hydrology

MDPI

Article

Possibility Assessment of Reservoir Expansion in the Conterminous United States

Hadi Heidari *, Baptiste Francois and Casey Brown

Department of Civil and Environmental Engineering, University of Massachusetts, Amherst, MA 01003, USA
* Correspondence: hheidari@umass.edu; Tel.: +1-206-465-7179

Abstract: Reservoir expansion is commonly considered an adaptation strategy to attenuate water shortage conditions. In many locations in the United States, there are ongoing discussions about the effectiveness and feasibility of reservoir expansion with regard to the growing drought conditions and a consequent significant decrease in surface water. This study investigates if the expansion of the existing Unites States reservoirs should be still considered an effective and adequate management solution to cope with water shortages. To this end, we have defined three reservoir expansion metrics to assess the efficiency, feasibility, and usefulness of increasing the storage capacity of 304 reservoirs across the conterminous United States (CONUS). The efficiency metric is defined as the ratio of reservoir average storage to maximum active storage. The feasibility metric is defined as the ratio of reservoir average annual inflow to maximum active storage and the usefulness metric is described as the ratio of the reservoir average annual excess inflow (average annual inflow–maximum active storage) to the average intensity of water shortages. The finding indicates that most reservoirs in Colorado and Utah currently have high or very high efficiency metrics meaning that these reservoirs are, on average, more than half full while most reservoirs in Texas have low or medium efficiency metrics indicating that these reservoirs are, on average, less than half full. Additionally, the feasibility metrics indicate that reservoir expansion in most western and southern states may not be fruitful because the average annual inflow to reservoirs is less than their maximum active storage over the historical period. Nevertheless, the usefulness metrics show that reservoir expansion can be a useful adaptation strategy to mitigate or attenuate water shortages for some reservoirs in California and Colorado while it cannot considerably decrease the intensity of water shortages in Texas. Findings from this study highlight the utility of the assessment of reservoir expansion at a regional scale considering both available freshwater as an input to reservoirs and the potential water shortage conditions as the main trigger.

Keywords: reservoir expansion; water shortages; water storage; drought; water yield; water supply

check for updates

Citation: Heidari, H.; Francois, B.; Brown, C. Possibility Assessment of Reservoir Expansion in the Conterminous United States. *Hydrology* **2022**, *9*, 175. https://doi.org/10.3390/hydrology9100175

Academic Editor: Ryan Bailey

Received: 23 August 2022
Accepted: 1 October 2022
Published: 7 October 2022

1. Introduction

Using building reservoirs to store surface water is a traditional strategy to deliver safe and reliable water and cope with water shortages [1–4]. The spatial and temporal mismatch between water supply and water demand triggers the design of water storage infrastructures such as reservoirs [1,5–8]. Most reservoirs with water supply purposes are technically implemented to store excess water during the wet season in order to be used during drought conditions [9,10].

Due to global concerns regarding water shortages, new water-storage projects are being developed in the traditional form of large reservoirs, particularly in developing countries. However, new water-storage projects in developed countries are mainly focused on reservoir enlargement not constructing new large reservoirs, because most suitable sites have been already developed or protected through related policies [11].

In the conterminous United States (CONUS), there are more than 52,000 reservoirs that can store approximately 600,000 million cubic meters of water [5]. Although the era of large reservoir construction in the CONUS ended in the 1970s, the expansion of current reservoir storage capacities has been proposed as an adaptation strategy to provide more water supplies to meet increasing needs, particularly in response to climate change and urban and agriculture growth [11–13].

Nover et al. (2019) [14] used hydro-economic optimization to determine the effects of increasing reservoir storage in California's water infrastructure system and reported that additional storage capacity has a higher value in the north of the state where more water is available compared to the southern regions. Brown et al. (2019) [12] investigated three levels of increases in reservoir storage capacity of 10%, 25%, and 50% for all basins in the CONUS and found that reservoir enlargement can have a moderate effect on water shortage conditions and can decrease the average annual shortage by 8%, 12%, and 16%, respectively. Furthermore, Heidari et al. (2021) [15] assessed the effects of changes in the water yield of U.S. river basins in response to climate change on the intensity, duration, and frequency of water shortage events and concluded that most river basins located in the southwest of U.S. can be categorized into supply-based basins indicating that changes in the water supply of these basins have more effects on water shortage intensity in comparison with changes in water demand. Thus, these basins are potentially a suitable region to implement supply-based adaptation strategies such as reservoir expansion because these regions are already conservative in the way they use water, and a further demand reduction is no longer an option for these regions.

The increasing interest in reservoir enlargement is demonstrated by recent and proposed projects in the U.S. For instance, the Shasta Dam and reservoir enlargement project was proposed to increase the height of Shasta Dam, California, in order to increase the volume of water storage and submerging of the McCloud River upstream of the current reservoir for irrigation purposes and provide ecological benefits for the fishery downstream of the dam [16]. Furthermore, Perry et al. (2017) [11] selected two case studies from the U.S. West, the Merced Irrigation District's Lake McClure Expansion Plan in California and the Umatilla Basin Aquifer Recharge Project in Oregon, to assess an emerging trend of auxiliary water supply infrastructure. They stated that the aforementioned projects are appealing to decision-makers to accommodate the demand for new strategies by working on the limitations of past infrastructural development and related policies [11].

