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Evaporation Loss From Small Agricultural Reservoirs in a Warming Climate: An Overlooked Component of Water Accounting

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Key Points:

- A physically-based framework was proposed to identify the extent of small reservoirs (<0.1 km^2) and quantify their evaporative losses
- Total number and cumulative area of small agricultural reservoirs in water-stressed regions of southern Europe doubled in two decades
- Strong correlations were found between expansion of agricultural reservoirs, air temperature and precipitation

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Abstract

Small agricultural reservoirs support water demands during dry spells. However, evaporative losses that are often overlooked in water accounting and management diminish the storage efficiency of these popular but un-inventoried resources. We developed a predictive framework to identify the spatio-temporal extent of small reservoirs (900–100,000 m^2) and quantify their evaporative losses using a physically-based model. Focusing on water-stressed regions of Europe (Italy, Spain, and Portugal), our results indicate that the total number and cumulative area of small reservoirs in drier areas of Europe almost doubled in two decades from about 6,200 reservoirs with the cumulative area of 46 km^2 in 2,000 to 11,800 reservoirs with the cumulative area of 93.5 km^2 in 2020. We observed climate-driven trends in the expansion of agricultural reservoirs and their evaporative losses which exceeded 72 million cubic meters during warm months (April to September) accounting for 38% of their total storage capacity.

Plain Language Summary

Small agricultural reservoirs play a key role in supporting irrigation and local demands in a warming climate. However, evaporation diminishes their storage efficiency. We provide a physically-based framework for estimating global abundance and evaporative losses from small reservoirs serving as a basis for improving water management and planning. To show the applicability of the proposed method, we focused on water-stressed regions of Europe (Italy, Spain, and Portugal). We found that cumulative area of small reservoirs in the study area has reached to 93.5 km^2 in 2020 with cumulative evaporative losses that may exceed 72 million cubic meters. The study offers new insights into the improved understanding of the role and efficiency of small water storage infrastructure in water planning strategies.

1. Introduction

Increasing water demands in a warming world intensify the pressure on dwindling freshwater resources and highlight the need for effective water storage in regions with chronic water shortage problems (Friedrich et al., 2018). Application of agricultural water reservoirs and small engineered impoundments is growing globally to support livestock, irrigation, and local municipal and industrial demands during dry spells. However, evaporation can considerably decrease their storage efficiency. Depending on the reservoir characteristics (e.g., area, depth, turbidity), geomorphological factors, and climate regimes, evaporation may account for up to 50% of the total storage in small reservoirs (Craig, 2005). Despite extensive studies on spatial distribution, storage capacity, surface area, and evaporation rate modeling of large reservoirs, dams, and lakes (Lehner et al., 2011; Zhao & Gao, 2019; Zhao et al., 2020), limited knowledge exists in relation to small on-farm reservoirs. These reservoirs with an area <0.1 km^2 are often neglected in the global data sets of surface water bodies (e.g., HydroLAKES (Messager et al., 2016), and GRanD (Lehner et al., 2011)). Consequently, the associated evaporative water losses of abundant small reservoirs around the world are also overlooked in water accounting and the available inventories (Mady et al., 2020).

The cumulative impact of small on-farm reservoirs on the management of freshwater resources in regions with acute water scarcity is indisputable (Lehner et al., 2011; Mady et al., 2020). While many water planning studies to improve water management at the farm level are often concerned with irrigation efficiency and crop water productivity (Molden & Sakthivadivel, 1999; Zhou et al., 2021), little attention has been paid to opportunities for improving water storage efficiency and reducing the evaporative losses of blue water from small agricultural reservoirs. Thus, potentially significant water losses from small reservoirs remain a missing

