# Water Value and Sustainable Use in the American SW

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## Abstract

As elsewhere in the world, anticipated population growth in the next 50 years, climate change and reduced surface water availability, water "productivity", or water use efficiency (WUE) must continue to improve in the American Southwest. Beyond the intrinsic value to life, water takes on additional value as food and fiber, fisheries and ecosystem benefits that are linked such that emphasis of one over the other benefit often results in losses neglected in the past. For example, development of upstream water storage exchanges downstream fisheries and ecosystems benefits for crop production, while reservoir evaporation losses further reduce possible downstream resource values. Unlike WUE improvements in the municipal sector, possible through metering and technological changes in flow devices and washing appliances, improved WUE in crop production is hampered by unidentified achievable water use targets. In terms of water use, the dominant crops in the Southwest are alfalfa and sudangrass hay and cotton lint production. The water use characteristics, average planted areas and yields, and water values are examined for these crops in Arizona, California and Idaho to determine possible target WUEs and assess possible on-farm water savings in the region based on actual production information from 1988-2000. Field-based WUEs of 1.7, kg/ha-mm for alfalfa and sudangrass hay and pima cotton, and 2.1 kg/ha-mm for upland cotton lint production appear to be practical target values from which to determine appropriate water use. Based on FAO #56 estimated and yield-based water use for these three crops, possible water savings of up to 50% exist with the greatest water savings potential in desert regions where current water values as hay or lint crops are low relative to other regions. Such high water savings in the desert region are unlikely and targets of 20-30% corroborated by research trials, are more likely. The greatest water values and least possible water savings occur in the southern San Joaquin Valley, CA where the combination of relatively high ET and some rainfall occur. This research is a starting point for assessing water use/savings at the field scale for hay and cotton productions and should be extended to other crops. Additional work may also be required considering water savings at the district scale associated with the water distribution systems.

**Keywords:** alfalfa hay, cotton, water use, water conservation, water value

## Introduction

The inextricable link between water and life is readily apparent in the competition and associated conflict surrounding water resources and its quality throughout the world. As population centers expand, this competition is becoming ever more keen and problematic with respect to meeting basic human needs while maintaining the very habitat upon which we depend and develop our food and fiber resources. Freshwater withdrawals, storage or degradation in one part of a basin for development of agricultural or municipal resources results in loss of downstream resources associated with fisheries and possible environmental (e.g. habitat, water purification) benefits associated with riparian zones or wetlands. While the cost of developing upstream infrastructure in order to translocate in time and space water resources for other beneficial uses may be offset in part by the value developed there from, downstream losses in resource values associated with water purification, aesthetic benefit and fisheries are generally neglected. For example, evaporation of water from upstream reservoirs that may provide a recreational benefit, while returning to the hydrologic cycle, result in loss of water use for agriculture and cities, as well as in-stream beneficial uses downstream. There is no "use" of water in upstream areas, for either resource development or as a waste stream carrier, which does not result in losses in value downstream. What remains is for society to determine where to gain the most "water value" (or "productivity") from limited water resources for [presumably] the greatest public good. Indeed, the United Nations and Ministerial Declaration at the 3rd World Water Forum in Kyoto (2003) recognized the basic human "right" to water and that "to ensure a sustainable water supply of good quality, we should protect and use in a sustainable manner the ecosystems that naturally filter, store and release water such as wetlands, forests and soils" (article 24). Further, noting that water is essential for rural development, "we should make every effort to reduce unsustainable water management and improve the efficiency of agricultural water use" (article 19). Society worldwide is grappling with possible solutions or changes in water resources paradigms to balance beneficial uses for all people as populations grow.

In many developed countries, annual freshwater withdrawals have already stabilized or fallen, despite ever increasing populations, resulting in less water use per capita, or greater water value per capita. The decreased water use per capita, or increased efficiency is largely due to increased municipal water conservation. In contrast to improving agricultural water use efficiency, municipal water conservation is more readily achievable through application of technological improvements in low-flow devices, reduced water use by washing appliances and the possibility of water metering. In developing countries, freshwater withdrawals continue to grow with increasing populations and agricultural development such that water use or value per capita is more-or-less constant. For example, the ratio of annual national gross domestic product (GDP), an indicator of overall economic well-being, to that of annual water withdrawals can be viewed as a measure of "water productivity". Figure 1 illustrates how this ratio has grown for the USA during the latter half of the past century and for Hong Kong during the past 40 years based on federal estimates of GDP and water withdrawals (Gleick, 2004). With the exception of the economic depression period after 1929, and the war period growth in the mid 1940s, "water productivity" in the USA from 1900 – 1980 remained more-or-less constant as water withdrawals kept pace with population growth and agricultural development in some ways similar to the present condition in developing countries. Water withdrawals in the USA leveled during the 1980s, such that present water productivity has been increasing with population growth; a similar, though more recent history and trend, is evident in Hong Kong. As has occurred nationally and internationally, increased “water productivity” in the American southwest has not come about without some difficulty and conflict at many levels. In the following, examples of differing scales and impacts are considered to illustrate some of the debate currently underway in the region.

As in much of the world, water resources development in California and the Colorado River basin of the arid southwest was directed at diverting streamflows into storage for municipal or agricultural use without consideration of downstream losses, or actual new water value developed from the new infrastructure versus that lost in downstream benefits. The following examples help set the stage for assessing, or determining the value associated with water conservation and how it might be achieved in agricultural production so as to continue improving “water productivity” to better serve a growing population with fixed water resources.

a) Lake Powell on the Colorado River – This is the upper basin reservoir designed to enable the upper basin states to meet the downstream discharge requirements of the lower basin states (see Figure 2). Completion of the 171 m tall dam in 1963 enabled the reservoir to fill by 1980 to a volume of 33.3 km$^3$ (27 000 000 ac-ft) with a surface area of approximately 681 km$^2$ (266 mi$^2$). The lake is approximately 298 km in length and there is approximately 3140 km of shoreline with 96 major side canyons. Average annual evaporation is estimated at 2.5-3% of the volume, or approximately 1 km$^3$/yr (860 000 ac-ft). At the time of construction environmental groups decried loss of the picturesque and historic Glen Canyon for a reservoir considered unnecessary or wasteful of precious water in the southwest. This debate was rekindled during the recent 2001-2005 drought period during which much of Glen Canyon was once again exposed as the reservoir declined to a small fraction of its full volume. Recreational boating interests around Lake Powell are adamant that the Lake serves a broad purpose and tourism value that alone justifies its continued operation. In opposition, environmental groups underscore the continued recreational value of the Glen Canyon region to hikers, rafting and archeologists, but of perhaps greater value is the possibility of recovering the significant evaporation water losses. The annual evaporation from Lake Powell is sufficient to supply the annual water need of a large metropolitan area, one-third of the annual irrigation water requirement of the Imperial Valley, more than half of the 1944 USA-Mexico treaty obligation of water delivery at the border, and all of the surplus water taken by California. Debate continues to rage concerning the “water value” of the reservoir.

