Regional Assessment of Evaporation from Agricultural Irrigation Reservoirs in a Semiarid Climate

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Abstract

The aim of this study was to assess the magnitude of evaporation loss from the Agricultural Water Reservoirs (AWRs) for Irrigation at a regional scale and to analyse its impact on water storage efficiency. To this end, we identified the extant AWRs for irrigation in the Segura River Basin (SRB) in southeastern Spain, and calculated the water loss from each AWR per month and year. In order to accomplish this, we determined the monthly and yearly values of the pan coefficient, K_p, taking into account the geometric dimensions (area and depth) of the AWRs and local climate conditions through a function of air vapour pressure deficit *VPD*. AWR areas were identified by interpreting aerial images, while climate conditions were assessed using daily meteorological data obtained from 74 automated agro-meteorological stations located in irrigated areas. Regional evaporation losses were estimated using aggregation GIS techniques. A total of 14,145 AWRs covering 4,901 ha were identified, which represents 0.26 and 1.81% of the total area of SRB and the irrigated land, respectively. Results indicated that annual water loss at a basin scale reaches 58.5 10^6 m^3, which corresponds to 1.404 m of water depth over the flooded area and to 8.3% of irrigation water use in the basin. This quantity is higher than the industrial demand and similar to the environmental demand, and is equivalent to 27% of the domestic water use in a region with approximately two million inhabitants. The method used, based on annual K_p, appears the most straightforward to assess regional evaporative losses from AWRs, and can be extended to other regions and climates, provided that the *VPD*-dependent function that gives the pan coefficient is available.

Keywords: storage efficiency, Class-A pan, pan coefficient, water loss, water management.

1. Introduction

Current global population growth, industrial development, sustained increase of living standards and the trend towards irrigated agriculture have produced a strong competition for water resources. In arid and semiarid climates, this causes water shortages that mainly affect agricultural users (Gleick, 1993) and the predicted global climate change may worsen this situation in the future (Bouwer, 2000). There is an urgent need to improve water management by developing new water-saving technologies, especially in agriculture (Pereira et al., 2002; Ortega et al., 2005).

In arid and semi-arid regions, evaporation loss from Agricultural Water Reservoirs (AWRs) for Irrigation can be potentially large. It is crucially important to accurately estimate evaporation from AWRs in order to optimize the design, survey and management of water resources, at both farm and regional or catchment scales (Morton, 1994; Stanhill, 2002). Gökbulak and Özhan (2006) estimated that annual evaporation from lakes and dams in Turkey is greater than the amount of water withdrawn from groundwater. They also reported that more water is lost by evaporation than is used for domestic and industrial purposes: a quantity greater than one-fifth of the irrigation water use. In the Rio Grande Basin (USA), evaporation from a mid-sized reservoir (Elephant Butte) accounts for 15 to 25% of the Rio Grande (New Mexico) water consumption allotment each year (Gupta et al., 2002) and represents enough water to satisfy the water needs of Albuquerque for 2 to 4 years.

The large area-to-volume ratio of AWRs is one reason that so much water is lost to evaporation, often a significant fraction of the total water managed during the irrigation season (Hudson, 1987). Craig et al. (2005) estimated that annual evaporation from on-farm storages in Queensland, Australia, was around 1,000 10^6 m^3 for a total storage capacity of 2,500 10^6 m^3. This amount of water is sufficient to irrigate about 125,000 ha and generate approximately US$ 375 million annually. They estimated that in many areas of Australia, up to 50% of the stored water may be lost through evaporation. Mugabe et al. (2003) and Ngigi et al. (2005) also identified substantial evaporation losses from AWRs in semiarid African countries like Zimbabwe and Kenya.