The aforementioned studies have investigated the feasibility of reservoir expansion in different regions of the United States [12,17]. However, there is a lack of nationwide studies to provide insight regarding the national scale picture of reservoir expansion potential [18]. Reliable surface water availability is a key factor in the implementation of reservoir expansion scenarios [19]. The increase in the frequency and severity of droughts in recent decades has led to a considerable decrease in the availability of water to be stored in many regions [20–26]. This situation sheds doubt on the feasibility of the reservoir expansion strategy and its effectiveness in the attenuation of water shortage conditions [14,27].

Previous studies often explored the relationship between reservoir storage capacity and yield (storage–yield analysis) to assess the required reservoir storage capacity with regard to the maximum water storage that reservoirs can supply for human consumption under given reliability [28–30]. To this end, different approaches were applied to model the storage–yield relationship and provide insight into various water shortage problems [31,32]. The storage–yield analysis at the regional scale can provide an estimation of hypothetical storage capacity to meet water demand and identify the need for further infrastructure investments such as reservoir expansion [33].

The main goal of this study is to investigate whether the expansion of CONUS reservoirs can still be considered a useful solution to decrease the vulnerability of water supply systems to a shortage. To this end, three important questions need to be addressed to provide insight into water planners and decision-makers at both national and local scales.

The first question is what proportion of the storage capacity of U.S. reservoirs has been currently filled on average. The answer to this question helps to better understand the efficiency of existing reservoirs across the CONUS and their flexibility for an increase in their storage capacity. We addressed this question by calculating the efficiency metrics as the ratio of the average storage of each reservoir to its maximum useable (active) storage over the historical period. The reservoir with a higher efficiency metric is potentially more appropriate for storage expansion compared to the reservoirs with a low efficiency metric.

The second question is if the current U.S. reservoir capacities are adequate to store available surface water. By finding the answer to this question, we can determine the feasibility of CONUS reservoir expansion at the regional scale. We addressed this question by calculating the feasibility metrics of reservoirs that compare the average annual inflow to each reservoir with its maximum active storage. We assumed that reservoir expansion is only adequate in the reservoirs in which their maximum storage is less than their average annual inflow [34].

The third question that should be addressed is how much an increase in the maximum storage capacity of reservoirs can be helpful to attenuate the intensity of water shortages [15]. The answer to this question is critical since the reservoir expansion can only be considered to be useful in the regions that cannot mostly meet their current demand. To this end, we first determine the reservoirs that are located in water shortage-prone regions. Then, we calculated the usefulness metric that shows to what extent reservoir expansion can decrease the intensity of current water shortage events.

This study is organized as follows. Section 2 illustrates the materials and methods applied in this study. The results are presented and discussed in Section 3. Finally, the most important highlights and findings that can be concluded from this study are provided in Section 4.

2. Materials and Methods

In this section, we first describe the research area and datasets that we used. Then, we outline the metrics that are applied to assess the efficiency, feasibility, and usefulness of reservoir expansion.

2.1. Data and Research Area

The United States reservoir information is obtained from the ResOpsUS dataset developed by Steyaert et al. (2022) [5]. ResOpsUS is the first dataset that includes the historical observation and operation of reservoirs across the CONUS from 1980 to 2020. Although the ResOpsUS dataset includes most U.S. reservoirs, we only used the information of 304 reservoirs that have a complete dataset of inflows and storage over the 1980–2020 period to avoid any inconsistency in the results. Figure 1 shows the research area (CONUS) and the location of 304 reservoirs. Additionally, Table S1 in the Supplementary Material provides the number of reservoirs and total active storage by state.

Furthermore, the historical water shortage data in the CONUS is obtained from Heidari et al. (2021) [15]. While they have calculated the intensity, duration, and frequency of water shortage events at both sub-annual and annual scales, we only focused on the intensity of water shortage events, which is in million cubic meters per year. It helps to provide insight into what extent the reservoir expansion can decrease the current water shortage in the CONUS at the regional scale.

Heidari et al. (2021) [15] found the relationship between the intensity and return period of water shortage events at the 4-digit hydrologic unit code (HUC4) basin scale across the United States over the 1986–2015 period by applying a mixture Gamma-Generalized Pareto (Gamma-GPD) model. They obtained the daily precipitation and temperature from the Daymet dataset [35] and bias-corrected the obtained data using the Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate dataset [36–39]. Then, they used the Variable Infiltration Capacity (VIC) version 4.1.1 hydrologic model [40] to obtain the water yield across the CONUS at the grid size of ~4 km (1/24°). The VIC model was calibrated using the aggregated monthly runoff obtained from the USGS National Water Information System gauge observations (WaterWatch data set) [41]. Next, they applied the Water Evaluation and Planning (WEAP) model [42] to calculate the water supply allocated to each basin based on the water demand obtained from the USGS water use circulars and for thermoelectric power water use from Diehl and Harris [12,43,44]. Finally, they used the calculated water supply and water demand from the previous steps as inputs to their probabilistic framework to characterize water shortage conditions. They defined the duration, intensity, and frequency of a water shortage event as the number of consecutive years where water demand exceeds water supply, the ratio of cumulative water deficit to its duration, and the number of times that the given water shortage event occurs, respectively. They reported the enhanced characterization of water shortage intensity–duration–frequency (IDF) by applying several goodness-of-fit tests such as the chi-square goodness-of-fit test, root-mean-square error (RMSE), and the coefficient of determination and found that their findings are generally consistent with the results of previous similar studies [45–48].

