought event) and d is the duration of the worst megadrought. RW can be estimated as follows:

$$\mathrm{RW} = P - E - Q \tag{2}$$

in which P, E, and Q are annual precipitation, total evaporation (including rainfall interception, soil evaporation, transpiration and water bodies evaporation (Shuttleworth 1993; Savenije 2004)), and runoff, respectively. It should be noted that eq. 2 is considered for a transient condition that exists for a changing world. Since the concept of the Probable Maximum Drought (PMD) has a holistic view, therefore, the Strategic Groundwater Reserve (SGR) should be considered over an extensive area (e.g., a state or province). Thus, additional groundwater import or export across the defined boundaries can be assumed to be negligible.

To obtain a reliable estimation of the Strategic Groundwater Reserve (SGR), it is crucial to estimate the renewable water for each year during the Probable Maximum Drought (PMD). Accordingly, the first step for estimation of the Strategic Groundwater Reserve (SGR) is identifying the Probable Maximum Drought (PMD) which can be determined similar to the concept of the Probable Maximum Flood (PMF; Mays (2005)) for designing the spillway of the large dams (see Section 4).

4 Probable Maximum Drought (PMD), Probable Maximum Flood (PMF) and Estimated Limiting Value (ELV): The Background of the Concepts

The spillways of large dams are designed based on the "Probable Maximum Floods" (PMF), which may happen in the future, in order to minimize the probability of dam failure and the associated downstream casualties and damages (Mays 2005). The Probable Maximum Flood (PMF) is defined as: "the theoretical maximum flood that poses extremely serious threats to the flood control of a given project in a design watershed" which is estimated based on the concept of "Probable Maximum Precipitation" (PMP) (WMO 2009). The Probable Maximum Precipitation (PMP) is "the theoretical maximum precipitation for a given duration under modern meteorological conditions" (WMO 2009) which is estimated by methods such as statistical analysis of extreme rainfall and storm model approaches (Hershfield 1961, 1965; Koutsoyiannis 1999; Papalexiou and Koutsoyiannis 2006; WMO 2009; Casas et al. 2011). By using the Probable Maximum Precipitation (PMP), the Probable Maximum Flood (PMF) is estimated by using unit hydrograph-based, rainfall-runoff, or the coupled hydrological-hydrodynamic models (Felder and Weingartner 2017). Given the destructive potential of dam failures and the associated public support for conservative design, the Probable Maximum Flood (PMF) concept serves as a robust design and decision basis for the implementation of dam safety policies (Dubler and Grigg 1996).

The safety and cost are important factors for designing the hydrological structures, and thus, the optimal magnitude for design is determined according to a balance between these two factors. Estimating the true upper limit of the hydrological design scale is unknown, but it can be estimated for practical purposes. The estimated upper limit which is named "Estimated Limiting Value" (ELV) is defined as "the largest magnitude possible for a hydrologic event at a given location, based on the available hydrologic information" (Mays 2005). The Estimated Limiting Value (ELV) is implicit in the Probable Maximum Precipitation (PMP) and the Probable Maximum Flood (PMF). According to global records, the return period of the Probable Maximum Precipitation (PMP) can be as long as 500 million years; however, it varies geographically (Mays 2005).

Analogous to the Probable Maximum Flood (PMF), the Probable Maximum Drought (PMD) concept is proposed in this study to limit casualties, damages and threats to societal stability, such as water-scarcity induced mass migration arising from megadroughts. The Probable Maximum Drought (PMD) is defined as the most severe and intense drought event with the longest duration which could potentially occur in the future in a specific region. In the case of a megadrought, we suggest to estimate the "lower" limit as the smallest possible magnitude for a hydrologic event at a given location (PmP: Probable minimum Precipitation), hence, the Estimated Limiting Value (ELV) is implicit in the Probable minimum Precipitation (PmP) and the Probable Maximum Drought (PMD). Hereafter, we refer to the Estimated Limiting Value (ELV) for the Probable Maximum Flood (PMF) and the Probable Maximum Drought (PMD) as ELVF and ELVD, respectively (see Fig. 1). According to the right panel of Fig. 1 (adopted from Mays (2005)), the design of structures with different sizes is based on the percentage of ELVF or the return period to meet a reasonable compromise between cost and safety of the structure. Such criterion is also valid for ELVD and the Probable Maximum Drought (PMD) in the lower limit of extreme events (left panel of Fig. 1). Therefore, it is assumed that the occurrence of any drought more severe and prolonged than the Probable Maximum Drought (PMD) is impossible over a given basin. The main difference between the Probable Maximum Drought (PMD) and the Probable Maximum Flood (PMF) concepts is the