In the semiarid region of southeastern Spain, sustained development of new irrigated lands over the last few decades has led to a drastic increase in water demand, which currently represents up to 80% of total water consumption in the area. This has caused a dramatic water deficit, estimated at 460 10^6 m^3 in the Segura River Basin (SRB), affecting 3.5 10^5 ha of irrigated farm lands (Ministry of Environment, 2000). The management of irrigation water in the SRB is structured in three levels. The *Confederación Hidrográfica del Segura* is the main agency of the basin and regulates the available water resources (surface water, groundwater and water transferred from adjacent basins) at regional scale. It manages the infrastructures for harvesting, long term storage and distribution of water allotments for urban, industrial, agricultural and environmental uses. Agricultural allotments mainly come from adjacent basins and its quantity and temporal availability mainly depends on political decisions that are difficult to anticipate, especially under drought periods. The second level of irrigation water management involves the collective irrigation schemes, which have intermediate infrastructures for medium-term storage of allotted water and its further distribution to farms, generally by turn. The third level of management is related to on-farm water distribution and in-field application to crops.

In order to deal with irregular water allotment and extended periods without water supply, many farms and collective irrigation schemes built and now use AWRs. These reservoirs guarantee water throughout the year and therefore have an important impact on agriculture productivity and revenues of farming systems. There are nearly 1.5 10^4 AWRs in the basin, mainly concentrated near the coast, where agriculture is most productive. Typical AWRs in southeastern Spain are characterized by moderate surface area (from 0.1 to 3 ha), low depth (from 5 to 10 m) and waterproof membranes to prevent seepage loss. Due to their relatively high area-to-depth ratio, AWRs experience significant evaporation, resulting in the loss of an important fraction of the total stored water. Bengoechea et al. (1991) estimated evaporation losses from AWRs in the climate of southeastern Spain at about 5% of the total water supplied to the irrigated areas, and stressed that overall agricultural water use efficiency in this region could be significantly improved with studies to characterize and reduce these losses.

The simplest way to estimate evaporation from AWRs is to use Class-A pan evaporation data, E_p. This method is commonly used to derive the evaporation rate, E, of a water surface, for hydrological applications (Linsley *et al*., 1992), or the reference crop evapotranspiration rate, ET, for agricultural and irrigation purposes (Doorenbos and Pruitt, 1977; Allen et al., 1998; López-Urrea et al., 2006). For both applications, an empirical pan coefficient, K_p (defined as the ratio of E or ET to E_p), is used to estimate either E or ET. For water body evaporation, annual K_p was found to be about 0.70 (Linacre, 2004), but with a wide variability, ranging from 0.60 to 0.82 (Kohler et al., 1955). Variations of annual K_p have been related to local climate conditions and the geometric dimensions of the water body. Martínez Álvarez et al. (2007) found that, at a given location in the SRB, annual K_p values mostly depend on the AWR flooded area, S, and depend loosely on depth, D. K_p decreases substantially with increasing S (from 0.86 for a small AWR of 0.05 ha to 0.76 for a large AWR of 5 ha). They also found that spatial variation of annual K_p at a regional or catchment scale is related to the annual air vapour pressure deficit, VPD. On a monthly scale, K_p was found to be strongly dependent on D and slightly influenced by S (Hounam, 1973; Martinez Álvarez et al., 2007).

These considerations form the basis of our interest in evaluating, at a regional scale, evaporation from AWRs as well as their importance in the basin water budget. This knowledge could be useful for regional water agencies for future planning and management. The main goals of this study were to analyze the characteristics of irrigation reservoirs in the SRB and to evaluate spatially and temporally water loss by evaporation. We discuss the impact of AWR evaporation on the basin water budget and analyze possible management solutions.

2. Material and methods

2.1. AWR data

The aerial orthophoto SIGPAC was used to identify all extant AWRs in the SRB. SIGPAC provides geometrically-corrected aerial images, and is a tool developed to meet the European Union regulation nº1593/2000, whose aim is the geographical identification of agricultural and livestock plots eligible for subsidies. The orthophoto has a pixel size of 0.5 m (available at the website http://sigpac.mapa.es/fega/visor/).

The SIGPAC orthophoto of year 2003 corresponding to SRB was downloaded and meticulously photointerpreted using ArcGIS 9.2 Geographical Information System (GIS). The inner perimeter of each identified AWR was digitized as a GIS polygon, allowing to calculate the floodable area (S) of each reservoir.