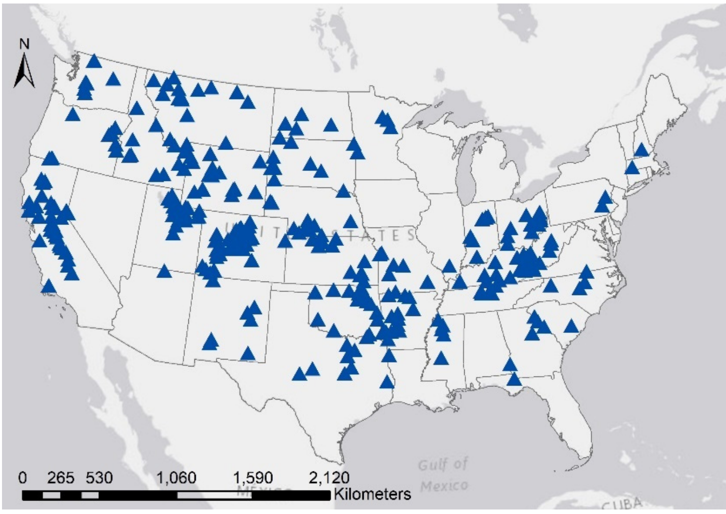

Figure 1. The location of 304 selected U.S. reservoirs.

Figure 2 provides the intensity of water shortage events under the current conditions for 10-, 25-, 50-, and 100-year return periods at the 4-digit hydrologic unit code (HUC4) basin scale that are obtained from Heidari et al. (2021) [15].

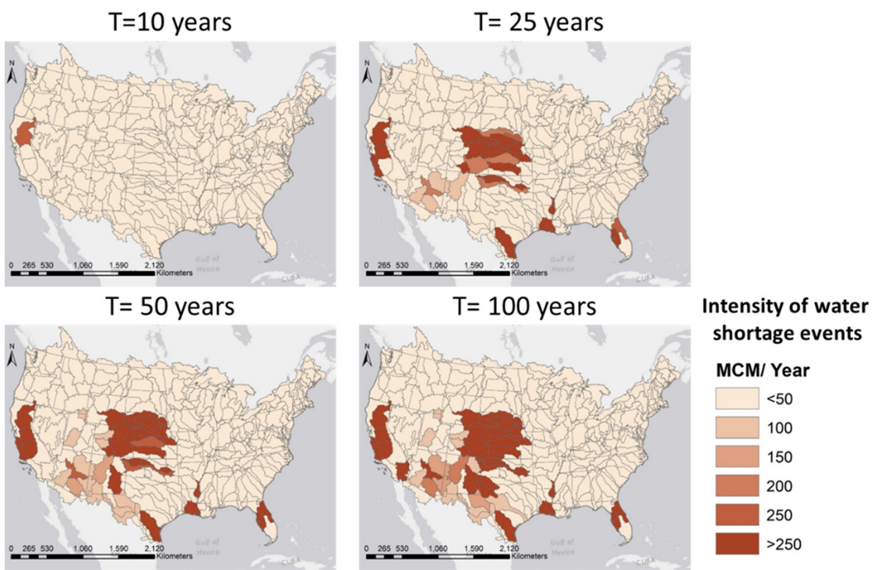

Figure 2. The intensity of water shortage events under the current conditions and at annual scale.

Then, we used the obtained U.S. reservoirs dataset [5] and water shortage dataset [15] to investigate if increasing the storage capacity of existing reservoirs across the United States can be still considered an effective, feasible, and useful solution to decrease water shortages at the regional scale. To this end, we defined three metrics, as follows.

2.2. Reservoir Expansion Metrics

We defined and applied three different reservoir expansion metrics including reservoir efficiency metric, reservoir expansion feasibility metric, and reservoir expansion usefulness metric to assess the possibility of reservoir expansion in the Contiguous United States. In this study, we defined the efficiency metric (E_{i}) for the reservoir i as

$$E_i = \frac{\overline{S}_i}{S_i^{max}} \tag{1}$$

where $\overline{S}_i$ and S_i^{max} are the average and maximum active storage for the reservoir i, respectively. E_{i} can be theoretically between 0 and 1 where 0 indicates the reservoir is always empty and 1 indicates the reservoir is always full. Thus, we categorized the reservoirs in the CONUS into 4 groups according to their reservoir efficiency metrics: 0–0.25 (low efficiency), 0.25–0.5 (medium efficiency), 0.5–0.75 (high efficiency), and 0.75–1 (very high efficiency). The reservoir with higher efficiency is potentially a better choice for expansion.

We assess the feasibility of reservoir expansion using the reservoir expansion feasibility metrics. Chen et al. (2019) [34] already defined the reservoir capacity factor, KI. as the ratio of the active reservoir capacity to the average annual reservoir net inflow and indicated that KI^{-1} can represent the average annual reservoir operation times. In this study, we used a similar factor to investigate whether increasing reservoir storage is feasible in a region or not. The reservoir expansion feasibility metric (F_i) for the reservoir i is defined as:

$$F_i = \frac{I_i}{S_i^{max}} \tag{2}$$

where I_i and S_i^{max} are the average annual inflow and maximum active storage, respectively. If F_{i} is greater than 1, it indicates that the reservoir expansion is likely to be feasible in the given region because there is enough annual inflow to the reservoir on average that it is greater than its maximum usable capacity. However, if F_{i} is less than one, it indicates that the reservoir expansion is not likely to be feasible because there is not enough water to fill even the existing capacity of reservoirs on an average basis.