b) Millerton Lake on the San Joaquin River – Friant Dam, completed in 1942 for storage of 0.64 km$^3$ (520 500 ac-ft) irrigation water to be delivered to some 416 000 ha of the southern San Joaquin Valley; the most productive agricultural region in the world. The 319-foot high dam is 40 km northeast of Fresno, in the shadow of the Sierra Nevada Mountains. The recent federal district court settlement in September, 2006 from more than 18 years of litigation, will result in release of 0.21 km$^3$ (170 000 ac-ft) into the San Joaquin River for stream rehabilitation and restoration of historic Chinook salmon runs at a cost of some

$800 million, $330 million of which is to come from farmers. Salmon runs prior to construction of the dam were said to be so abundant that the fish were used for hog feed. This unprecedented settlement between federal agencies, farmers and environmental groups appears to usher in a new era of better cooperation for water resources in the San Joaquin Valley, though the downstream fisheries benefit remains unclear as yet.

c) Hetch Hetchy Reservoir on the Tuolumne River – The O'Shaughnessy dam created Hetch Hetchy Reservoir on the main stem of the Tuolumne River in Hetch Hetchy Valley of the southern Sierra Nevada. The original dam was a 95 m high gravity-arch concrete dam completed in 1924 and raised to the current height of 131 m in 1947. The reservoir, with a capacity of 0.44 $km^3$ (360 360 ac-ft), is supplied primarily by snowmelt from an 1175 $km^2$ (459 $mi^2$) watershed located entirely within Yosemite National Park. The reservoir is managed by a San Francisco Bay area public utility that has paid $30 000/yr since 1923 to lease the reservoir area in the National Park from the federal government. It is the drinking water supply for some 2.4 million people in the San Francisco Bay area, while providing roughly 20% of its power needs. Hotly contested at the time of its creation by John Muir, the reservoir covers the “second Yosemite Valley”, considered a national treasure by many. Initial estimates of roughly $500 million to remove the dam and replace the San Francisco water supply downstream are considered high, but considerable public support in the Bay area has developed. Restoration of the Valley would create a new precedent for dam removal on the grounds of aesthetic or moral value alone.

d) Tule Lake Water District – In the northeast corner of California and southern central Oregon large shallow lakes and wetlands existed prior to conversion to agricultural production some 80 years ago through diversion and storage of Klamath River flows supplying the lake/wetland system by the federal government. One such historic lake area was Tule Lake. Collapse of the California north coast salmon fisheries in the past five years resulted in an unanticipated mandated reduction of 0.12 $km^3$ (100 000 ac-ft) in irrigation water deliveries in 2001 from the Tule Lake water district to local farmers. This sudden reduction in water deliveries resulted in subsequent drying of Tule Lake from groundwater extractions by 2005, idling of nearly 10 000 ha of farmland and loss of approximately $43 million in agricultural production for the 2001 production year. The north coast salmon fishery remains tenuous and was declared eligible for disaster relief funds of $25 million, far short of the $81 million requested, in August, 2006. The value of the exchange of agricultural production inland with fisheries production at the coast is unclear in part due to other factors (e.g. logging) affecting the fisheries, however, continued decreased irrigation water deliveries are anticipated as part of the salmon recovery planning.

All four examples above illustrate paradigm shifts in allocation of water resources for benefits not previously considered during the early to mid 20th century period of dam construction in the American southwest. Three of the four examples involve exchange of irrigation water resources for anticipated, though to some degree unproven, downstream fisheries benefits. The cost to agriculture alone of this exchange ranges from roughly $0.35/m³ at Tule Lake to $1.57/m³ in the San Joaquin Valley. This range encompasses the water cost to recover Hetch Hetchy Valley of roughly \$1.12/m$^3$. While each example has specific nuances particular to the local, there appears to be no clear water cost/value principle that might better guide society's acceptance of such exchanges. [In some cases, changes in water resource project water availability associated with global warming may drive reductions in agricultural water deliveries.] If water presently provided irrigated agriculture is to be reduced, what volumes of water can be practically expected from water conservation efforts before crop yields are significantly diminished, and at what costs? If yields losses cannot be avoided are there other regions in which the crop production can occur with smaller or no yield losses? Developing answers to these questions at the farm scale is the focus of this paper. Improving water distribution system efficiencies at the district scale is beyond the scope of this paper, but an important overall consideration.

However "water productivity" is characterized, it is clear that water use in agricultural production must become more efficient in order to meet the demands of growing populations. Unlike water conservation programs in municipal areas where clearly identifiable water use target values can be developed, no clearly identifiable pragmatic water use efficiencies or water values are readily available for agricultural production. Herein, drawing on research conducted primarily in California, but applicable across the southwest USA, is an attempt to develop a rationale, or determine water use efficiencies and water values for three crops grown in the southwest having some of the greatest gross water demand (see Table 1). Alfalfa hay, sudangrass hay and cotton lint production are selected not only because of their overall high water need in the southwest region, but because they also represent multi-year and annual crops in which yield is generally evapotranspiration (ET) dependent when not soil moisture limited, and a more complex flowering crop in which yield is less dependent on ET.

## Water Use Efficiency Studies

As a perennial crop having nearly complete canopy coverage, alfalfa hay production is the dominant water use in the western states. Sudangrass hay, though an annual crop with greater heat and salinity tolerance is similar to alfalfa hay in terms of production methods and water use characteristics. Ultimately, alfalfa hay is used for cattle or dairy production and may be considered a resource for these industries. The water use characteristics of alfalfa have been studied intensively (e.g. see Guitjens, 1990) and efforts have been directed at determining appropriate crop production functions for different areas, or to assess the effects of limiting water applications on hay yield.