The usual practice in southeastern Spain is to maintain AWR water level above one third of its total depth, in order to maintain some level of insurance against the uncertain and poorly-timed delivery of irrigation water to farms. For this reason, a floodable area corresponding to two thirds of the total depth of each AWR ($S_{2/3}$) was considered a realistic value for determining the average annual evaporative area. Earthwork embankments of small AWRs (0.1-0.3 ha) usually have an inner slope of 1/1, while large AWRs (1–3 ha) generally have 2/1, so $S_{2/3}$ represents about 85% of the floodable area for most cases. In the following, two figures were considered for evaporation calculations: (i) maximum floodable area (= S_{mx}) and (ii) average annual floodable area (= $S_{2/3}$).

The depth of each AWR is also needed to calculate monthly values of K_p (Martínez Álvarez et al., 2007). However, D values are not available for all AWRs and it is not possible to estimate them from aerial images. Values of D were therefore derived from an analysis of S and D data collected for one hundred AWRs. No significant correlation was observed between S and D; the value of the latter was 5-8 m for 90% of the AWRs. Since the distribution mode (D = 6 m, for 32% of the analysed AWRIs) was very close to the mean value (5.8 m), the former was selected as a representative depth for all AWRIs.

2.2. Pan evaporation and climate data

Daily data from 74 automated stations of two agrometeorological networks were used (*Servicio de Información Agraria de Murcia*, SIAM, http://siam.imida.es, 38 stations; and *Sistema de Información Agroclimática para el Regadío*, SIAR, http://www.mapa.es/siar, 36 stations). The stations are located in irrigated areas of the SRB, which are mainly devoted to horticultural crops, orchards and vineyards. Their spatial distribution is irregular, but like AWRs, they are more concentrated near the coast and decrease inland.

The following data, measured 2 m above the ground, were provided by the meteorological stations: air temperature (T_a) and relative humidity (*RH*; Vaisala HMP45C probe), precipitation (ARG100 rain gauge), wind speed (*U*) and wind direction (RM YOUNG 05103 anemometer and wind vane), and solar global radiation (R_s; SKYE SP1110 or Kipp & Zonen CMP6 pyranometers). Sensors were periodically maintained and calibrated, and all data was recorded and averaged hourly on a data logger (Campbell CR10X). Daily, monthly and yearly data of the climate variables were downloaded from the network web-sites for the period 2000-2006.

Some stations of the SIAM network were equipped with Class-A pan evaporimeters, installed and operated following the recommendations of the *World Meteorological Organization* (WMO, 1995). E_p was measured by using a temperature-compensated ultrasonic sensor placed in an empty cylinder immerged in the pan to determine the daily difference of water level. Only 25% of the stations provided E_p measurements, with a rather high percentage of missing data, mainly due to maintenance problems or sensor failures, especially of the water level sensor. Applying cumulative residuals and double-mass techniques (Allen et al., 1998) to assess the integrity of registered data led to the conclusion that only a few stations supplied reliable E_p measurements. To solve this problem, estimates of monthly E_p values were calculated for each station using a previously validated energy balance model for a thermally-insulated Class-A pan (Molina Martínez et al., 2006), modified to include the effect of excess energy transferred through the pan walls, following the method proposed by Linacre (1994). This model only requires daily values of routine climate variables (R_s, U, HR and T_a), and was evaluated at several locations in the SRB with satisfactory results.

The SRB is characterised by a Mediterranean semiarid climate, with warm and dry summers and mild winter conditions. Annual rainfall is typically around 350 mm with high seasonal and interannual variability; most rain falls during the fall and winter months. Basin-scale climate trends are given in Martínez Álvarez et al. (2007). Figure 1 shows the location of the studied area and the selected stations.