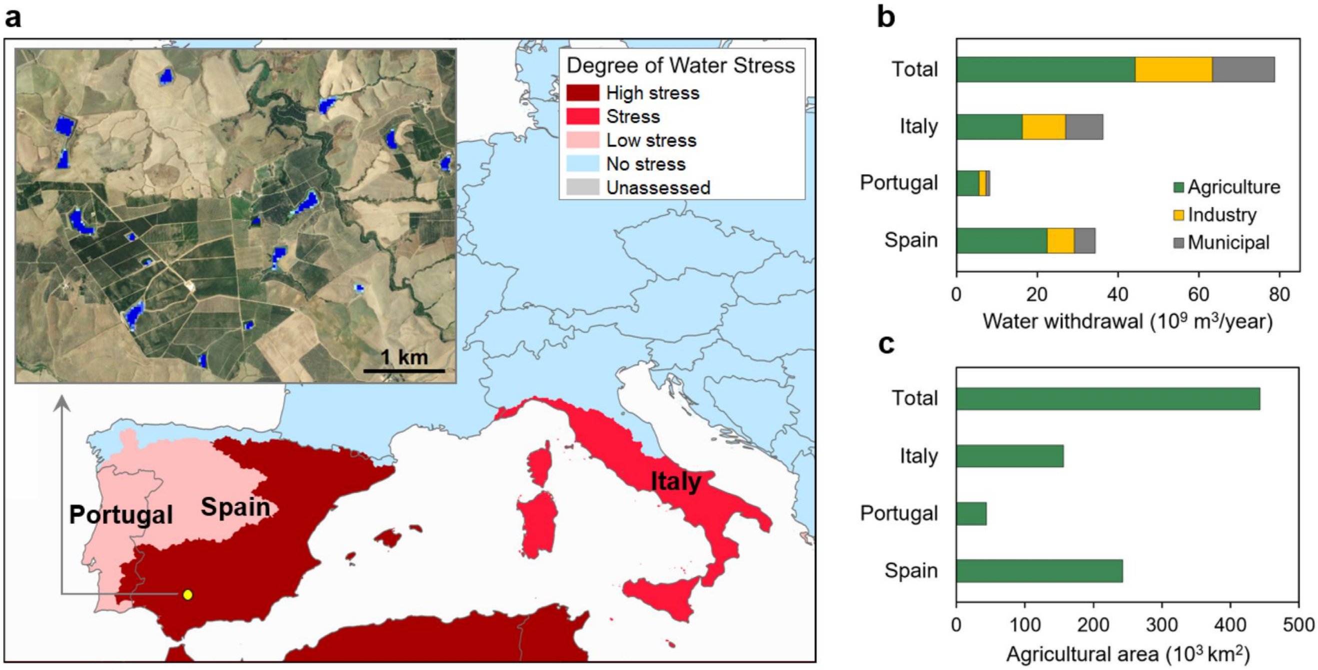

Figure 1. Water stress in southern Europe. (a) Spain, Portugal, and Italy with considerable agricultural activities in southern Europe experience severe water shortage problems (Hoekstra et al., 2010). The inset shows the extent of small water reservoirs (marked in blue) identified based on GSW data set (Pekel et al., 2016) in an agricultural region in Seville, Spain. (b) The average water withdrawal (2000–2019) by agricultural, industrial, and municipal sectors in the study area (AQUASTAT, 2023). (c) The average extent of agricultural area (2000–2018) in these countries (EEA, 2022).

component in water balance and budgeting analyses. Physically-based quantification of evaporative losses from agricultural reservoirs and prediction of their storage efficiency in a changing climate can produce critical insights to inform policy decisions regarding water allocation and water rights. Accordingly, here we develop a predictive framework that improves water accounting by identifying spatio-temporal distribution and storage capacity of small reservoirs and quantifying their associated evaporative losses based on reservoir characteristics and climatic conditions. To showcase the utility of the developed framework, we apply it to Spain, Portugal, and Italy as the major hub of agricultural activities in southern Europe with chronic water stress problems (Rolle et al., 2022) (Figure 1). According to some estimates, agricultural water withdrawal accounts for 40%–80% of the annual water consumptions in these countries where irrigation relies largely on local water storage infrastructure (AQUASTAT, 2023; Bazzani et al., 2004; Tójar-Hurtado et al., 2017). The expansion of irrigation lands and livestock farms along with the rising temperature and modified precipitation patterns under climate change have increased water demands and exacerbated pressure on unevenly distributed freshwater resources in the study area (Bisselink et al., 2020; Iglesias & Garrote, 2015; Webber et al., 2018). Estimating the extent of relying on small water reservoirs thus enables us to delineate the significance of evaporative losses of precious blue water and the efficiency of small water storage infrastructure in these water-stressed countries of southern Europe.

2. Methods and Data

2.1. Identification of Small Reservoirs and Their Storage Capacity

We used the Global Surface Water (GSW) data set to identify small reservoirs and calculate their surface area. The data set uses Landsat 5, 7, and 8 satellite images since 1984 to create long-term information on the extent and spatio-temporal variability of surface water at 30 m resolution (Pekel et al., 2016). This global data set classifies each pixel as water, land or non-valid observations. Every open water surface larger than 30×30 m^2 not covered by vegetation or infrastructures was detected. Overall, the water detection algorithm only misses about 5% of water surfaces and produces less than 1% false water detections (Pekel et al., 2016). We obtained land cover information from the European Environment Agency (EEA) within the Coordination of Information on the Environment (CORINE) project (EEA, 2022) with spatial resolution of 100 m to focus our analyses on agricultural areas. The

Global River Width from Landsat (GRWL) database (Allen & Pavelsky, 2018) was further employed to mask the reaches of ephemeral/intermittent streams and narrow water canals in agricultural areas. In this study, a water reservoir was defined as a stretch of connected water pixels within an agricultural area with a minimum surface area of 900 m^2 arising from the spatial resolution of water data (i.e., 30 m). Considering the focus of the study on small water reservoirs (<0.1 km^2), the maximum surface area of reservoirs was limited to 100,000 m^2.

To estimate the storage capacity of water reservoirs, we determined their size distribution based on 10 equally spaced size classes, each spanning 10,000 m^2 (except for the first class that included reservoirs smaller than 10,000 m^2; see Figure 2d). According to the power law relation proposed by Mady et al. (2020), volume of reservoirs within each size class can be estimated as $V = 0.38 \times n \times A^{1.173}$ with n and A ($= \sqrt{a_{\min} \times a_{\max}}$) as the number and representative area of reservoirs in each size class (with area between $a_{\min}$ and $a_{\max}$).

2.2. Physically-Based Modeling of Evaporation Dynamics in Water Reservoirs

Quantifying evaporative losses from water reservoirs relies largely on pan measurements or Penman-type estimates with locally calibrated vapor transfer coefficients (Althoff et al., 2019; Mady et al., 2020). The physically-based modeling of evaporation from shallow water bodies by Aminzadeh et al. (2018) has revealed that thermal feedbacks at the reservoir surface, inherent reservoir characteristics (e.g., depth, light attenuation), and energy exchanges with underlying soil layer modify energy balance dynamics and evaporation rates from a reservoir.