The reservoir expansion can be assumed to be only useful in the regions that are currently struggling with water shortage problems. Therefore, we assess the usefulness of reservoir expansion using the reservoir expansion usefulness metric to show if increasing the storage capacity of reservoirs can lead to decreasing the current water shortage intensity or not. To this end, the reservoir expansion usefulness metric (U_i) for reservoir i is defined as:

$$U_i = \frac{I_i - S_i^{max}}{\overline{D}_i} \tag{3}$$

where I_i is the average annual inflow, S_i^{max} is the maximum active storage, and $\overline{D}_i$ is the average intensity of water deficits. Reservoirs with $U_i > 0$ indicate that increasing the storage capacity of the given reservoir can be useful in the reduction of the intensity of water shortage events.

3. Results and Discussion

The possibility of enlarging the storage capacity of 304 reservoirs across the CONUS is investigated in this section by calculating the three metrics, including the reservoir expansion efficiency metric, reservoir expansion feasibility metric, and reservoir expansion usefulness metric over the 1980–2020 period.

3.1. Reservoir Expansion Efficiency Metric

Figure 3 illustrates the average efficiency metric of 304 reservoirs across the CONUS over the 1980–2014 period. In general, there are 46 reservoirs with low efficiency, 82 reservoirs with medium efficiency, 134 reservoirs with high efficiency, and 42 reservoirs with very high efficiency. While these reservoirs in terms of efficiency are distributed across the CONUS, it can be noted that most reservoirs in Colorado and Utah currently have high or very high efficiency meaning that they are, on average, more than half full over the 1980–2020 period. However, the reservoirs in Texas have mostly low or medium efficiency indicating that they are less than half full, on average. The reservoirs located in California are equally distributed in terms of efficiency.

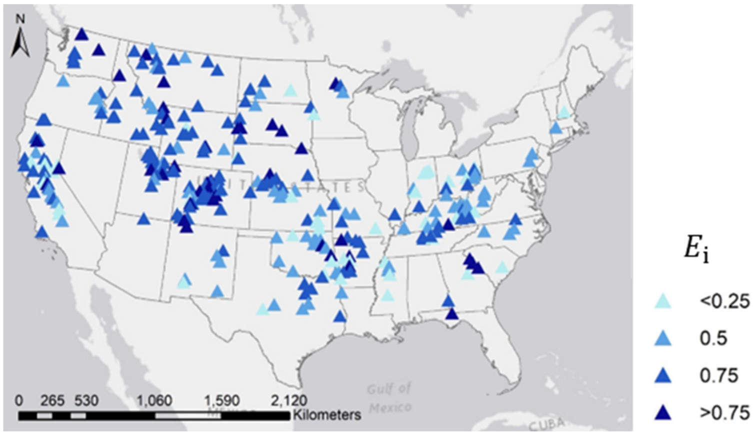

Figure 3. The efficiency metrics of reservoir.

Thus, by focusing on only the efficiency metrics, it seems that the 42 reservoirs with a very high efficiency metric and the 134 reservoirs with a high efficiency metric can be suitable candidates for expansion because they were, on average, more than half full over 1980–2020. Besides, Colorado, Utah, and California seem to be the best potential states in this case. However, the efficiency metrics only show the ratio of filled storage and we still need to investigate if there is enough water to be used as inflows to these reservoirs. Note that the finding is obtained using the average data from 1980 to 2020. Thus, the nonstationary changes in the trend of hydrological variables in response to climate change and variability are not considered here.

3.2. Reservoir Expansion Feasibility Metric

Figure 4 illustrates the distribution of reservoir expansion feasibility metrics across the CONUS. As is shown in Figure 4, most reservoirs located in the eastern states have an expansion feasibility metric that indicates they can be expanded if needed. However, there are many reservoirs located in the southern and western states that have an expansion feasibility metric of less than one, indicating that increasing the existing reservoir capacity storage is not likely a feasible strategy in these areas. The reservoirs located in Colorado can be included in both categories, meaning that there are some reservoirs in which additional capacity can be theoretically achieved.

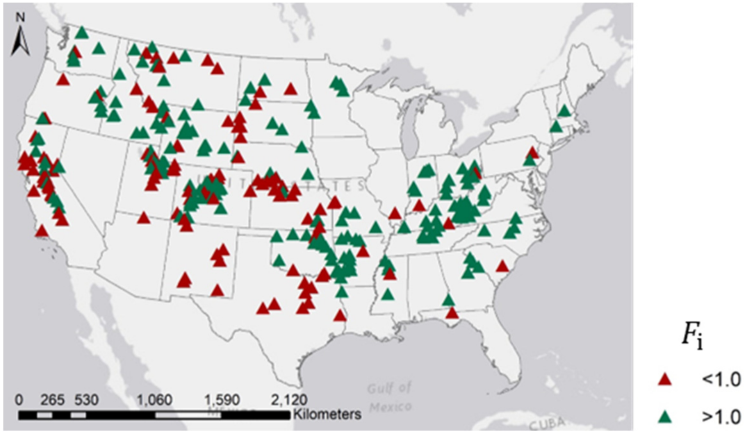

Figure 4. The expansion feasibility metrics of reservoir.

Although the efficiency metrics and feasibility metrics are informative regarding the possibility of reservoir expansion, we should consider that they do not show the usefulness of increasing storage capacity since the reservoir expansion is only useful in the regions that are experiencing water shortage conditions. Therefore, we still need to determine if the reservoirs with feasible and effective expansion are located in water-shortage-prone regions and if they can be useful to attenuate or mitigate the occurrence of water shortage events.