2.3 Estimation of annual and monthly evaporation from AWRs

2.3.1. Annual values of K_p and E_p derived from daily climate data

Annual variations of K_p were related to local climate conditions and the geometric dimensions of the water body following Martínez Álvarez et al. (2007). For the climate conditions prevailing in the SRB, the following equation is proposed to estimate K_p, incorporating an AWR surface dependent function, $f_1(S)$, and a VPD-dependent function, $f_2(VPD)$:

$$K_p = f_1(S)\, f_2(VPD) \tag{1a}$$

with:

$$f_1(S) = \frac{a_1 + \log_{10} S}{a_2 + (\log_{10} S)^{a_3}} \tag{1b}$$

$$f_2(VPD) = (1 - a_4\, VPD) \tag{1c}$$

where S refers to free AWR water area (m^2) and VPD is the annual air vapour pressure deficit (kPa). The values of the parameters of Eq. (1) (a_1, a_2, a_3 and a_4) are given in Table 1.

Annual evaporation was estimated as follows:

Step (1): The water area (m^2) of AWR 'i,' S_i (= $S_{mx,i}$ or $S_{2/3,i}$), was determined from the digitized GIS polygon.

Step (2): Two GIS raster coverages were performed to interpolate the mean annual values of E_p and *VPD*, both calculated from GIS inverse distance weighting techniques.

Step (3): The mean annual value of E_p (mm year^{-1}) and *VPD* corresponding to each AWR (E_{pi} and VPD_i, respectively) was calculated using GIS overlapping techniques.

Step (4): The K_p value of each AWR [K_{pi}, Eq. (1)] was derived from the corresponding values of S_i ($S_{mx,i}$ or $S_{2/3,i}$) and VPD_i.

Step (5): For each AWR, the annual evaporation rate, E_i (m^3 year^{-1}), was estimated from:

$$E_i = S_i K_{pi} E_{pi} . \qquad (2)$$

Step (6): Results from Eq. (2) were aggregated at different scales (whole basin, hydrologic zones and irrigation zones), allowing the spatial distribution of the annual *E* to be analyzed.

2.3.2. Monthly values of K_p and E_p derived from daily climate data

The relationship giving monthly values of the pan coefficient, K_{pm}, for *D* = 6 m was obtained using the methodology proposed by Martínez Álvarez et al. (2007). To apply this method, monthly evaporation, E_m, from a 6 m deep AWR was predicted at six locations in the SRB from 2001 to 2004. First E_m was estimated at daily scale with the energy balance model described above using R_s, *U*, *HR* and T_a data, and afterwards averaged to obtain monthly values. Then E_m (mm month^{-1}) was compared to monthly values of pan evaporation, E_{pm} (mm month^{-1}) collected at the same six locations from 2001 to 2004. The annual evolution of K_{pm} supplied by the model is presented in Fig. 2. The monthly evaporation rate, E_m (m^3 month^{-1}), was calculated for each AWR as follows:

$$E_{mi} = K_{pm} E_{pm,i} S_i \qquad (3)$$

where $E_{pm,i}$ corresponds to the monthly pan evaporation at AWR 'i,' derived as indicated in Section 2.3.1, steps 2-3.

Integrating E_{mi} over one year supplied the annual evaporation for AWR 'i,' E'_i (m^3 $year^{-1}$), which was compared to the value of E_i previously determined using the empirical formulae of annual K_p (Eq. 2). Aggregating the individual values of E'_i supplied E', the annual water loss over the basin.

3. Results and discussion

3.1. Characterization of AWRs

A total of 14,145 irrigation reservoirs covering 4,901 ha were identified in the basin. The floodable area of the reservoirs (S_{mx}) represents 0.26 and 1.81% of the whole basin and irrigated land areas, respectively. Their spatial distribution (Fig. 3) is characterised by decreasing coverage density (expressed in AWR area per unit area of irrigated land) with respect to the distance from the coast. The highest density of coverage (about 5% of the irrigated area) was found in the coastal plains and the Segura and Guadalentín river valleys, where the most intensive irrigated agriculture occurs.

The size distributions of AWRs and the total surface areas corresponding to several predefined classes (from S < 0.1 ha to S > 5 ha) indicated that two main types of AWRs can be distinguished: individual and collective. The former and most frequent have relatively small areas (0.05 to 0.5 ha). Located at the farm, they are used as medium-term storage (usually 1 month) to match the periodical water supply in the farm (usually every 1-2 weeks) to the daily demand of drip-irrigated crops. The latter have larger areas (>0.5 ha) and provide water to collective irrigation schemes. They are used as long-term (seasonal) storage and are managed by SRB water agencies.