Evaporation flux from a water reservoir was thus quantified based on the physically-based model of Aminzadeh et al. (2018) which solves the 1D energy equation with radiative energy absorption in depth of the reservoir to obtain the vertical temperature profile:

$$\frac{\partial T_w}{\partial t} = \frac{\partial}{\partial z}\left((\alpha_{T,w} + D_w)\frac{\partial T_w}{\partial z}\right) + \frac{Q(z,t)}{\rho_w c_w} \tag{1}$$

where T_w [K] is water temperature at depth z [m], $\alpha_{T,w}$ [m^2/s] is molecular thermal diffusion, D_w is eddy thermal diffusivity [m^2/s], ρ_w [kg/m^3] is water density, c_w [J/kgK] is specific heat of water, and Q [W/m^3] represents absorption of radiative flux within the water body (see Aminzadeh et al. (2018) for details). The lower boundary condition of Equation 1 is defined based on the intercepted radiative flux at the bottom of the reservoir and heat exchanges with soil layer beneath (Aminzadeh & Or, 2014). Surface heat exchanges through radiative, sensible, and latent heat fluxes govern the upper boundary condition. The inherent coupling of evaporative flux and water temperature (through the temperature dependency of saturated vapor concentration) enables calculation of evaporation loss from the water body by quantifying water temperature at the surface of the reservoir (Brutsaert, 2005):

$$E = 86.4 \times 10^6 \frac{0.622\, \kappa^2\, U}{\rho_w\, R_d\, T_a \left[\ln\left(\frac{z_m}{z_0}\right)\right]^2}(e_s(T_{ws}) - e_a) \tag{2}$$

where E is evaporation rate [mm/day], κ is von Karman's constant, U is the wind speed [m/s], R_d is the gas constant for dry air [J/kgK], T_a is the air temperature [K], T_{ws} is the water surface temperature [K], z_0 is the roughness length [m], z_m is the measurement height for wind speed and air temperature [m], e_s and e_a [Pa] are saturated vapor pressure at the water surface and vapor pressure within the air mass above the surface, respectively. Solution of Equations 1 and 2 subjected to local atmospheric forcing parameters (i.e., wind, radiation, air temperature and humidity) allows us to delineate spatio-temporal variation of evaporative losses from the agricultural reservoirs in the study area.

Model estimates of evaporative loss from small reservoirs were primarily evaluated using available evaporation data from an agricultural reservoir in southeastern Spain measured by Maestre-Valero et al. (2011) (see details in Figure 3b). The reservoir with 2,400 m^2 of surface area and 5 m of depth was located in Cartagena (37°41′N, 0° 57′W) which is characterized by a Mediterranean, semi-arid climate with dry and warm summers and thus high atmospheric evaporative demand. Bottom and side walls of the reservoir were covered with a waterproof liner. The change in water level due to surface evaporation was monitored by a pressure transducer during a 2-year experiment from April 2007 to April 2009. We only used monthly evaporation data during the warm months from April to September 2007 for the sake of model evaluation (the surface of the reservoir was kept covered during the second year to suppress evaporative losses).

2.3. Spatio-Temporal Estimation of Evaporative Losses in the Study Area

To calculate spatial distribution of small reservoirs and their evaporative losses, the study region was divided into rectangular grid cells of approximately 50×50 km^2. We calculated potential daily evaporation rate (evaporated water volume per square surface area) for a typical agricultural reservoir in each grid cell subjected to atmospheric forcing variables (incoming radiation flux, wind, air temperature and humidity). According to the relations between surface area, volume, and depth of small reservoirs proposed in Mady et al. (2020), the corresponding depth of the reservoirs in this study was estimated between 2 and 4 m. Hence, we first calculated the potential evaporation rate for a typical reservoir in each grid cell with an average depth of 3 m from April 1 to September 30 in 2000, 2005, 2010, 2015, and 2020. Total evaporative water loss from all reservoirs in a cell [m^3] was thus quantified by multiplying the cumulative surface area of reservoirs in the cell [m^2] by the potential evaporation rate in that cell from April to September [m^3/m^2].

Considering the key role of climatic conditions in surface exchanges and energy budget of a reservoir, we coupled the spatial information regarding the location and extent of small reservoirs with their corresponding climatic conditions. We extracted hourly meteorological data including radiation, wind speed, air temperature, and humidity for each grid cell from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) at the spatial resolution of $0.625° \times 0.5°$ to determine associated boundary conditions (Gelaro et al., 2017; Global Modeling and Assimilation Office (GMAO), 2015a, 2015b). Daily precipitation was also obtained from PERSIANN-CDR (Ashouri et al., 2015) data sets at the spatial resolution of 0.25°. The meteorological data were interpolated to the 50×50 km^2-rectangular grid using the bilinear method.

3. Results

3.1. Spatio-Temporal Distribution of Water Reservoirs

The Global Surface Water (GSW) data set of European Commission's Joint Research Centre (JRC) with 30 m spatial resolution (Pekel et al., 2016) was used to identify small water reservoirs and calculate their surface area in Spain, Portugal, and Italy. Cumulative surface area of water reservoirs in each grid cell (50×50 km^2) in the study region in 2000, 2005, 2010, 2015, and 2020 is depicted in Figure 2a. Results indicate that the small reservoirs of the study region are primarily aggregated in southern Portugal and Spain with considerable agricultural activities. While the cumulative surface area of reservoirs in most grid cells was less than 2 km^2, a maximum cumulative surface area (in a grid cell) of 2.3 km^2 was detected in southern Portugal in 2010. Another region with a high reservoir density in Iberian Peninsula is in the northeastern Spain, where detected cumulative reservoir area exceeded 1.92 km^2 per cell. Less density of small water reservoirs in the other regions (e.g., northern regions) could be attributed to the less agricultural lands and availability of alternate freshwater resources due to more precipitation (Estrela et al., 2012).