3.3. Reservoir Expansion Usefulness Metric

Figure 5 shows the expansion usefulness metrics of reservoirs located in water-shortage-prone regions. Note that 102 out of 304 reservoirs are located in regions currently experiencing water shortage conditions.

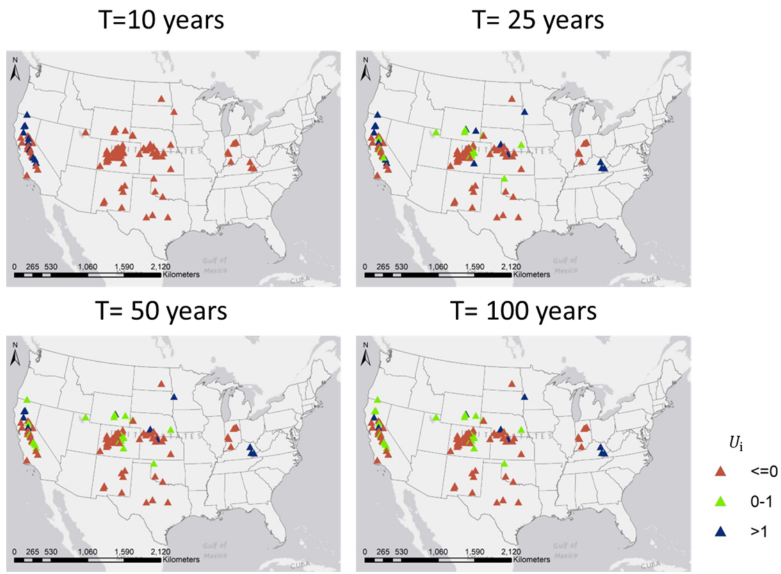

Figure 5. The expansion usefulness metrics of reservoir.

Additionally, it should be noted that the average intensity of water shortage events was calculated on the HUC4 basin scale. Therefore, a usefulness metric of greater than 1 indicates that expanding the storage of the given reservoir can potentially mitigate the water shortages in the given HUC4 basin. Additionally, increasing the storage capacity of reservoirs with usefulness metrics lower than 1 can be still considered a useful solution on a finer scale.

Among the 102 reservoirs located in water-shortage-prone regions, increasing the storage capacities of 10 reservoirs can potentially mitigate the occurrence of water shortage events with a return period of 10 years at the HUC4 level. As it is shown in Figure 5, these 10 reservoirs are mostly located in California. Adding more storage capacity to 33 reservoirs out of the 102 reservoirs can completely mitigate the water shortage events with return periods of 25 years at the HUC4 level. However, additional storage capacity can also help 16 more reservoirs to attenuate the intensity of water shortage events with a return period of 25 years at a finer spatial scale.

For water shortage events with a return period of 50 years, the storage expansion in 12 reservoirs can completely mitigate the occurrence of water shortage events at the HUC4 level and in 21 reservoirs can help to decrease the intensity of water shortage events at a finer spatial scale. Furthermore, for water shortage events with return periods of 100 years, increasing the storage capacities of 9 reservoirs can completely avoid the occurrence of water shortage events. In addition, reservoir expansion can be also used in 24 more reservoirs to attenuate the intensity of water shortage events.

In general, reservoir expansion does not seem to be a useful solution to mitigate or attenuate the water shortage events in Texas, but it can be an effective adaptation strategy in California and Colorado.

3.4. Discussion

While this study aimed to provide some insight to water managers, planners, and decision-makers into the feasibility and usefulness of reservoir expansion as a solution to attenuate or mitigate the occurrence of water scarcity events across the CONUS under the current conditions, there are still some considerations that should be addressed.

First, although reservoirs aimed to maintain a balance between water supply and water demand and increase the reliability of water supply systems, there is ongoing discussion that expanding and building the reservoirs may increase long-term water use and lead to more severe drought conditions. For instance, Baldassarre et al. (2018) [17] found that increasing reservoir storage over the last decades has affected downstream flows and highlighted that reservoir expansion can worsen the water shortage conditions if other aspects are not given enough attention.

Second, the expansion of reservoirs may affect meteorological characteristics and climates [19]. Reservoir enlargement can change the hydrological and ecological conditions of a region and consequently alter the distribution of precipitation and streamflow in the basin in the future.

Third, there are other aspects in operating a reservoir such as water rights, policies, pumping and transmission capacities, required instream flow rules, etc. In general, economic, social, and environmental factors can be the main drivers in the decision-making procedure of adaptation and mitigation strategies. Therefore, reservoir expansion only focusing on providing more supply and ignoring other aspects is not ideal.

Fourth, this study used the historical operation dataset from 1980 to 2020. However, climate change can lead to a shift in surface water and can affect the finding of this study [49]. For instance, previous studies found that the wet regions of the United States are getting wetter, and the dry regions are getting drier [15]. This finding reveals that the dry regions of the United States that have already been vulnerable to water shortage conditions can experience less surface flow in the future and consequently less inflow to their reservoirs. Therefore, while the reservoir expansion can be currently understood as an effective solution, its usefulness may fluctuate under future climate change and increasing hydrological uncertainty. However, note that the effect of climate change on streamflow is uncertain [50] and might change the seasonal distribution of streamflow and even lead to an increase in streamflow during spring seasons due to warming and glacier melt [51]. Besides, the findings of this study may be dependent on stationary assumptions that are considered over the 1980–2020 period. Considering nonstationary trends of streamflow in response to climate change and variability can affect the current findings and can be considered a prospect for further study.