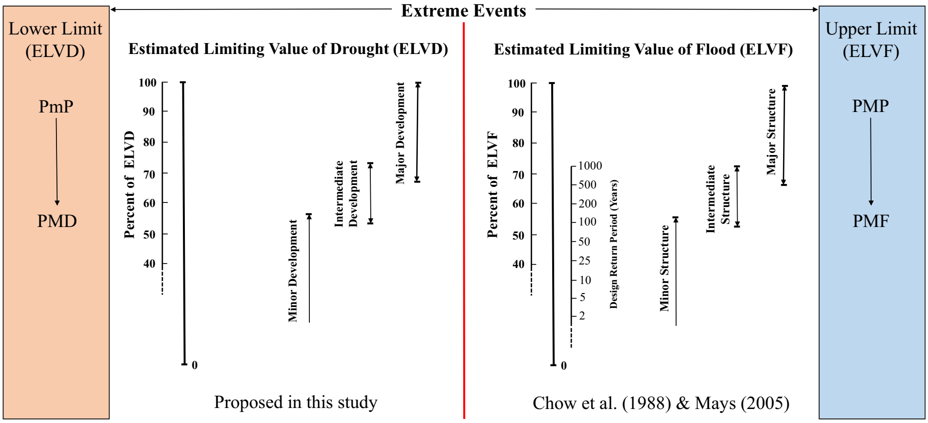

Fig. 1 A schematic view of comparison between the concepts of the Probable Maximum Flood (PMF) and the Probable Maximum Drought (PMD), by considering the approximate range of the Estimated Limiting Value (ELV) for different structures (in the case of maximum flood (right panel)) and different development (in the case of megadrought (left panel))

duration of the event. While generally, droughts will have a long duration up to many years, floods at most last for several days (Wilhite 2000; McLeman and Hunter 2010; Koubi et al. 2016). Analogous to the PMF-ELVF concept which helps to calculate sizing spillways (minor, intermediate and major structures; right panel in Fig. 1), the PMD-ELVD concept is used to calculate the Strategic Groundwater Reserve (SGR) for different scales of development (minor, intermediate and major development; left panel in Fig. 1; also see section 5). By doing so, reduction in renewable water is a basis for achieving the primary estimation of the Strategic Groundwater Reserve (SGR) which then can be adjusted using the megadrought risk management plans (section 6).

5 Risk of Megadrought Events According to the Scale of Development

In the context of natural hazards, “risk” represents the probability of a hazard. It depends not only on the hazard itself occurring in a given region but also on the exposure and vulnerability

Fig. 2 Intersection of hazard, exposure, and vulnerability yielding the risk (IPCC 2014)

of that region to the hazard (Fig. 2). According to Fig. 2, risk can be expressed as follows:

$$R = H \times E \times V \tag{3}$$

in which R, H, E, and V are risk, hazard, exposure, and vulnerability, respectively. Hazard is defined as follows:

$$H = P \times M = P \times \int I \times \mathrm{d}t \tag{4}$$

where P is the probability of a hazard occurring and M is the magnitude of the hazard which is defined as the integral intensity (I) during dt.

In this paper, the outmost hazard is considered to be the Probable Maximum Drought (PMD), which may occur in the future and cannot be avoided. The exposure to such hazards is also inevitable in some cases unless some part of the population could be moved to other regions according to the drought management plans. The only factor which is considered to be manageable is vulnerability (vulnerability of development to the Probable Maximum Drought (PMD) in this case, i.e. how much groundwater can be extracted for sustainable development with the lowest rate of vulnerability). This can help to work out the Strategic Groundwater Reserve (SGR) based on the scale of development (minor, intermediate or major development). Vulnerability, in general, is defined as “the potential to get harmed”, but it can also be used with different definitions in various disciplines and contexts of the study (Babel et al. 2011). For example, Intergovernmental Panel on Climate Change (IPCC) defined vulnerability as “the degree to which a system is susceptible to, or unable to cope with adverse effects (of climate change)” (McCarthy et al. 2001). The knowledge of vulnerability can be useful for decision-makers to prioritize the appropriate actions. Furthermore, paying attention to the main sources of vulnerability can provide opportunities for adaptive water resources management (Babel et al. 2011).