The highest density of small water reservoirs in Italy was detected in northern region. This region, known as Po Valley, is one of the main agricultural areas in Italy. Cumulative surface area of reservoirs exceeded 1 km^2 per cell in northern Italy, where a maximum reservoirs area of 1.23 km^2 was detected in 2020. Some regional hotspots can also be identified in the west of Sardinia, and the east of Sicily (southern Italy).

Variations of the total number of small reservoirs and their cumulative surface area in Spain, Portugal, and Italy during the study period from 2000 to 2020 are depicted in Figures 2b and 2c. In general, increasing trends in the total number and cumulative surface area of water reservoirs were observed in the study area. The increase in number of small reservoirs from about 6,200 in 2000 to more than 11,800 in 2020 indicates 91% growth. The cumulative surface area also expanded from 46 km^2 in 2000 to 93.5 km^2 in 2020, reflecting a 103% increase. Our results show that Italy has experienced the highest rate of increase in number (117%) and cumulative area of reservoirs (129%) during this 20-year study period.

The maximum cumulative reservoir area in Spain, Portugal, and Italy was estimated as 43.9 km^2 (2020), 18.4 km^2 (2010), and 33.3 km^2 (2020), respectively. The estimated cumulative surface area of small agricultural reservoirs in Spain and Portugal (62.3 km^2) is about double the size of the Castelo de Bode reservoir in Iberian Peninsula.