Water production functions, often used by agricultural economists to estimate the water use needed to generate the greatest economic returns to the grower, ideally relate crop yield (Y) and crop water use ($ET_c$), though some have related Y to applied water (AW). From a plant physiology perspective, under non-stress conditions the function $Y=f(ET_c)$ is linear with a positive slope referred to as the crop water-use-efficiency (WUE). When using the dry matter yield of harvestable alfalfa, $Y=f(ET_c)$ should have a negative yield intercept, due to non-harvestable root development, and a maximum yield point associated with the maximum $ET_c$. Since $Y=f(ET_c)$ is linear, WUE is independent of $ET_c$ (Guitjens, 1982) and instead depends primarily on the plant's $CO_2$ assimilation capacity (e.g. Asseng and Hsiao, 2000) or $C^{13}/C^{12}$ ratio (Saranga et al., 1998), hence photosynthetic efficiency, or plant type (e.g. C3, C4, or leguminous).

By definition, WUE is constant for particular plant species and values in the range of 16-18 kg/ha-mm have been measured for alfalfa hay using lysimeters in Idaho (Fortier, 1940; Hill et al., 1982; and Wright, 1988) and Nevada (Guitjens, 1982; and Hill et al., 1982) and $CO_2$ assimilation techniques in Central California (Asseng and Hsiao, 2000). Asseng and Hsiao (2000) noted that alfalfa hay WUE is less than that reported for non-legumes, but similar to that of other legumes such as soybeans. The lower WUE for alfalfa may be attributed to its partial allocation of carbon for symbiotic nitrogen fixation as compared to that for non-legumes. Little information is available regarding the sudangrass hay $Y=f(ET_c)$ relationship. Though this relationship is expected to be similar to that for alfalfa, sudangrass is more salt-tolerant, capable of substantial osmotic adjustment (Li et al., 1993), and as a non-legume should result in this relationship having a somewhat greater WUE, and smaller yield intercept. Grismer and Bali (2001) and Jensen (1995) measured and estimated, respectively, a sudangrass $Y/ET_c$ ratio of 15.6 kg/ha-mm for production in the Imperial Valley during the period 1995-98. Grismer and Bali (2001) however, noted that their ratio was low by about 15% due to salinity-induced yield losses (Maas and Hoffman, 1977) suggesting a non-salinity stress WUE~18kg/ha-mm. Based on estimated water use values, Grismer (2001b) determined a WUE of 20.7 kg/ha-mm for sudangrass in the San Joaquin Valley. Figure 3 provides an example of the linear $Y=f(ET_c)$ relationship for alfalfa hay production in the Sacramento and San Joaquin Valleys of California based on estimated water use (Grismer, 2001a); note that the slope or WUE is equivalent to 18.7 kg/ha-mm and the negative intercept corresponds roughly to less than a single hay cutting.

When relating alfalfa yield to AW rather then $ET_c$, the initially linear function reaches a maximum yield and either levels off, or decreases with increasing AW as a result of excess water application beyond accumulated $ET_c$. Slopes of the linear portion of the curve, measured using seasonal field plot (Tovey, 1963; Peterson, 1972; Donovan and Meek, 1983; Frate et al., 1988; Rechel et al., 1991; and Guitjens, 1996) and line source (Sammis, 1981; Hill et al., 1982; Smeal et al., 1991; Grimes et al., 1992; and Hanson, 1996) experiments in the western states, range widely (10-25 kg/ha-mm). Coincidentally, the average ratio from these studies (Y/AW=17.4 kg/ha-mm) is the same as $WUE=Y/ET_c$ as cited above and is within the generally-accepted range of 15-20 kg/ha-mm (Doorenbos and Kassam, 1979). Smaller Y/AW slopes (10-13 kg/ha-mm) are found in desert regions (e.g. Erie et al., 1981; Donovan and Meek, 1983; Ottman et al., 1996; and Ottman, 1999).

Cotton lint or seed WUE studies have had varied results reflecting the difficulties in determining values consistent across the range of conditions encountered in the field (Grismer 2001c). Plant physiologists and others have been evaluating the range in cotton genotypic variation in order to select for greater WUE characteristics (e.g. Gerik et al., 1996; Saranga et al., 1998 & 1999; and Leidi et al., 1999) for both arid and elevated $CO_2$ atmospheric conditions. For example, Gerik et al. (1996) found that cotton boll weight was independent of cultivar (among six tested) and water stress, but that cultivars had significantly different vegetative production, and bolls/ha production. Ayars et al. (1993) and Hamdy et al. (1993) identify the sensitive growth stages and long-term management of saline water application to cotton.

Cotton lint WUE also appears to be affected by planting patterns (spacing and location relative to furrows), mulching, tillage conditions and irrigation scheduling. Narkhede and Bharad (1994) found that two plants per hill on a 1.5m by 1.0m spacing improved cotton WUE significantly over a single plant per hill, while Shelke et al. (1999) found that seed cotton yield was not significantly affected by planting patterns unless irrigation was reduced to approximately half of $ET_c$. Singh and Bhan (1993) reported that maize-stove mulch laid between cotton rows improved cotton WUE, while Jin et al. (1999) found that furrow planted cotton combined with plastic mulch WUE by more than 50%. While improved tillage practices may increase soil moisture storage conditions (e.g. no-till in Texas improved water storage and dryland cotton yield; Baumhardt et al., 1993), tillage effects on cotton WUE are unclear. Conservation tillage under dryland growing conditions in Texas (Baumhardt and Lascano, 2000) and deep-ripping of vertisols in Australia (Hulme et al., 1996) did not result in improved cotton WUE. However, in Sudan Salih et al. (1998) found that cotton WUE increased by 25% when sub-soiling vertisols as compared to disking cultivation methods. Effects of irrigation management on cotton water use and soil salinity are summarized by Grimes and El-Zik (1982), Hunsaker et al. (1998) and Ayars et al. (1999). Generally, cotton water use is greatest during the peak blooming period and limiting soil-water availability at this time reduces lint/seed yield, however this depends to some extent on the irrigation method. For example, using drip irrigation Wanjura et al. (1996) found that cotton lint WUE increased when delaying early season irrigation while providing sufficient water during the blooming stage. Stone and Nofziger (1993) reported increased cotton WUE through use of more widely–spaced (every other) furrow irrigation. Similarly, Sethi et al. (1995) found that cotton WUE decreased with increasing soil wetness treatments and El-Awad (2000) found that WUE was greater when furrow irrigating at three-week intervals as compared to two-week intervals. Cotton water use from shallow water tables may reduce short-term irrigation water needs (e.g. see Ayars, 1996; Hutmacher et al., 1996 and Soppe, 2000), but depends on shallow groundwater salinity and is of limited value if dense soil layers are present (Cohen et al., 1995).