Vulnerability to a megadrought may be mitigated in two ways. First, storing enough water in the aquifer as Strategic Groundwater Reserve (SGR) for utilizing during megadrought event, and/or second, water consumption management by the preparedness plans for such events (i.e. adaptation to megadrought). The Strategic Groundwater Reserve (SGR) is estimated based on the Probable Maximum Drought (PMD), however, appropriate adaptation strategies and preparedness plans for megadrought would lead to less amount of water needed to be stored as the Strategic Groundwater Reserve (SGR). Although there are several factors affecting vulnerability, however, four factors including population, socioeconomic values of development, the spatial extent of drought, and the level of dependency on groundwater are considered in this paper to estimate the vulnerability of development to the Probable Maximum Drought (PMD).

Population The population is an important factor that determines the vulnerability of a community, a city or a region to megadrought. The cities may be classified as small, medium, big and metropolitans, depending on their population. In most developing countries, the population is mostly concentrated in a few big cities or metropolitans. Generally, the concentration of population in limited areas increases the vulnerability of those areas to the natural hazards (Martine and Guzman 2002; Perrow 2011; UNISDR 2012; Danan et al. 2015). This is also valid for megadrought events since areas with dense populations have less per capita groundwater reserves for dealing with such natural events.

Socioeconomic Values of Development Population concentration and the abundance of trade exchanges and human activities in each area, increase the socio-economic values of that area. Moreover, an increase in population density is likely to lead to increasingly undesirable consequences of future natural hazards. Thus, for achieving the highest socio-economic development (or higher than given social values or economic capitals) in a given area, the society must be ensured that such development of that area will almost never be endangered. Megadroughts may endanger the economic capital (e.g., developmental turnover) and social values (e.g., historical monuments, religious and cultural values) of a given area. Mays (2005) suggested that the intermediate and large dams might be designed based on even 100% of the Estimated Limiting Value (ELV) (which may never happen) to have a high degree of protection with little damages to residents, infrastructures, structures, contents, and agricultural properties. Such criteria are also valid for drought events.

The Spatial Extent of Drought The spatial extent of drought puts the socio-economic values and population at risk. It is obvious that the larger the extent of drought, the larger the socio-economic values and more population would be at risk.

The Level of Dependency on Groundwater The dependency of the development on groundwater is defined as the ratio of groundwater supply to the total water supply (Riedel and Döll 2015), varying between zero when there is no aquifer to supply water and one when groundwater is the only source of water supply.

To estimate the megadrought risk, a framework needs to be prepared similar to the one presented for flood risk assessment. Chow et al. (1988) and Mays (2005) proposed some design criteria for different types of water-control structures (large, intermediate and small dams). Similarly, the sizing of the Strategic Groundwater Reserve (SGR) can be determined to limit water shortages during and after megadroughts by considering the four factors affecting the Probable Maximum Drought (PMD). As illustrated in Fig. 1, for major developments having the highest rate of risk (i.e. large population with high level of socioeconomic values, complete dependency on groundwater and elevated spatial extent of drought), a considerable substantiate volume of water should be retained as the Strategic Groundwater Reserve (SGR) to be stored in the aquifer for a reliable megadrought risk management plan. In such cases, if the groundwater resource (according to the estimated Strategic Groundwater Reserve (SGR)) is not enough for the current and the predicted population and economic activities in the future, it may be needed to provide some preparedness plans, e.g., encouraging people for migration or reducing the economic activities. For the development plans with a lower rate of risk (intermediate and minor development), a specific percentage of ELVD based on different sectors' water consumptions, can be utilized during the normal periods prior to megadrought events.

6 Strategic Groundwater Reserve (SGR) and Development Plans

The Available Groundwater Reserve (AGR) in a catchment (i.e. renewable water) during the megadrought event may be less, greater or equal to the Strategic Groundwater Reserve (SGR). By comparing the Available Groundwater Reserve (AGR) and the Strategic Groundwater Reserve (SGR), two states can be described (see Table 2). If AGR ≥ SGR, it means that there is enough water in the aquifer to cope with the megadrought event. However, water withdrawal

Table 2 Development plans based on Strategic Groundwater Reserve (SGR)