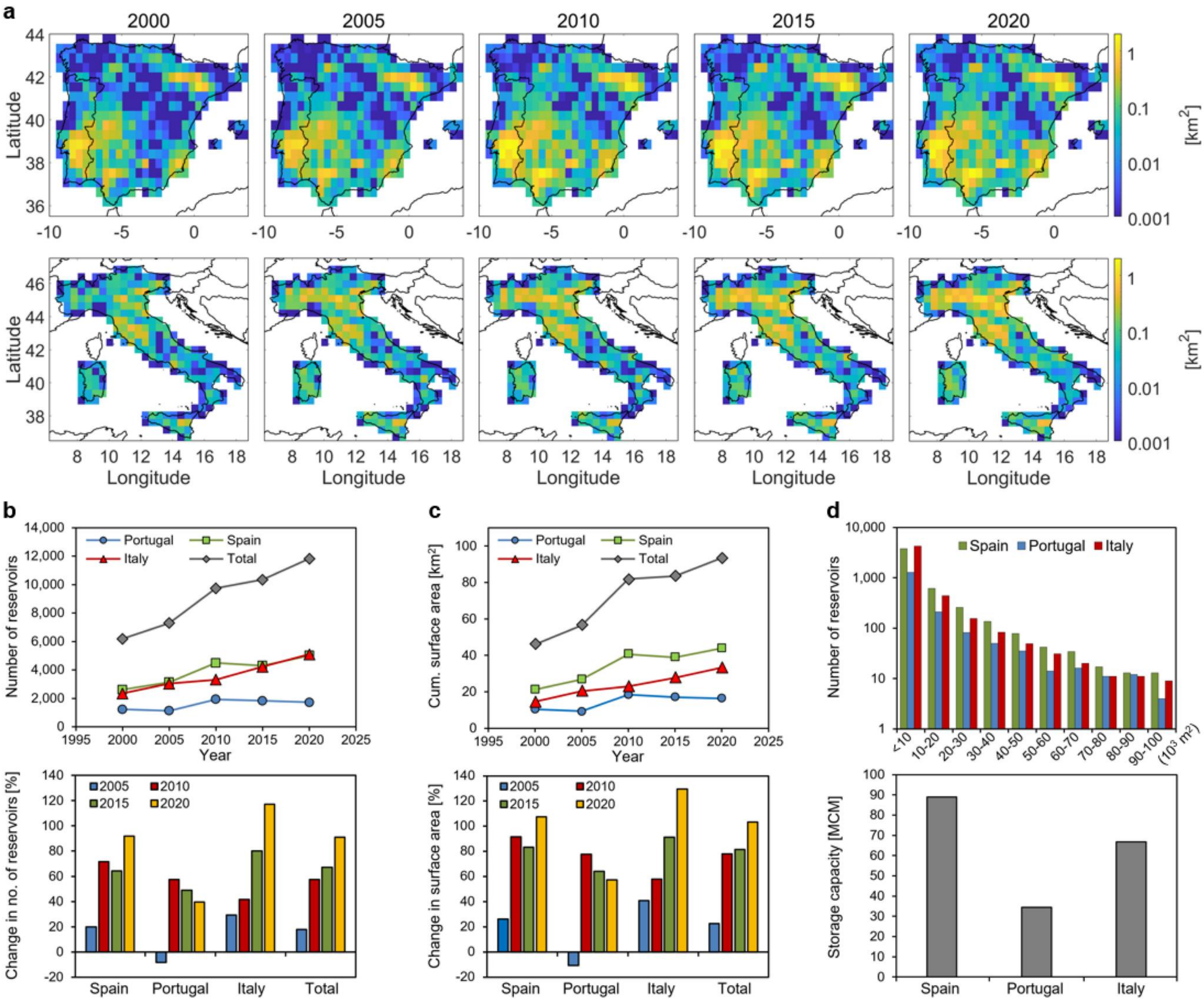

Figure 2. Spatio-temporal distribution of small water reservoirs. (a) Cumulative surface area of small water reservoirs in Spain and Portugal (top), and Italy (bottom) in 2000, 2005, 2010, 2015, and 2020. Given the large span of reservoir area in different grid cells (pixels), the data is shown using a logarithmic color bar representing cumulative area of reservoirs in each 50 × 50 km^2 pixel. The color bar extends to 2 km^2. (b) Variation of the number of reservoirs from 2000 to 2020 (top), and their changes relative to 2000 (bottom); (c) variation of cumulative surface area of small water reservoirs from 2000 to 2020 (top), and changes in the cumulative area relative to 2000 (bottom). (d) The size distribution of small water reservoirs in Spain, Portugal, and Italy in 2020 with 10 equally spaced size classes (top), and their estimated storage capacity in million cubic meters (bottom).

The cumulative area of reservoirs in Italy (33.3 km^2) is also comparable with the area of Lake Omodeo in Sardinia (Italy). We further extracted size distribution of reservoirs in 2020 (Figure 2d) to estimate their storage capacity. Our results indicate that the total storage capacity of agricultural reservoirs in Spain, Portugal, and Italy has reached to 88.9, 34.5, and 66.8 million cubic meters (MCM) in 2020 (Figure 2d). Considering the yearly household water consumption of ∼53 m^3 per capita in Europe (EEA, 2023), the estimated total storage capacity of small agricultural reservoirs in these three countries (∼190 MCM) is sufficient to satisfy the annual household water demands of about 3.6 million Europeans.

3.2. Evaporative Water Losses From Small Reservoirs

We employed the physically-based model of Aminzadeh et al. (2018) to quantify potential evaporative losses from small reservoirs in Spain, Portugal, and Italy. The span of small water reservoirs with different characteristics (in terms of geometrical factors and thermal and radiative properties) hinders quantifying evaporative

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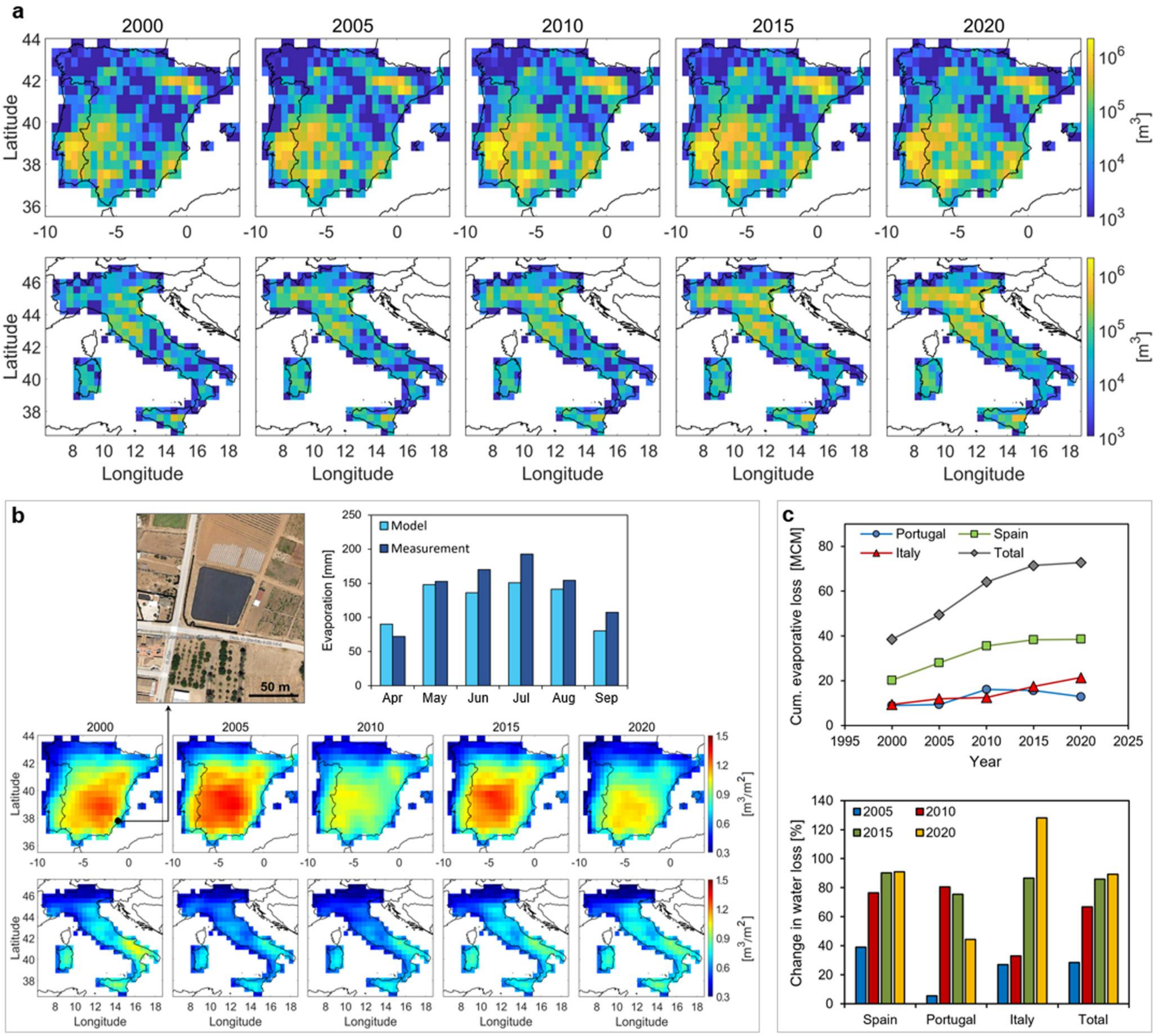