As briefly summarized above from plant physiology studies, cotton seed/lint WUE is affected by a wide range of factors. This variability is also reflected in cotton lint yield-water use ($LY/ET_c$) ratios determined from several recent studies summarized by Grismer (2001c) in Table 2. This table focuses on more recent studies as new cotton cultivars continue to be developed (as noted above) and soil-water management practices improve. Generally, WUE = $LY/ET_c$ values >3 kg/ha-mm appear possible under drip or possibly furrow irrigation systems, far exceeding earlier estimates of 1.4-2 kg/ha-mm (Doorenbos and Kassam (FAO #33), 1979; Grimes, 1982 and Davis, 1983), even under moderately high soil salinity conditions. Note that in Table 2 estimates of $ET_c$ determined from micro-met station data (CIMIS and AZMET) and FAO #56 (Allen, et al., 1998) $K_c$ values are much larger than study $ET_c$ values suggesting a significant opportunity to reduce water applications based on these estimates without loss in yield (see Figure 4) regardless of the method of irrigation. Not surprisingly, the error in estimation of cotton water use diminishes as $ET_c$ increases to very high values where actual $ET_c$ and estimated values appear to converge suggesting that more attention be given to such estimates at low $ET_c$ conditions, thereby potentially reducing water applications and improving net WUE.

## Methodology

In order to determine target WUEs for hay and cotton lint production across the greater southwest region, county-wide, or multiple county hay and lint yields, prices and estimated $ET_c$ were obtained from county data and micro-met station networks across the southwest and southern Idaho. Using actual production values incorporates the range of climate, soils and salinity stress effects on yield commonly encountered in the southwest (Grismer 2001a, 2001b & 2001c). No "adjustments" for irrigation application efficiencies or leaching fractions were applied as these are not normally included in the definition of $ET_c$ and would unnecessarily obfuscate estimated $Y=f(ET_c)$, functions, as well as limiting the meaningfulness of computed $Y/ET_c$ mean "target" values. While Grismer et al., (1997) estimated water value ($/ha-m) based on the "cost" of yield loss and water savings, here irrigation water value (IW$, $/ha-m) is taken as the product of average county (region) market-year hay or lint price ($/Mg) and Y/IW (Mg/ha-m) for the county (region) each year.

## Results and Discussion

A linear $Y=f(ET_c)$ function suggests that irrigation water value as hay or lint should be greatest in areas having matching rainfall contributing to crop $ET_c$, however, this "matching investment" may be countered by the smaller available "ET energy" in these areas and its greater variability, or investment "risk". Grismer (2001a) found that maximum irrigation water values for alfalfa hay production in fact occurred in areas having a combination of some rainfall and high available "ET energy". Mean $Y/ET_c$ values (with their associated variance) may serve as "target", or "reference" values to which those resulting from alternative irrigation water strategies may be compared within a desired confidence level (variance). Tables 3 and 4 summarize the mean values and their variation of $ET_c$, Yield/$ET_c$ and irrigation water values for hay and cotton lint production, respectively, primarily in Arizona and California. Yield/$ET_c$ variations are generally much smaller than water value variations and hay Yield/$ET_c$ variations are less than those of cotton, perhaps reflecting the myriad factors affecting cotton lint as compared to hay production. Yield/$ET_c$ ratios and irrigation water values decline with increasing $ET_c$ as shown in Figures 5 and 6, respectively, for hay production, and in Figures 7 and 8, respectively, for cotton lint production. Note that sudangrass Yield/$ET_c$ ratios are similar to that of alfalfa, though irrigation water values are considerably less. Similarly, water values from upland cotton are roughly 10% less than that of pima cotton lint production, though pima lint yields are 20-30% less than that of upland varieties. Linear regression intercept values from Figures 5 and 7 are consistent with expected WUEs for both crops, that is, about 18 kg/ha-mm for hay and 2.5 kg/ha-mm for cotton lint production.

Both the tables and figures suggest that crop production in the high ET desert regions do not generate the greatest return on water "investment" as compared to more moderate ET conditions found in cooler areas inland or in some cases along the coast. Conceptually, Yield/$ET_c$ should not be function of $ET_c$, and if the desert area (high ET) data is separated, there is in fact no relationship between Yield/$ET_c$ and $ET_c$ for either subset of data. From Tables 3 and 4, it is apparent that expected WUEs are only approached in the San Joaquin Valley (or along the coast and LA where total planted areas are relatively small). There appears to be an opportunity then to allocate less water to the other areas without loss in yields and this volume of "saved" water can be determined and compared to anticipated reductions in reservoir releases for agriculture. Perhaps hay and cotton lint production in desert environments may not be tenable and the water may have greater value in other applications. On the other hand, is it possible to increase hay or lint yields in the desert areas to levels comparable to that found inland? For example, in the Imperial Valley intense summer heat results in relatively low hay yields but high water use, so it has been suggested that summer irrigations be reduced to simply that necessary to maintain the hay stand but not achieve significant production. How much improvement can be obtained and do other farm water management techniques exist that enable expected WUEs to be achieved? If so, how much water "savings" might be expected?

For alfalfa and sudangrass hay production on heavy clay soils in the Imperial Valley, Bali et al. (2001) and Grismer and Bali (2001) found that the "reduced runoff" surface irrigation (a simplified volume-balance model approach to determining irrigation cut-off time or distance developed by Grismer and Tod, 1994) resulted in greater hay Yield/$ET_c$ ratios. In practice the methods requires measurement of a presumably nearly constant onflow rate and a single measurement of surface water advance rate down the field. During the three-year studies, the average alfalfa Yield/$ET_c$ ratio was increased from an estimated Valley average of 8.9 to 15.2 kg/ha-mm. This latter value is comparable to that obtained in high production regions of the southern San Joaquin Valley (see Table 3). Correcting project hay yields for an estimated 30% reduction associated with an average soil salinity of 6 dS/m (Maas and Hoffman, 1977) suggests that the reduced-runoff irrigation method resulted in a Yield/$ET_c$ ratio of nearly 21 kg/ha-mm, a value similar to the maximum WUE expected for alfalfa hay. Similarly, a Yield/$ET_c$ ratio of 15.5 kg/ha-mm was obtained for sudangrass hay production approximately 15% less than expected WUE as a result of an estimated 15% salinity-stress induced loss. Average seasonal water application was reduced by about 0.4 m, or an estimated 20% for sudangrass hay production and by 28% annually for alfalfa hay through elimination of tail-water runoff. Improved Yield/$ET_c$ ratios were obtained in part from limited use of shallow groundwater by the stressed alfalfa crop during its first year of production. These results from the reduced-runoff irrigation trials as well as those from the drip and furrow irrigation trials under high soil-salinity conditions in the San Joaquin Valley (see Table 2) suggest that greater attention be given to anticipated salinity effects on hay and cotton crop coefficients, and subsequent estimations of applied water depths. Moreover, the results suggest that significant water savings of 20-30% are possible as compared to present irrigation methods in the desert regions for these crops if lower yields are to be expected in desert production.