Finally, there are many other water supply alternatives such as water recycling or reclamation, groundwater recharge, and desalination. Additionally, the re-operation of current reservoirs may be another way to improve the efficiency of existing dams instead of their expansion. Aquifer storage and recovery (ASR) is also an example of auxiliary infrastructure that is based on the artificial recharge of groundwater [11]. Furthermore, the maximum storage of existing reservoirs sometime decreases as a result of increased sediment levels within a river and aggregated sedimentation in the reservoir over time. Therefore, the maintenance and cleaning of current reservoirs can be crucial factors to enhance their optimal performance [52,53].

4. Summary and Conclusions

Enhancing reservoir storage capacity is known as a possible adaptation and mitigation strategy to attenuate the adverse effects of water shortage conditions on water supply systems. This study investigated the effectiveness, feasibility, and usefulness of increasing storage capacities of 304 reservoirs across the CONUS over the 1980–2020 period. Overall, the most important outcomes of this study are:

1. The possible assessment of reservoir expansion should be investigated by considering efficiency, feasibility, and usefulness metrics together.
2. From the efficiency metrics, Colorado, Utah, and California seem to be the best candidate states for reservoir expansion under historical conditions, while Texas' reservoirs are mostly less than half full.
3. From the feasibility metrics, most eastern states are suitable for an increase in the storage capacity of their reservoirs. In the western states, there are some reservoirs in which the inflow is greater than the usable storage.
4. From the usefulness metrics, reservoir enlargement is not likely to be considered a useful solution in Texas, while it may be an effective option in California and Colorado.
5. The expansion of U.S. reservoir capacity should not be known as a nationwide management strategy in planning for increasing the water supply reliability of U.S. regional water systems.

Note that the above findings may be dependent on aforementioned assumptions of this study. Thus, a comprehensive research study on the possibility of reservoir expansion across the United States at different spatial and temporal scales that includes all limitations discussed in Section 3.3 is recommended as a prospect for future study. The findings of this study are beneficial for water managers, planners, and decision-makers across the nation and provide an improved understanding of the possibility of reservoir expansion as an adaptation and mitigation strategy to decrease the vulnerability of water supply systems to water shortages. The improved understanding of the national-scale picture of reservoir expansion can provide insight into implementing adequate preparedness plans to attenuate the negative effects of possible water shortage conditions in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/hydrology9100175/s1, Table S1. Characteristics of studied reservoirs.

Author Contributions: Conceptualization, H.H.; methodology, H.H.; software, H.H.; validation, H.H.; formal analysis, H.H.; investigation, H.H.; resources, H.H.; writing—original draft preparation, H.H.; writing—review and editing, H.H., B.F., and C.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Acknowledgments: The reservoir dataset was obtained from the ResOpsUS dataset developed by Steyaert et al. (2022) [5] from 1980 to 2020. The water shortage data were obtained from Heidari et al. (2021) [15].