Figure 3. Evaporative losses from small water reservoirs in the study area. (a) Spatio-temporal distribution of cumulative evaporative loss in Spain and Portugal (top), and Italy (bottom) from 2000 to 2020. The logarithmic color bar extends to 2×10^6 m^3. (b) Model estimates of the variation of potential evaporation rate from a typical reservoir in each grid cell during warm months (April to September) from 2000 to 2020 in Spain, Portugal, and Italy. Also the evaluation of the evaporation model of Aminzadeh et al. (2018) is presented based on the measurements from an agricultural reservoir in Cartagena, Spain with 2,400 m^2 surface area and 5 m depth from April to September 2007 (Maestre-Valero et al., 2011). Satellite image of this reservoir was reproduced from Google Earth (Google Earth 7.3.6.9345, 2022). (c) Variation of cumulative evaporative loss in the study area from 2000 to 2020 (top) and changes in the evaporative water loss relative to 2000 (bottom).

losses from individual reservoirs in each grid cell. Hence, we quantified the potential evaporation rate (evaporated water volume per surface area) from a typical water reservoir in a grid cell subjected to local atmospheric forcing variables and then upscaled results based on the cumulative surface area of reservoirs in the cell (Figure 2a) to estimate total evaporative water losses in that cell.

Spatio-temporal variation of cumulative water volume that may be lost via evaporation from small agricultural reservoirs in the study area is depicted in Figure 3a. As seen, highest evaporative losses occur in hotspot areas of agricultural reservoirs depicted in Figure 2a, that is, southern and northeastern Spain, southern Portugal, and northern Italy. The results were obtained based on the calculated potential evaporation from a typical reservoir in each cell (pixel) from April to September (Figure 3b). According to Figure 3b, evaporation hotspots are observed

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in the central and southern regions of Iberian Peninsula with potential evaporation rates exceeding 1.4 m^3/m^2 during April to September 2005. Maximum potential evaporation in Italy occurs in the eastern and southern regions with values of more than 1 m^3/m^2 from April to September 2000. Model calculations of evaporative water losses from small water reservoirs were evaluated based on the measured evaporation data of Maestre-Valero et al. (2011) in an agricultural reservoir with the surface area of 2,400 m^2, located in Cartagena (Spain). Figure 3b compares model estimates of monthly evaporation from the reservoir with in situ measurements from April to September 2007. Cumulative evaporative loss over this 6-month period was slightly underestimated by the model (∼12%) relative to the measurements. The difference between modeled and measured evaporative losses could be attributed to relatively coarse resolution of atmospheric forcing data obtained from MERRA-2 reanalysis data sets, that may not exactly represent above surface meteorological variables.

The maximum cumulative evaporative losses (April to September) from agricultural reservoirs in Spain, Portugal, and Italy were estimated as 38.5 MCM (2020), 16.1 MCM (2010), and 21.4 MCM (2020), respectively (Figure 3c). The results indicate that the total evaporative loss reached to 72.7 MCM in 2020. The increase in total surface area of reservoirs in the study area from 2000 to 2020 (Figure 2c) is accompanied by the increase in total evaporative mass losses (Figure 3c). Notwithstanding a rather constant surface area of reservoirs from 2010 to 2015 (Figure 2c), the increase in atmospheric evaporative demand (potential evaporation) in 2015 resulted in an increase in evaporative mass losses as shown in Figure 3c.

4. Discussion

4.1. Expansion of Water Reservoirs in a Changing Climate

Changes in the cumulative area of reservoirs (Figure 2) could primarily be linked to the changes in freshwater availability and demands arising from climatic factors and agricultural activities. Investigating land cover changes in Spain, Italy, and Portugal reveals that agricultural areas have remained almost unchanged during the past two decades (2000–2018) with a slight decrease of 0.35%, 1.3%, and 0.52%, respectively (EEA, 2022). In addition, agricultural production in the study area from 2000 to 2020 indicates a decreasing pattern (Eurostat, 2023), suggesting that expansion of water reservoirs (Figure 2) may not be directly in response to the expansion of agricultural activities. Thus, one needs to investigate the role of climatic variables such as precipitation and temperature on the expansion of the cumulative area of small reservoirs. Climatic changes can motivate expansion of water storage as the alternation of precipitation patterns affects water availability and the need for storages over dry spells, and the change in air temperature affects evapotranspiration and crop water demand (Aminzadeh et al., 2016). Figure 4a depicts Pearson correlation coefficients between the cumulative surface area of reservoirs and mean annual air temperature and precipitation from 2000 to 2020. The results generally indicate positive correlations between variation of cumulative reservoir area with variation of air temperature (influencing evaporative demand) in the study area and negative correlations with variation of precipitation (representing water availability) in Italy and northern Spain suggesting that the changes in the abundance of water reservoirs is primarily the product of climatic changes. Further investigation of changes in air temperature and precipitation in Iberian Peninsula and Italy indicates an increasing trend in air temperature and a decreasing trend in precipitation during the study period (Figure 4b). The findings here confirm climate-driven trends in expansion of local water storages where a warmer and drier atmosphere enhances evapotranspiration and increases irrigation water demand and thus increases the desire for increasing local water storage capacities (Aminzadeh & Or, 2017; Rolle et al., 2022).