Allowing for potential depressed yields as a result of salinity stress as well as pragmatic considerations of crop production, average water allocations (neglecting rainfall) sufficient to achieve target WUEs of say 17, 1.7 and 2.1 kg/ha-mm for hay, pima and upland cotton lint production, respectively, can be determined from average yields and planted areas and compared to Yield/$ET_c$ presently obtained to determine potential water savings at the farm level per county or area. Tables 5 and 6 summarize harvested areas, yields and potential water savings for hay and cotton lint production, respectively, as a result of improving area Yield/$ET_c$ ratios to the target WUEs above. Possible water savings appear to be substantial at the farm scale ranging up to nearly 50% of estimated ET (see Figure 9). It may be possible that crop coefficients are large for hay and cotton crops under desert cultivation, or that desert production may simply result in less efficient water use and regional planning for water allocations should be cognizant of this problem. Improving Yield/$ET_c$ ratios for alfalfa hay and cotton lint production in the southern San Joaquin Valley, partially a service area of Friant Dam, may result in a water savings 2.4 times the recently mandated water releases for in-stream fisheries. Similarly, possible water savings in the Imperial Valley from hay and cotton production total nearly 19% of its entire Colorado River allocation. On the other hand, the combined annual water savings potential from the Imperial and southern San Joaquin Valleys for hay and cotton production total just over the evaporation losses at Lake Powell.

## Summary & Conclusions

Anticipated population growth, climate change and reduced surface water availability will strain already overused water supplies of the American Southwest such that overall water "productivity", or WUE must increase in the region. Agricultural production is the dominant water user and public demand for fisheries and ecosystem benefits limits development of additional water storage. Past development of upstream water storage has exchanged downstream fisheries and ecosystems benefits for crop production in many cases, while reservoir evaporation losses further reduce possible downstream resource values. Unlike WUE improvements in the municipal sector, possible through metering and technological changes in flow devices and washing appliances, improved WUE in crop production is hampered by unidentified achievable water use targets at the farm level, and to a smaller degree at the irrigation/water district level. In terms of water use, alfalfa and sudangrass hay and cotton lint production are the dominant crops in the Southwest. The water-use characteristics from research studies, average planted areas and yields, estimated water use and water values are examined for these crops in Arizona, California and Idaho to determine possible target WUEs and assess possible on-farm water savings in the region based on actual production information from 1988-2000. Field-based WUEs of 1.7, kg/ha-mm for alfalfa and sudangrass hay and pima cotton, and 2.1 kg/ha-mm for upland cotton lint production appear to be practical target values from which to determine appropriate water use. Based on FAO #56 estimated and yield-based water use for these three crops, possible water savings of up to 50% exist with the greatest water savings potential in desert regions where current water values as hay or lint crops are low relative to other regions. Such high water savings in the desert region are unlikely and targets of 20-30% corroborated by the research trials, are more likely. These results suggest that crop coefficients may be large for these crops under desert cultivation, or that desert production may simply result in less efficient water use. The greatest water values and least possible water savings occur in the southern San Joaquin Valley, CA where the combination of relatively high ET and some rainfall occur. Increasing WUE of the hay and cotton crops in the desert regions would make water values as crops in these regions more consistent with that of other water uses. This research is a starting point for assessing water use/savings at the field scale for hay and cotton productions and should be extended to other crops. Additional work may also be required considering water savings at the district scale associated with the water distribution systems.

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**Table 1.** The top ten crops in terms of water demands grown using CO River water in the American southwest.

| **Crop** | **Consumptive Use (ha-m/yr) each year** | | | |
|---|---|---|---|---|
| | **2000** | **2001** | **2002** | **Average** |
| ***Alfalfa hay*** | ***100019*** | ***101594*** | ***104128*** | ***101914*** |
| bermuda | 28568 | 32430 | 34643 | 31880 |
| ***Sudangrass hay*** | ***19629*** | ***18495*** | ***17497*** | ***18540*** |
| sugar beets | 12544 | 10415 | 9989 | 10983 |
| wheat | 10280 | 8592 | 9643 | 9505 |
| ***Cotton lint*** | ***2379*** | ***5499*** | ***3766*** | ***3881*** |
| carrots | 4035 | 3635 | 3832 | 3834 |
| citrus | 3369 | 3352 | 3415 | 3378 |
| onions | 4013 | 2898 | 2666 | 3192 |
| Misc. field crops | 2210 | 3017 | 3032 | 2753 |

**Table 2.** Recent cotton yield - water use studies around the world.

| Location | Irrigation Method | Study $ET_c$ (mm) | FAO #56 $ET_c$ (mm) | Lint Yield (Mg/ha) | $LY/ET_c$ (kg/ha-mm) |
|---|---|---|---|---|---|
| San Joaquin Valley, CA (high salinity) | Drip irrig.- lysimeters | | | | |
| | 1998 | 710 | 914 | 1.32 | 1.86 |
| | 1999 | 845 | 988 | 2.16 | 2.56 |
| | Sprinkler/furrow– | | | | |
| | 1997 | 567 | 1005 | 1.16 | 2.04 |
| | 1998 | 561 | 914 | 0.62 | 1.12 |
| | 1999 | 561 | 988 | 1.23 | 2.19 |
| San Joaquin Valley, CA (high salinity) | Drip systems | | | | |
| | 1992 | 549 | 1011 | 1.78 | 3.24 |
| | 1993 | 691 | 994 | 2.04 | 2.95 |
| | Furrow systems | | | | |
| | 1992 | 437 | 1011 | 1.40 | 3.20 |
| | 1993 | 645 | 994 | 1.50 | 2.33 |
| Turkey | Furrow systems | | | | |
| | 1993 | 834 | ? | 1.16 | 1.39 |
| | 1994 | 899 | | 1.21 | 1.34 |
| Argentina | Furrow systems | | | | |
| | 1991 | 736 | | 1.68 | 2.29 |
| | 1992 | 495 | ? | 1.92 | 3.87 |
| | 1993 | 631 | | 1.95 | 3.09 |
| Texas | Dryland (1992-95) | | | | |
| | Clean tillage | 200-300 | ? | 0.29-0.51 | 1.51-1.66 |
| | Wheat residue | 300 | | 0.37 | 1.22 |
| East Hebei Plain, North China | Furrow systems (1994) | | | | |
| | No mulch | 506 | ? | 0.85 | 1.67 |
| | Plastic mulch | 426 | | 1.13 | 2.62 |
| Negev, Israel | Drip systems (1994-95) | | | | |
| | Full irrigation | 491-566 | ? | – | 2.1-3.4 |
| | Irrigation @ 50-100% $ET_o$ | 349-390 | | – | 2.1-3.4 |
| Central Arizona | Level basin (1993-94) | | 1338 | | |
| | Low frequency | 852-867 | | 1.14-1.32 | 1.32-1.55 |
| | Low-high-low freq. | 889-894 | | 1.38-1.52 | 1.47-1.63 |
| | High frequency | 932-939 | | 1.25-1.47 | 1.41-1.64 |
| San Joaquin Valley, CA | Drip systems (1993-94) | | 992 | | |
| | Early irrigation | 620 | | 1.46 | 2.36 |
| | Delayed, low freq. | 477 | | 1.59 | 3.33 |
| | Delayed, high freq. | 605 | | 1.46 | 2.42 |
| SJ Valley, CA (high salinity) | Drip & Furrow (1993-94) | 713-805 | 992 | 1.23-1.55 | 1.53-2.03 |