3.2. Characterization of monthly and annual E_p

Figures 4a-f present the spatial distribution of the mean E_{pm} values obtained from inverse distance interpolation in January, March, May, July, September and November, respectively. Fig. 4g displays the spatial distribution of mean annual E_p values.

E_{pm} shows well-defined temporal and spatial patterns, although local variability of *U* and *VPD* can perturb the general traits. A marked minimum is observed throughout the year in the eastern coastal part of the SRB, close to the mouth of the Segura River. For the rest of the basin, E_{pm} is evenly distributed, with some seasonal differences where maximum values are observed. During autumn and winter (Figs 4a, b and f), the maximum values of E_{pm} were observed in the central part of the basin (corresponding approximately to Zone 2 in Fig. 3). In March, when a transition period occurs characterized by a rapid increase of E_{pm}, a moderate local maximum can be observed in the extreme southern coastal zone, probably due to locally high wind and *VPD*. In the summer, the maximum clearly shifts towards the western part, an inner mountainous forestland, with values of E_{pm} close to 280-290 mm month^{-1}.

This behaviour indicates seasonal climate variations across the watershed: the climate is Mediterranean near the coast (east) and becomes Continental in the interior rangelands (west and northwest). Figure 5a illustrates these seasonal patterns of E_{pm} in three places in the SRB: next to the Mediterranean coast (Pilar Horadada), in the central part of the basin (Abarán) and in the inner mountainous rangelands (Hellín). Their locations are shown in Fig. 1.

Annual values of E_p range from 1600 to 1900 mm, with a marked positive gradient from northeast to southwest. This trend is altered in the central part of the basin, where *VPD* reaches its highest values. The lowest annual values are observed at the mouth of the Segura River valley (eastern part of the basin, next to the Mediterranean coast).

3.3. Characterization of monthly and annual VPD

The spatial distribution of mean monthly *VPD* values, VPD_m, is presented in Figs 6a-f for the same months as E_{pm} (Figs 4a-f). VPD_m follows a temporal trend similar to air temperature, reaching its minima and maxima during winter and summer, respectively. The maximum values are observed in the central part of the basin for the whole year, with the exception of the summer months, when maximum VPD_m moves towards the inner rangelands and forestlands.

These variations agree with those previously described for E_{pm}, that is, during autumn and winter, the areas with higher E_{pm} (Figs 4a, b and f) correspond to those with higher VPD_m (Figs 6a, b and f). This behaviour is also observed during summer, when maximum values of E_{pm} (Fig. 4d) and *VPD* (Fig. 6d) move to the interior. During spring and autumn, the areas with higher values of E_{pm} are found in the southern part of the basin (Figs 4c and e), where VPD_m also presents relatively high values. Figure 5b illustrates the annual trend of VPD_m in the same three locations selected in Fig. 5a for E_{pm}.

Mean annual values of *VPD* (Fig. 6g) ranged from 650 to 900 Pa, with a clear positive gradient from the coast (east) to the central part of the basin, where the maxima are reached. From this part to the interior lands (west), annual *VPD* ranged in a narrow interval (800-850 Pa).

3.4. Regional evaporation from AWRs

3.4.1. Annual values

Figure 7 shows the frequency distribution of annual K_p for all AWRs over the basin, calculated from Eq. (1) with $S = S_{2/3}$. The most frequent K_p values are between 0.80 and 0.84.

Annual water loss from evaporation, *E*, determined from Eq. (2), amounts to 68.8 10^6 m^3 at a regional scale considering $S = S_{mx}$, and 58.5 10^6 m^3 considering $S = S_{2/3}$. The latter amount corresponds to a mean annual evaporation rate of 1.404 m over the flooded area. The spatial distribution of annual water loss in relation to the hydrologic partitioning of the basin (Hydrologic Zones, HZ) is presented in Fig. 8, and the distribution in relation to collective schemes (Irrigation Zones, IZ) in Fig. 9.