4.2. Water Management Implications of Evaporative Water Loss in Southern Europe

The estimated evaporative loss from small water reservoirs in Spain, Portugal, and Italy exceeded 72 MCM during the warm months (April to September) in 2020. This accounts for 38% of the total storage capacity of small agricultural reservoirs in these countries (∼190 MCM). This amount of water is sufficient to produce 39,300 tons of wheat (with global average water footprint of 1,830 m^3/ton (Mekonnen & Hoekstra, 2010)), equal to the annual consumption of about 600,000 people (66 kg per capita (Erenstein et al., 2022)).

Beyond the importance of evaporative losses in drastically decreasing the storage efficiency of local reservoirs, the significance of fresh surface water losses in a water-scarce region can be better understood by gauging the economic and environmental costs of producing the same amount of freshwater through alternative methods such as groundwater extraction or desalination, where feasible.

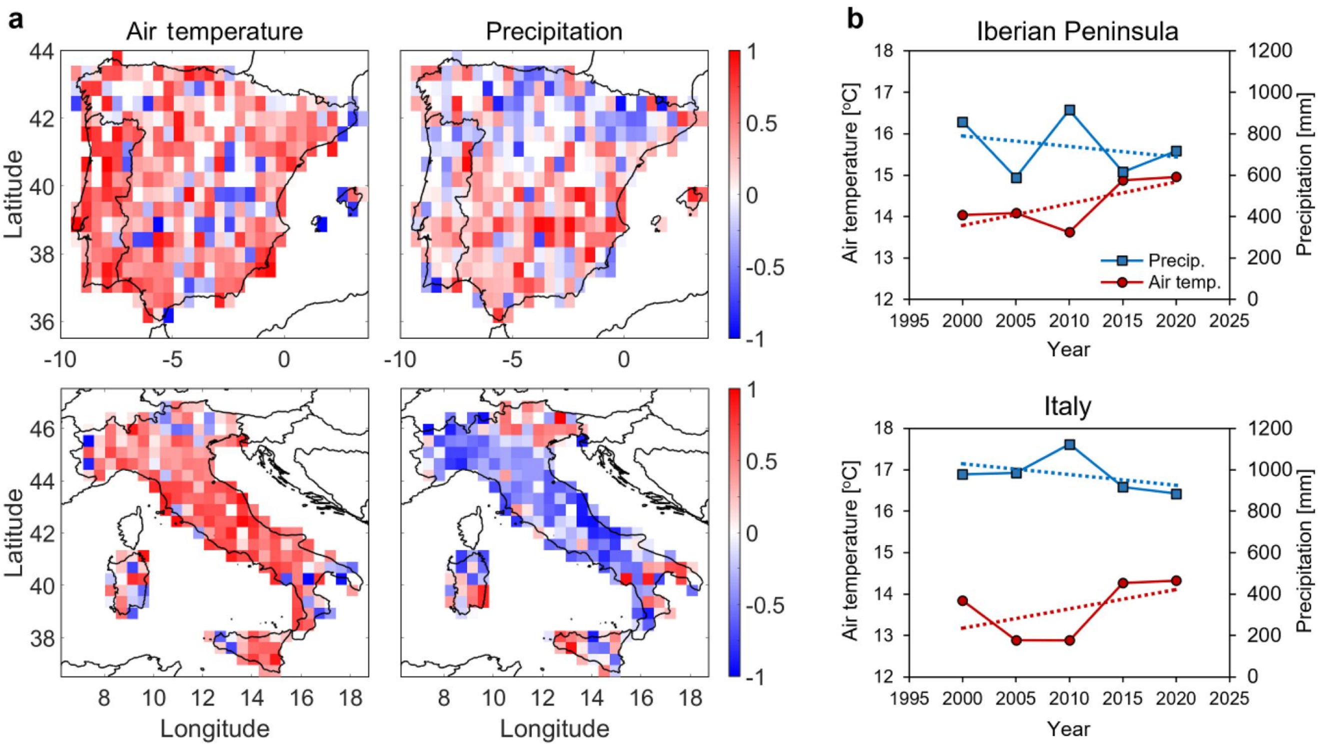

Figure 4. Climate-driven trends in expansion of small water reservoirs. (a) Spatial variation of Pearson correlation coefficient between the cumulative surface area of reservoirs in 2000, 2005, 2010, 2015, and 2020 and mean annual air temperature (left) and mean annual precipitation (right). (b) Variation of mean annual temperature and precipitation in Iberian Peninsula (top) and Italy (bottom). Precipitation data were obtained from PERSIANN-CDR (Ashouri et al., 2015).