**Table 3.** Estimates of mean alfalfa and sudangrass hay ET$_c$, Yield/ET$_c$ and irrigation water values (IW$) and their variability for production in Arizona, California and southern Idaho (from Grismer, 2001a & b).

| **Region** | **ET$_c$ (mm)** | **Y/ET$_c$ (kg/ha-mm)** | **Y/ET$_c$ *CV*[1] (%)** | **IW$ (USD/ ha-m)** | **IW$ *CV* (%)** |
|---|---|---|---|---|---|
| **Arizona – alfalfa** | | | | | |
| Lapaz | 1979 | 9.04 | *6.83* | 945 | *15.7* |
| Maricopa | 1817 | 9.74 | *4.97* | 1082 | *12.3* |
| Mohave | 1892 | 8.77 | *10.2* | 963 | *9.61* |
| Pinal | 1812 | 9.71 | *9.15* | 1107 | *20.3* |
| Yuma | 1882 | 10.4 | *8.81* | 1078 | *16.4* |
| **California – alfalfa** | | | | | |
| NE Plateau | 979 | 10.4 | *8.61* | 1344 | *22.5* |
| N. Sacram. V. | 951 | 11.7 | *7.87* | 1733 | *29.2* |
| C. Sacram. V. | 1066 | 13.7 | *5.46* | 1900 | *20.3* |
| S. Sacram. V. | 1145 | 12.5 | *7.07* | 2166 | *29.6* |
| N. S Joaq. V. | 1166 | 13.6 | *4.80* | 1931 | *19.0* |
| C. S Joaq. V. | 1220 | 14.9 | *7.68* | 2031 | *17.8* |
| S. S Joaq. V. | 1292 | 14.0 | *4.02* | 1861 | *16.9* |
| C. Coast | 971 | 19.3 | *6.39* | 2792 | *20.4* |
| LA Basin | 1105 | 17.2 | *5.87* | 2967 | *14.1* |
| Rivers.-SB | 1651 | 9.33 | *6.94* | 1420 | *18.1* |
| N. Desert | 1337 | 13.9 | *11.5* | 1187 | *17.7* |
| Imperial V. | 1657 | 7.91 | *8.57* | 1213 | *15.2* |
| **Idaho - alfalfa** | | | | | |
| S. West | 882 | 14.0 | *7.48* | 1630 | *17.5* |
| S. Central | 788 | 14.6 | *6.49* | 1814 | *15.3* |
| S. East | 695 | 13.5 | *9.62* | 1789 | *19.8* |
| **California - sudangrass** | | | | | |
| C. S Joaq. V. | 825 | 9.56 | *13.6* | 721 | *29.2* |
| Rivers.-SB | 1003 | 13.8 | *18.3* | 1202 | *23.5* |
| Imperial V. | 1054 | 12.5 | *18.4* | 1213 | *22.8* |

[1] *CV* is the Coefficient of Variation = standard deviation/mean.

**Table 4.** Estimates of mean cotton lint $ET_c$, Yield/$ET_c$ ratios and irrigation water values (IW$) and their variability (from Grismer, 2001c).

| **Region** | **$ET_c$ (mm)** | **LY/$ET_c$ (kg/ ha-mm)** | **LY/$ET_c$ *CV* (%)** | **IW$ (USD/ ha-m)** | **IW$ *CV* (%)** |
|---|---|---|---|---|---|
| **Arizona (Upland cotton)** | | | | | |
| Lapaz | 1362 | 1.28 | *10.2* | 1870 | *8.56* |
| Maricopa | 1023 | 1.33 | *6.68* | 2111 | *12.5* |
| Mohave | 1034 | 1.27 | *17.8* | 1867 | *16.5* |
| Pinal | 1007 | 1.34 | *8.41* | 2180 | *16.3* |
| Yuma | 1035 | 1.38 | *13.1* | 2057 | *15.6* |
| **Arizona (Pima cotton)** | | | | | |
| Lapaz | 1362 | 0.92 | *18.2* | 2094 | *20.4* |
| Maricopa | 1023 | 0.90 | *9.84* | 2244 | *17.4* |
| Pinal | 1007 | 0.90 | *13.2* | 2266 | *23.3* |
| Yuma | 1035 | 1.09 | *21.5* | 2507 | *27.8* |
| **California (Upland cotton)** | | | | | |
| C. Sacram. V. | 656 | 1.73 | *28.5* | 3293 | *26.6* |
| S. Sacram. V. | 672 | 1.64 | *17.1* | 4821 | *49.7* |
| N. S Joaq. V. | 684 | 2.10 | *10.3* | 3777 | *15.3* |
| C. S Joaq. V. | 750 | 1.91 | *8.60* | 3411 | *10.9* |
| S. S Joaq. V. | 776 | 1.67 | *12.0* | 3038 | *5.99* |
| S. Desert | 990 | 1.34 | *19.6* | 2334 | *24.3* |
| Imperial V. | 1008 | 1.37 | *20.4* | 2384 | *35.3* |
| **California (Pima cotton)** | | | | | |
| C. S Joaq. V. | 750 | 1.77 | *9.95* | 4172 | *13.6* |
| S. S Joaq. V. | 776 | 1.51 | *16.6* | 3500 | *9.57* |