The HZ-distribution shows that most of the water loss from AWRs occurs in the eastern coastal plain (Mar Menor and Sur de Alicante, 15.43 10^6 and 9.50 10^6 m^3 y^{-1}, respectively), followed by the Segura and Guadalentín river valleys (Vega Alta and Guadalentín, 6.93 10^6 and 9.17 10^6 m^3 y^{-1}, respectively). These zones, where irrigation water availability is uncertain, are dense in irrigated lands (Fig. 9) and grow high-revenue crops (fruits and vegetables). The IZ-distribution (Fig. 9) clearly indicates the importance of AWR loss in the most important irrigation scheme of the SRB (three IZ in the coastal plain with 24,851, 5,199 and 11,408 ha), reflecting the high density of farmers' AWRs in this zone, and the fact that 95% of the farms are equipped with drip irrigation systems.

3.4.2. Monthly values

Figure 10 shows monthly evaporation from extant AWRs aggregated at the basin scale, E_m, determined from Eq. (3), using the values of K_{pm} given in Fig. 2 and the values of E_{pm} presented in Figs 4a-f. The evolution of E_m shows a delay of one month between the maximum solar radiation (reached in June), and the maximum monthly evaporation (reached in July). Evaporation loss was of the same order of magnitude in October-November as in March-April, despite the large differences in solar radiation between these periods. These results can be ascribed to the thermal inertia of irrigation reservoirs, which leads to warmer surface temperature in autumn than in spring (Martínez Álvarez et al., 2007). This behaviour confirms previous observations by Kohler (1954) and Sellers (1965) for shallow lakes (D < 10 m) under similar climate conditions (California, USA). At the basin scale, the annual value of E' derived from Eq. (3) was 68.2 10^6 and 58.1 10^6 m^3 using S_{mx} and $S_{2/3}$, respectively. These values are very similar to those calculated from Eq. (2) (E = 68.8 10^6 and 58.5 10^6 m^3, respectively), underpinning the consistency of the two methods. Values of E_m for HZ and IZ showed a spatial distribution similar to that observed for annual loss.

The small interannual and spatial variability of monthly values of K_p (Fig. 2) observed for the SRB indicates that the annual estimation method could be used without introducing large errors compared to the monthly method.

3.5. Importance of evaporation loss in the basin water budget

The structural water deficit of the SRB estimated by its main water agency (Confederación Hidrográfica del Segura, 1998) is close to 460 10^6 m^3 (Fig. 11). This deficit is mainly due to the increasing number of irrigation schemes developed over the last decade, based on an optimistic prediction of water transfer from other basins. As a consequence of the frequent drought conditions in Spain, water transfers between adjacent basins is becoming much less common (e.g. only 38 10^6 and 31 10^6 m^3 of the planned 540 10^6 m^3 for agricultural use were transferred during the 2005-2006 and 2006-2007 hydrologic years, respectively). Without the extra 540 10^6 m^3, the deficit would near 1,000 10^6 m^3. This uncertainty, related to the characteristics of the SRB water resource system, stresses that efforts to increase agricultural water management efficiency are crucial (Bouwer, 2000).

The estimated annual evaporation from AWRs in the SRB (≈58 10^6 m^3) is higher than the industrial demand (23 10^6 m^3), similar to the environmental demand (60 10^6 m^3) and equivalent to 27% of the urban demand. Annual evaporation represents 8.3% of the currently estimated water consumption for irrigation by the agricultural sector (≈700 10^6 m^3). This figure reflects globally poor water storage efficiency, which significantly affects the overall agricultural water use efficiency, and counterbalances most of the gains derived from the generalized application of efficient on-farm irrigation techniques (drip and micro-sprinkling). Therefore, any savings from reducing the evaporation rate from AWRs could significantly increase overall agricultural water use efficiency in the SRB and, probably, in similar irrigated lands under arid and semiarid conditions.

3.6. The origin of the problem and possible solutions

The concentration of AWRs in southeastern Spain is one of the highest in the world and can mainly be ascribed to four factors:

(1) The high number of collective irrigation schemes in the SRB, which require large buffer reservoirs to regulate the uneven supply of water resources (e.g., transfers from other basins) and to best match irrigation needs.