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bhadoriya, U.P.S.; Mishra, A.; Singh, R.; Chatterjee, C. Implications of climate change on water storage and filling time of a multipurpose reservoir in India. *J. Hydrol.* **2020**, *590*, 125542. [CrossRef]
2. He, C.; Liu, Z.; Wu, J.; Pan, X.; Fang, Z.; Li, J.; Bryan, B.A. Future global urban water scarcity and potential solutions. *Nat. Commun.* **2021**, *12*, 4667. [CrossRef] [PubMed]
3. Maliva, R.; Missimer, T. *Arid Lands Water Evaluation and Management*; Springer: Berlin/Heidelberg, Germany, 2013; ISBN 9783642291036.
4. Gain, A.K.; Giupponi, C.; Renaud, F.G. Climate change adaptation and vulnerability assessment of water resources systems in developing countries: A generalized framework and a feasibility study in Bangladesh. *Water* **2012**, *4*, 345–366. [CrossRef]
5. Steyaert, J.C.; Condon, L.E.; Turner, S.W.D.; Voisin, N. ResOpsUS, a dataset of historical reservoir operations in the contiguous United States. *Sci. Data* **2022**, *9*, 34. [CrossRef]
6. Brunner, M.I.; Björnsen Gurung, A.; Zappa, M.; Zekollari, H.; Farinotti, D.; Stähli, M. Present and future water scarcity in Switzerland: Potential for alleviation through reservoirs and lakes. *Sci. Total Environ.* **2019**, *666*, 1033–1047. [CrossRef] [PubMed]
7. Otkin, J.A.; Svoboda, M.; Hunt, E.D.; Ford, T.W.; Anderson, M.C.; Hain, C.; Basara, J.B. Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States. *Bull. Am. Meteorol. Soc.* **2018**, *99*, 911–919. [CrossRef]
8. Joyce, L.A.; Blate, G.M.; Littell, J.S.; McNulty, S.G.; Millar, C.I.; Moser, S.C.; Neilson, R.P.; O'Halloran, K.; Peterson, D. Adaptation Options for Climate-Sensitive Ecosystems and Resources. *Natl. Serv. Cent. Environ. Publ.* **2008**, *60*, 129.
9. Haro-Monteagudo, D.; Palazón, L.; Beguería, S. Long-term sustainability of large water resource systems under climate change: A cascade modeling approach. *J. Hydrol.* **2020**, *582*, 124546. [CrossRef]
10. Hagenlocher, M.; Meza, I.; Anderson, C.C.; Min, A.; Renaud, F.G.; Walz, Y.; Siebert, S.; Sebesvari, Z. Drought vulnerability and risk assessments: State of the art, persistent gaps, and research agenda. *Environ. Res. Lett.* **2019**, *14*, 083002. [CrossRef]
11. Perry, D.M.; Praskievicz, S.J. A new era of big infrastructure? (Re)developing water storage in the U.S. West in the context of climate change and environmental regulation. *Water Altern.* **2017**, *10*, 437–454.
12. Brown, T.C.; Mahat, V.; Ramirez, J.A. Adaptation to future water shortages in the United States caused by population growth and climate change. *Earth's Future* **2019**, *7*, 219–234. [CrossRef]
13. Heidari, H. Shifts in hydro climatology of U.S. croplands. *J. Ecol. Nat. Resour.* **2022**, *6*, 000270. [CrossRef]
14. Nover, D.M.; Dogan, M.S.; Ragatz, R.; Booth, L.; Medellín-Azuara, J.; Lund, J.R.; Viers, J.H. Does more storage give California more water? *JAWRA J. Am. Water Resour. Assoc.* **2019**, *55*, 759–771. [CrossRef]
15. Heidari, H.; Arabi, M.; Warziniack, T. Vulnerability to water shortage under current and future water supply-demand conditions across U.S. river basins. *Earth's Future* **2021**, *9*, e2021EF002278. [CrossRef]
16. Dallman, S.; Ngo, M.; Laris, P.; Thien, D. Political ecology of emotion and sacred space: The Winnemem Wintu struggles with California water policy. *Emot. Sp. Soc.* **2013**, *6*, 33–43. [CrossRef]
17. Di Baldassarre, G.; Wanders, N.; AghaKouchak, A.; Kuil, L.; Rangecroft, S.; Veldkamp, T.I.E.; Garcia, M.; van Oel, P.R.; Breinl, K.; Van Loon, A.F. Water shortages worsened by reservoir effects. *Nat. Sustain.* **2018**, *1*, 617–622. [CrossRef]
18. Kellner, E. The controversial debate on the role of water reservoirs in reducing water scarcity. *Wiley Interdiscip. Rev. Water* **2021**, *8*, e1514. [CrossRef]
19. Vanderkelen, I.; van Lipzig, N.P.M.; Sacks, W.J.; Lawrence, D.M.; Clark, M.P.; Mizukami, N.; Pokhrel, Y.; Thiery, W. Simulating the impact of global reservoir expansion on the present-day climate. *J. Geophys. Res. Atmos.* **2021**, *126*, e2020JD034485. [CrossRef]
20. Heidari, H.; Arabi, M.; Warziniack, T.; Sharvelle, S. Effects of urban development patterns on municipal water shortage. *Front. Water* **2021**, *3*, 694817. [CrossRef]
21. Heidari, H. An Integrated Understanding of changes in the water budget and climate of various US sectors over the 21st Century. *J. Earth Environ. Sci. Res.* **2022**, *4*, 1–4. [CrossRef]
22. Heidari, H.; Arabi, M.; Warziniack, T.; Kao, S.-C. Shifts in hydroclimatology of US megaregions in response to climate change. *Environ. Res. Commun.* **2021**, *3*, 065002. [CrossRef]
23. Heidari, H.; Arabi, M.; Warziniack, T.; Kao, S.C. Assessing shifts in regional hydroclimatic conditions of U.S. river basins in response to climate change over the 21st century. *Earth's Future* **2020**, *8*, e2020EF001657. [CrossRef]
24. Rocha, J.; Carvalho-Santos, C.; Diogo, P.; Beça, P.; Keizer, J.J.; Nunes, J.P. Impacts of climate change on reservoir water availability, quality and irrigation needs in a water scarce Mediterranean region (southern Portugal). *Sci. Total Environ.* **2020**, *736*, 139477. [CrossRef] [PubMed]
25. Chien, H.; Yeh, P.J.F.; Knouft, J.H. Modeling the potential impacts of climate change on streamflow in agricultural watersheds of the Midwestern United States. *J. Hydrol.* **2013**, *491*, 73–88. [CrossRef]