**Table 5.** Average hay harvested areas, yields possible water savings through achieving expected WUE.

| State/Region | Counties | Harvested hectares | Average Hay Yield (Mg/ha) | Water Savings? (ha-m/yr) |
|---|---|---|---|---|
| **Arizona - alfalfa** | | | | |
| | Lapaz | 17 523 | 17.9 | 16227 |
| | Maricopa | 20 936 | 17.7 | 16243 |
| | Mohave | 2610 | 16.6 | 2390 |
| | Pinal | 6610 | 17.6 | 5134 |
| | Yuma | 13 341 | 19.5 | 9805 |
| **California - alfalfa** | | | | |
| NE Plateau | Lassen/ Modoc | 24 427 | 10.2 | 9258 |
| N. Sac. V. | Shasta/ Siskiyou | 27 374 | 11.1 | 8159 |
| C. Sac. V. | Butte/ Colusa/ Glenn/ Sutter/ Tehema/ Yuba | 17 068 | 14.6 | 3536 |
| S. Sac. V. | Sacramento/ Yolo | 16 427 | 14.3 | 4991 |
| North San Joaquin V. (N. SJV) | Contra Costa/ Merced/ San Joaquin/ Stanislaus | 72 762 | 15.8 | 17215 |
| C. SJV | Fresno | 29 452 | 18.2 | 4400 |
| S. SJV | Kern/ Kings/ Tulare | 89 597 | 18.1 | 20365 |
| C. Coast | Monterey/ San Luis Obispo/ S. Barbara | 2363 | 18.7 | 0 |
| LA Basin | Los Angeles | 3543 | 19.0 | 0 |
| Riverside/SB | Riverside/ San Bernardino | 27 431 | 15.4 | 2640 |
| N. Desert | Inyo | 1544 | 18.6 | 375 |
| S. Desert | Imperial | 73 531 | 13.1 | 65179 |
| **Idaho - alfalfa** | | | | |
| S. West | (see footnote 1) | 73 403 | 12.3 | 11632 |
| S. Central | (see footnote 2) | 102 917 | 11.5 | 11478 |
| S. East | (see footnote 3) | 168 819 | 9.41 | 23883 |
| **California - sudangrass** | | | | |
| N. SJV | Merced/ Stanis. | 1158 | 7.88 | 419 |
| Riverside/SB | Riverside/ San Bernardino | 2943 | 13.8 | 563 |
| S. Desert | Imperial | 27115 | 13.1 | 7621 |

[1] Ada, Adams, Boise, Canyon, Elmore, Gem, Owyhee, Payette, Valley & Washington counties.

[2] Blaine, Camas, Cassia, Gooding, Jerome, Lincoln, Minidoka, & Twin Falls counties.

[3] Bannock, Bear Lake, Bingham, Bonneville, Butte, caribou, Clark, Custer, Franklin, Fremont, Jefferson, Lemhi, Madison, Oneida, Power & Teton counties.

**Table 6.** Average cotton lint harvested areas, yields possible water savings through achieving expected WUE.

| **Region** | **Counties** | **Harvested hectares** | **Avg. Lint Yield (Mg/ha)** | **Water Savings? (ha-m/yr)** |
|---|---|---|---|---|
| **Arizona (Upland cotton)** | | | | |
| | Lapaz | 10 033 | 1.42 | 4346 |
| | Maricopa | 48 752 | 1.36 | 18279 |
| | Mohave | 2283 | 1.28 | 909 |
| | Pinal | 43 285 | 1.35 | 15782 |
| | Yuma | 9291 | 1.42 | 3278 |
| **Arizona (Pima cotton)** | | | | |
| | La Paz | 1814 | 1.01 | 914 |
| | Maricopa | 7516 | 0.93 | 3655 |
| | Pinal | 14 404 | 0.91 | 6854 |
| | Yuma | 1491 | 1.12 | 550 |
| **California (Upland cotton)** | | | | |
| C. Sac.V.('95-99) | Colusa/Glenn | 2194 | 1.14 | 255 |
| S. Sac.V.('96-99) | Yolo | 1076 | 1.11 | 160 |
| N. SJV | Merced | 30 102 | 1.44 | 0 |
| C. SJV[1] | Madera/Fresno/ Tulare | 195 926 | 1.44 | 13365 |
| S. SJV[2] | Kern/ Kings | 183 149 | 1.30 | 29193 |
| S. Desert[3] | Riverside | 5900 | 1.35 | 2151 |
| Low Desert[4] | Imperial | 4433 | 1.39 | 1563 |
| **California (Pima cotton)** | | | | |
| C. SJV ('92-99) | Fresno | 27 287 | 1.34 | 0 |
| S. SJV ('92-99) | Kern/ Kings | 37 071 | 1.17 | 3210 |

[1] Upland cotton area has decreased ~30% since 1988 while Pima area has tripled since 1992.

[2] Upland cotton area has decreased ~50% since 1988 while Pima area has doubled since 1992.

[3] Cotton planted area has decreased by a factor of ~2.4 since 1988.

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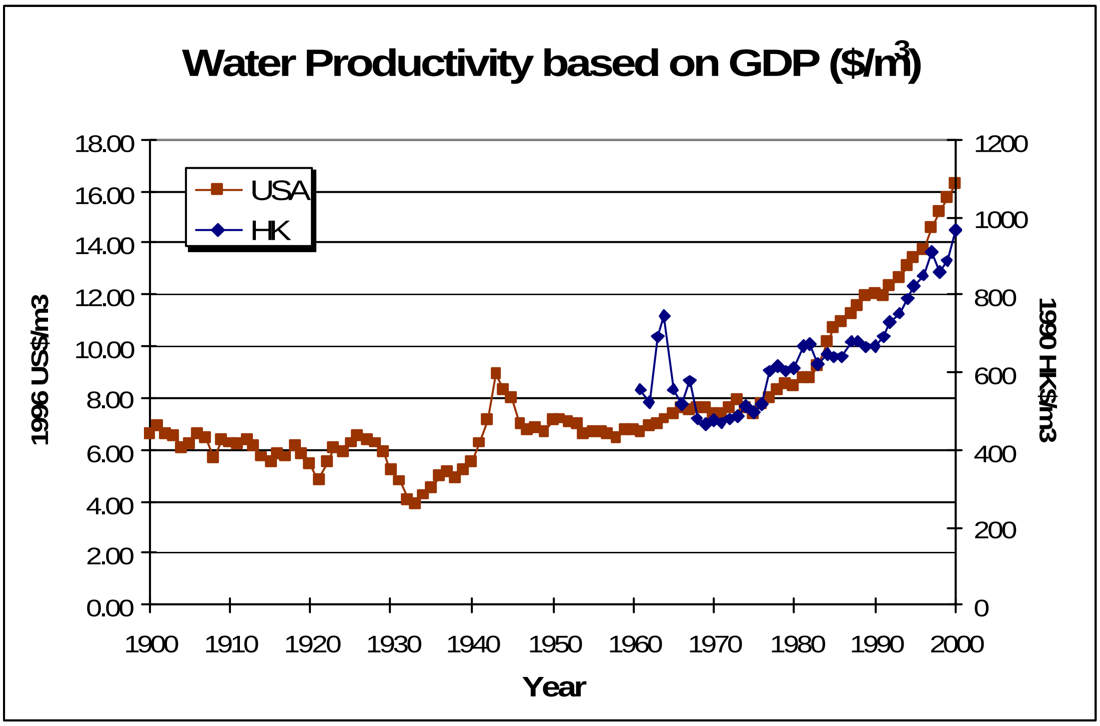