(2) The need for farmers to temporarily store water transferred to the farm in the usual case where water is distributed by turn. Medium-term storage is required due to the generalized use of localized and high-frequency irrigation systems.

(3) The role of the reservoirs in making water available when resources are scarce, by using a variety of sources with different qualities (mixture of good quality water with salty groundwater or reused wastewater).

(4) The high uncertainty caused by temporally random water supply in a water-stressed region like the SRB, where water availability depends strongly on water regulations, policies and governance by contiguous basins from which the SRB could get water by transfer. Storage in AWRs represents therefore a safety measure and a guarantee that minimum levels of irrigation will remain possible, allowing crops to survive during periods of water shortage, especially perennial crops (orchards).

From these considerations, reducing evaporation in the SRB should be tackled through three main measures:

(1) First, the massive construction of AWRs at the farm scale must be controlled, through stronger regulations and surveys by public agencies (water and irrigation management agencies). To this end, irrigation distribution systems must be modernized so that they can supply a continuous irrigation flow with the required pressure and farmers do not need to build AWRs for irrigation.

(2) The study highlights that, besides the use of techniques to limit evaporation loss at the farm level, mentioned below, some management measures could be envisioned by water agencies to reduce evaporation losses at the HZ or regional scale. Amongst them, a possibility would be to modulate the amount of water allocation in function of the estimated evaporation and K_p values, giving priority to areas and/or periods of lower E and/or K_p. A more drastic measure would be to avoid water storage during the most demanding periods (summer), especially in areas presenting the highest evaporation rate, although this type of measure could strongly affect the productivity of drought-sensitive crops. Such a measure would require a previous assessment of its socio-economical impact on the farm revenues.

(3) In addition, specific technologies must be implemented to reduce evaporation from AWRs. Several methods and techniques to reduce evaporation loss have been tested (Brown, 1988), but most of them were not successful, due to high costs or difficulties with practical implementation, or because they were inefficient under natural working conditions**.** Of these methods, the use of shading meshed nets over reservoirs, either floating at the surface or aerial (Craig et al., 2005; Martínez Álvarez et al., 2006), appears feasible and efficient, allowing a reduction in evaporation of 70-90%, without significant technical or maintenance problems. Other interesting possibilities include windbreaks (Hipsey and Sivapalan, 2003) and underground storage (Nilsson, 1988).

4. Conclusion

Evaporation loss from lakes and reservoirs can potentially be large, particularly in arid and semiarid climates. An accurate estimate of this loss, at a local or regional scale, is usually not available, making it difficult to carry out a cost-benefit evaluation of available technical solutions aimed at reducing evaporative loss. In this paper, two different methods were applied to the Segura River Basin, after identifying the average flooding area of all extant AWRs. The first method relies only on empirical formulae of mean annual K_p, while the second is based on mean monthly K_p values derived from a physical model of AWR evaporation and pan data. The two methods, together with routine data provided by regional meteorological networks and aerial images, and interpolation and aggregation GIS techniques, appear to provide coherent and plausible estimates of the evaporation of each individual reservoir, as well as the total water loss at a regional scale. Both methodologies could easily be implemented in technical and information services of regional water agencies, and should improve planning and management decision-making at the local and the basin scale. We recommend the method based on annual K_p. It is straightforward and easy to apply, and can be extended to other regions and climates, as well as to other types of shallow water bodies (e.g., small dams, shallow lakes, paddy rice fields), provided that the *VPD*-dependent function giving K_p is available.

Overall, this study demonstrates that evaporation from all AWRs for irrigation operating in the SRB represents a substantial fraction of the agricultural water use of the basin. Annual losses were estimated at 58 10^6 m^3, which represents 8.3% of the total water resources dedicated to the agricultural sector. These figures indicate that, in addition to using high efficiency on-farm irrigation techniques (surface or subsurface drip irrigation, micro-sprinkling) and deficit irrigation practices throughout the SRB, it would be worthwhile to evaluate water savings measures aimed at reducing evaporation from AWRs, such as protective floating covers, shading screens, windbreaks or underground water storage.

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