Depending on the technology, energy efficiency, and capacity of desalination plants, the cost of desalinated water often varies between 0.5 and 2 USD per cubic meter (Caldera et al., 2018; Pistocchi et al., 2020). Hence, the direct economic value of more than 72 MCM evaporative loss in the study area can be estimated up to 145 million USD/year. Declining groundwater table and quality, land subsidence, saltwater intrusion, disposal of concentrated salts, marine ecosystem damages, increasing energy demands and CO_2 emissions are among the most typical consequences of producing water through groundwater extraction and desalination. Evaporative water losses can further be gauged by the economic productivity of irrigation water (Tatlhego et al., 2022). According to D'Odorico et al. (2020), the value of irrigation water in Europe is estimated from 0.42 USD/m^3 (based on the current crop distribution) to 1.12 USD/m^3 (with crops that maximize economic productivity). This suggests that the economic value of evaporative water loss from agricultural reservoirs in Spain, Portugal, and Italy may exceed 80 million USD/year. These examples highlight the significance of freshwater losses through evaporation from reservoirs and reveal the need for increasing the efficiency of small reservoirs for storing the scarce blue water in dry regions (Elsaid et al., 2020; Gelati et al., 2020; Guzy & Malinowska, 2020; Nassrullah et al., 2020). Additionally, the significant economic and environmental implications of overlooked evaporative water losses from small reservoirs underline the need for improved representation of agricultural reservoirs in water accounting and planning studies. The proposed framework in this study addresses an important knowledge gap and provides a scientific basis to improve water accounting and allocation of limited freshwater resources in water-stressed regions of the world with high atmospheric evaporative demands.

Considerable evaporation from small agricultural reservoirs calls for enhancing the efficiency of the on-farm water storage infrastructure. Depending on the environmental conditions and reservoir characteristics, common measures for suppressing evaporative losses include deepening the reservoirs, covering the surface, or deploying wind breakers (Aminzadeh et al., 2018; Bakhtiar et al., 2022; Lehmann et al., 2019; Maestre-Valero et al., 2011; Rezazadeh et al., 2020). Among different techniques, modular floating covers offer an efficient and scalable solution for suppressing evaporative losses from small reservoirs. Mechanistic modeling accompanied by laboratory and field measurements indicate that floating covers may suppress evaporative losses by more than 80% while supporting multiuse applications (e.g., fish cultures and floating photovoltaic plants) and maintaining water quality for certain purposes (e.g., drip irrigation) (Aminzadeh et al., 2018; Bakhtiar et al., 2022; Jin et al., 2023; Lehmann et al., 2019; Pourmand et al., 2022).

4.3. Limitations and Future Perspectives

The proposed framework enables estimating spatio-temporal distribution of small agricultural reservoirs and their associated evaporative losses thus improving water accounting across scales. Improved understanding of the role and efficiency of often un-inventoried water storage infrastructure can play a key role in devising the necessary action plans and implementing appropriate adaptation schemes to cope with water scarcity in a warming climate. Similar to any estimation method, the proposed framework is associated with a few limitations that must be noted and might be addressed in future investigations. Estimating the number and cumulative surface area of reservoirs relies on the accuracy and spatial resolution of GSW data set (i.e., 30 m). This primarily makes the identification of reservoirs with a surface area below 900 m^2 challenging. Future investigations may benefit from high resolution satellite products such as Sentinel-2 (available from 2015) with the spatial resolution of 10 m to quantify spatio-temporal extent of water reservoirs with different sizes. The dynamic changes in physical, chemical, and biological characteristics of a water body (e.g., water depth, turbidity, algae growth) could change thermal and radiative properties of reservoirs and consequently affect water evaporation (Bakhtiar et al., 2022). Considering the lack of such detailed information for individual reservoirs in the scale of the present study, our theoretical calculations tacitly ignore such inherent variations to retain model applicability for estimating evaporative losses from water reservoirs. Nevertheless, our physically-based estimates of evaporative losses could be improved wherever detailed reservoir's characteristics are available. The evaluation of the model's performance for quantifying evaporation dynamics was based on the available evaporation data from an agricultural reservoir in Cartagena, Spain. Future extension of the proposed approach could primarily benefit from assessing the evaporation model under different geomorphological and climatic conditions. Lastly, model estimates of evaporative losses from water reservoirs are affected by the spatial and temporal resolution of meteorological inputs. Existence of highly resolved atmospheric forcing variables (such as 1 km-scale climatic information planned to be generated within Destination Earth project (Bauer et al., 2021; Shokri et al., 2023)) will enable us to improve model estimates of water evaporation with a much better spatial resolution.

5. Conclusions

We proposed a predictive framework to identify the extent of small reservoirs (900–100,000 m^2) and quantify their evaporative losses. To showcase utility of the framework, we focused on water-stressed regions of southern Europe, that is, Spain, Portugal, and Italy, which are the hub of agricultural activities with considerable water use. Our results showed that total number of reservoirs has increased from 6,200 reservoirs in 2000 to 11,800 reservoirs in 2020. The cumulative surface area of reservoirs also doubled up from 46 to 93.5 km^2 during this period. We observed that Italy has experienced the highest rate of increase in number (117%) and cumulative area of reservoirs (129%).

Physically-based calculation of evaporation from reservoirs indicated that cumulative evaporative losses (April to September) from small agricultural reservoirs in these three countries has exceeded 72 million cubic meters in 2020 accounting for 38% of their total storage capacity. Focusing on the role of air temperature and precipitation in a changing climate, we found climate-driven trends in expansion of local water storages and their evaporative losses. The study provides a theoretical basis for delineating the extent of small water reservoirs that are often overlooked in the present inventories and the impact of evaporative losses from them on water management and budgeting in a warming world.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The required data of the study explained in Section 2 were obtained from the following sources: MERRA-2 reanalyses meteorological data sets are available at Global Modeling and Assimilation Office

(GMAO) (2015a, 2015b). The Global Surface Water data sets are available through Pekel et al. (2017). Daily precipitation was obtained from PERSIANN-CDR data sets (CHRS, 2023). Land cover information was downloaded from the European Environment Agency (EEA) (EEA, 2022).

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