26. Li, Y.; Liu, C.; Yu, W.; Tian, D.; Bai, P. Response of streamflow to environmental changes: A Budyko-type analysis based on 144 river basins over China. *Sci. Total Environ.* **2019**, *664*, 824–833. [CrossRef] [PubMed]
27. Guo, A.; Liu, S.; Zhu, Z.; Xu, Z.; Xiao, Q.; Ju, Q.; Zhang, Y.; Yang, X. Impact of lake/reservoir expansion and shrinkage on energy and water vapor fluxes in the surrounding area. *J. Geophys. Res. Atmos.* **2020**, *125*, e2020JD032833. [CrossRef]
28. Liu, L.; Parkinson, S.; Gidden, M.; Byers, E.; Satoh, Y.; Riahi, K.; Forman, B. Quantifying the potential for reservoirs to secure future surface water yields in the world's largest river basins. *Environ. Res. Lett.* **2018**, *13*, 044026. [CrossRef]
29. Vogel, R.M.; Bolognese, R.A. Storage-reliability-resilience-yield relations for over-year water supply systems. *Water Resour. Res.* **1995**, *31*, 645–654. [CrossRef]
30. Vogel, R.M.; Lane, M.; Ravindiran, R.S.; Kirshen, P. Storage reservoir behavior in the United States. *J. Water Resour. Plan. Manag.* **1999**, *125*, 245–254. [CrossRef]
31. Wiberg, D.; Strzepek, K.M. *Development of Regional Economic Supply Curves for Surface Water Resources and Climate Change Assessments: A Case Study of China*; IIASA: Laxenburg, Austria, 2005; ISBN 3704501433.
32. Boehlert, B.; Solomon, S.; Strzepek, K.M. Water under a changing and uncertain climate: Lessons from climate model ensembles. *J. Clim.* **2015**, *28*, 9561–9582. [CrossRef]
33. Gaupp, F.; Hall, J.; Dadson, S. The role of storage capacity in coping with intra- and inter-annual water variability in large river basins. *Environ. Res. Lett.* **2015**, *10*, 3943. [CrossRef]
34. Chen, B.P.-T.; Chen, C.-S. Feasibility Assessment of a Water Supply Reliability Index for Water Resources Project Planning and Evaluation. *Water* **2019**, *11*, 1977. [CrossRef]
35. Thornton, P.E.; Running, S.W.; White, M.A. Generating surfaces of daily meteorological variables over large regions of complex terrain. *J. Hydrol.* **1997**, *190*, 214–251. [CrossRef]
36. Naz, B.S.; Kao, S.C.; Ashfaq, M.; Rastogi, D.; Mei, R.; Bowling, L.C. Regional hydrologic response to climate change in the conterminous United States using high-resolution hydroclimate simulations. *Glob. Planet. Chang.* **2016**, *143*, 100–117. [CrossRef]
37. Oubeidillah, A.A.; Kao, S.C.; Ashfaq, M.; Naz, B.S.; Tootle, G. A large-scale, high-resolution hydrological model parameter data set for climate change impact assessment for the conterminous US. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 67–84. [CrossRef]
38. Daly, C.; Halbleib, M.; Smith, J.I.; Gibson, W.P.; Doggett, M.K.; Taylor, G.H.; Curtis, J.; Pasteris, P.P. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *Int. J. Climatol.* **2008**, *28*, 2031–2064. [CrossRef]
39. Heidari, H. Vulnerability of U.S. River Basins to Water Shortage over the 21st Century. Ph.D. Thesis, Colorado State University, Fort Collins, CO, USA, 2021.
40. Cherkauer, K.A.; Lettenmaier, D.P. Simulation of spatial variability in snow and frozen soil. *J. Geophys. Res. D Atmos.* **2003**, *108*, 8858. [CrossRef]
41. Brakebill, J.W.; Wolock, D.M.; Terziotti, S.E. Digital hydrologic networks supporting applications related to spatially referenced regression modeling. *JAWRA J. Am. Water Resour. Assoc.* **2011**, *47*, 916–932. [CrossRef]
42. Yates, D.; Sieber, J.; Purkey, D.; Huber-Lee, A. WEAP2—A demand-, priority-, and preference-driven water planning model part 1: Model characteristics. *Water Int.* **2005**, *30*, 487–500. [CrossRef]
43. Brown, T.C.; Foti, R.; Ramirez, J.A. Projected freshwater withdrawals in the United States under a changing climate. *Water Resour. Res.* **2013**, *49*, 1259–1276. [CrossRef]
44. Diehl, T.H.; Harris, M.A. *Withdrawal and Consumption of Water by Thermoelectric Power Plants in the United States, 2010*; United States Geological Survey: Reston, VA, USA, 2014; ISBN 9781411338517.
45. Foti, R.; Ramirez, J.A.; Brown, T.C. *Vulnerability of U.S. Water Supply to Shortage: A Technical Document Supporting the Forest Service 2010 RPA Assessment*; U.S. Department of Agriculture: Washington, DC, USA, 2012.
46. Jaeger, W.K.; Amos, A.; Bigelow, D.P.; Chang, H.; Conklin, D.R.; Haggerty, R.; Langpap, C.; Moore, K.; Mote, P.W.; Nolin, A.W.; et al. Finding water scarcity amid abundance using human–natural system models. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 11884–11889. [CrossRef] [PubMed]
47. Gober, P.; Kirkwood, C.W. Vulnerability assessment of climate-induced water shortage in Phoenix. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 21295–21299. [CrossRef] [PubMed]
48. Yigzaw, W.; Hossain, F. Water sustainability of large cities in the United States from the perspectives of population increase, anthropogenic activities, and climate change. *Earth's Future* **2016**, *4*, 603–617. [CrossRef]
49. Heidari, H.; Arabi, M.; Ghanbari, M.; Warziniack, T. A probabilistic approach for characterization of sub-annual socioeconomic drought Intensity-Duration-Frequency (IDF) relationships in a changing environment. *Water* **2020**, *12*, 1522. [CrossRef]
50. Heidari, H.; Warziniack, T.; Brown, T.C.; Arabi, M. Impacts of climate change on hydroclimatic conditions of U.S. national forests and grasslands. *Forests* **2021**, *12*, 139. [CrossRef]
51. Shahid, M.; Rahman, K.U. Identifying the annual and seasonal trends of hydrological and climatic variables in the Indus Basin Pakistan. *Asia-Pacific J. Atmos. Sci.* **2021**, *57*, 191–205. [CrossRef]
52. Todd, C.R.; Lintermans, M.; Raymond, S.; Ryall, J. Assessing the impacts of reservoir expansion using a population model for a threatened riverine fish. *Ecol. Indic.* **2017**, *80*, 204–214. [CrossRef]
53. Morris, G.L.; Fan, J. Design and management of dams, reservoirs, watersheds for sustainable use; a reservoir sedimentation. *J. Chem. Inf. Model.* **2013**, *53*, 1689–1699.