State	Condition	If such condition is valid	Strategy
$AGR \geq SGR$	Does this amount of water withdrawal (the Strategic Groundwater Reserve (SGR)) during the megadrought event, have any adverse consequences on the aquifer (e.g., water quality degradation or land subsidence)?	Yes	Development plans based on the Strategic Groundwater Reserve (SGR) are not reliable. The total amount of the Strategic Groundwater Reserve (SGR) cannot be withdrawn, and therefore, drought preparedness plans for megadrought events are needed.
		No	Development plans based on the Strategic Groundwater Reserve (SGR) are reliable.
$AGR < SGR$	Does the aquifer have adequate capacity for water to be increased from the Available Groundwater Reserve (AGR) to the Strategic Groundwater Reserve (SGR)?	Yes	Groundwater reserve should be elevated up to the Strategic Groundwater Reserve (SGR).
		No	Groundwater reserve should be increased up to its capacity (AC), while for the rest ($SGR - AC$), drought preparedness plans for megadrought events are needed and development plans should be restricted solely to the megadrought risk management.

up to the Strategic Groundwater Reserve (SGR) during the megadrought event, may lead to adverse consequences for aquifer (e.g., land subsidence or decline in groundwater quality). In this case, the total amount of the Strategic Groundwater Reserve (SGR) cannot be withdrawn, and therefore, drought preparedness plans for megadrought events are needed. In contrast, if water withdrawal up to the Strategic Groundwater Reserve (SGR) during the megadrought event, does not have any adverse consequences for the aquifer, then the development plans based on the Strategic Groundwater Reserve (SGR) can be considered reliable. In the case when $AGR < SGR$, then the strategies should be concentrated on increasing the groundwater reserve volume. Under this circumstance, the vital question would be whether the aquifer has enough storage capacity to reserve the increased volume of water. If the aquifer has adequate capacity, the groundwater reserve should be increased up to the Strategic Groundwater Reserve (SGR). Otherwise, groundwater reserve should be increased up to its available capacity (AC), while for the rest ($SGR - AC$), drought preparedness plans for megadrought are needed and development plans should be restricted to the megadrought risk management.

7 Conclusion

It is an obligation for groundwater managers to have appropriate and realistic knowledge of the upcoming drought events and their corresponding levels of damages and impacts in order to choose the most reliable strategies for risk management. For a megadrought risk management, it is crucial to provide an appropriate groundwater management plan in order to have a reliable water reserve during a probable megadrought event. Particularly, this issue is more vital for arid and semiarid regions of the world which are commonly dependent on groundwater resources. Storing a portion of groundwater (as the Strategic Groundwater Reserve (SGR)) plays an important role in mitigating vulnerability to such destructive events.

The Strategic Groundwater Reserve (SGR) is defined as the reduction in renewable water compared to the average (Eq. 1). Therefore, estimating the renewable water deficit during drought periods is a fundamental challenge in drought risk management. For this purpose, first, it is needed to have a reliable estimation of the Probable Maximum Drought (PMD) and its duration in order to estimate the renewable water during that event and consequently to estimate the Strategic Groundwater Reserve (SGR).

Similar to the concept of the Probable Maximum Precipitation (PMP) and the Probable Maximum Flood (PMF) for flood risk management, the concept of the Probable Maximum Drought (PMD) for megadrought risk management is proposed in this study. As the spillways of the large dams are designed based on the Probable Maximum Flood (PMF) that could happen in the future, the utilization of the groundwater resources in the area with the higher probability of megadrought occurrence (or the Probable Maximum Drought (PMD)) should be managed such that a reliable water storage during that period is assured. The amount of water which is needed to be stored in the aquifer to use during the Probable Maximum Drought (PMD), can be determined based on population, the socio-economic value of development, the spatial span of drought and the level of dependency on groundwater, as proposed in this paper.

Although developing the concept of the Probable Maximum Drought (PMD) is obviously important for an appropriate megadrought risk management, there are still challenges about the estimation of the Probable minimum Precipitation (PmP) and identifying the Probable Maximum Drought (PMD), its time and duration. As the Probable Maximum Precipitation (PMP) is unknown and is estimated by some methods such as statistical analysis of extreme rainfall and storm model approaches, reliable and functional methods for estimating the Probable minimum Precipitation (PmP) are also needed to be developed. For example, by analyzing precipitation data (if such data is available) or data generating methods for a given period (if enough data is not available) or by Markov chain method, the periods with the minimum amount of precipitation could be identified. Thus, future research can be focusing on this issue.

It should be also pointed out that megadrought risk management plans are dependent on both the quantity and quality of groundwater reserves. The quality of the groundwater deteriorates as the groundwater level declines. Therefore, it is important to consider the water quality for determining the Strategic Groundwater Reserve (SGR) along with the amount of water required to fill the aquifer. This subject also should be assessed in future studies.

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Compliance with Ethical Standards

Conflict of Interest None.

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