**Figure 1.** Water productivity (value) in the USA and Hong Kong during the 20th century.

**Figure 2.** Schematic illustration of the upper and lower basins of the Colorado River.

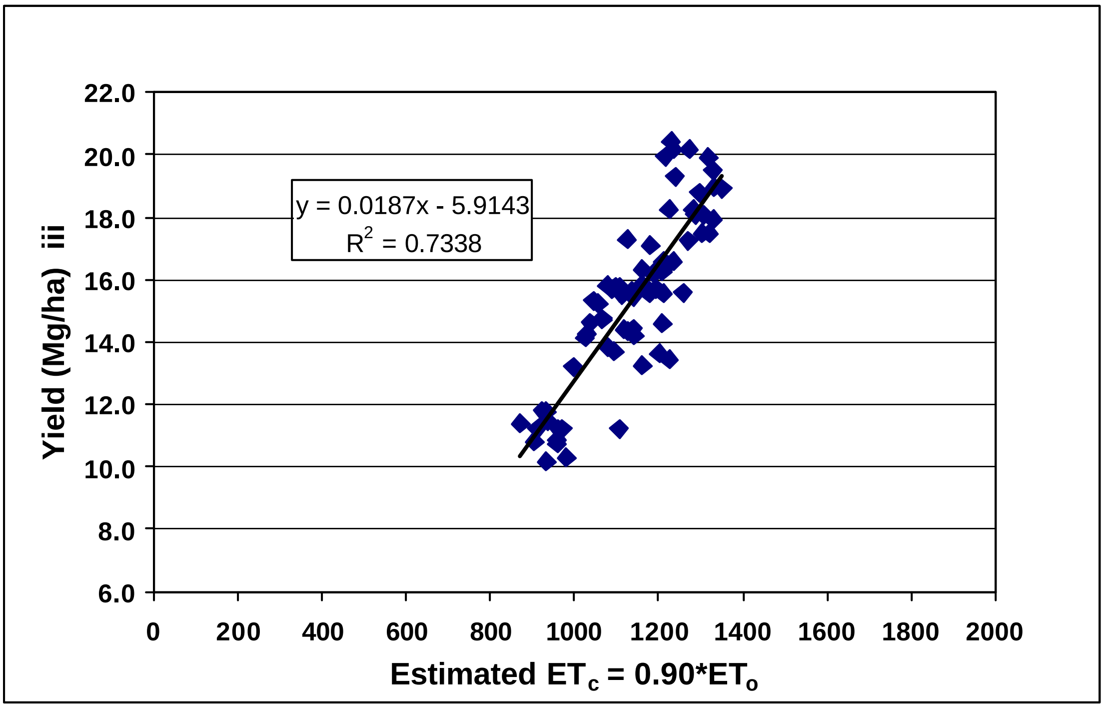

**Figure 3.** Y=*f*($ET_c$) relationship for alfalfa hay production in the Great Valley, California.

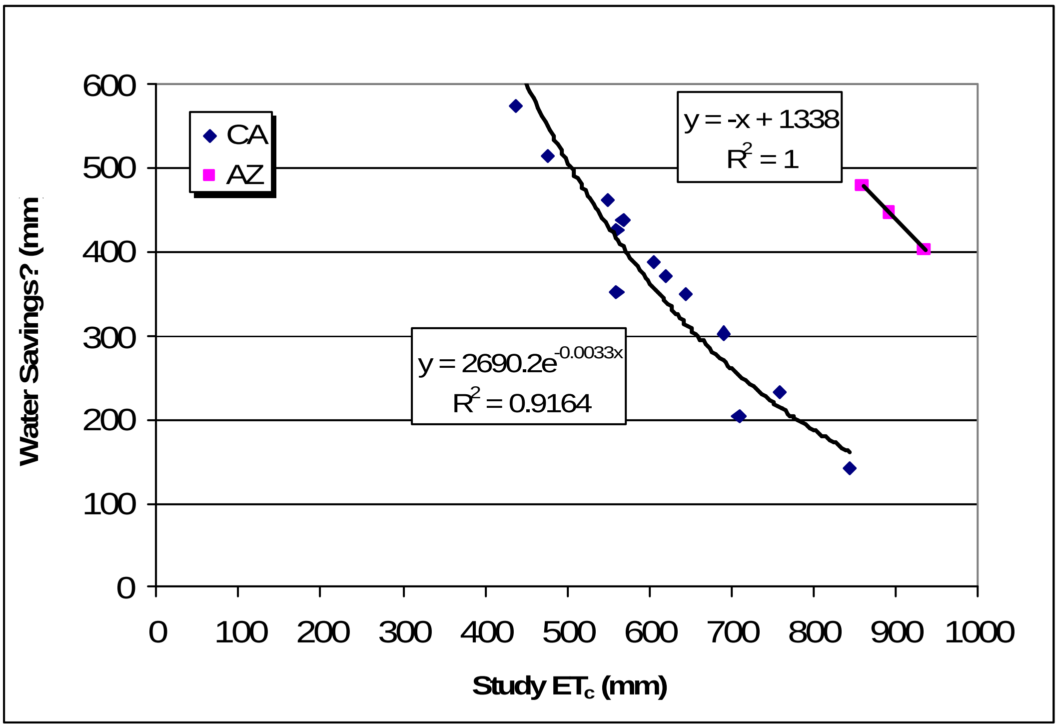

**Figure 4.** Potential water savings associated with cotton production based on estimated and actual water requirements from field trials in Arizona and southern California.

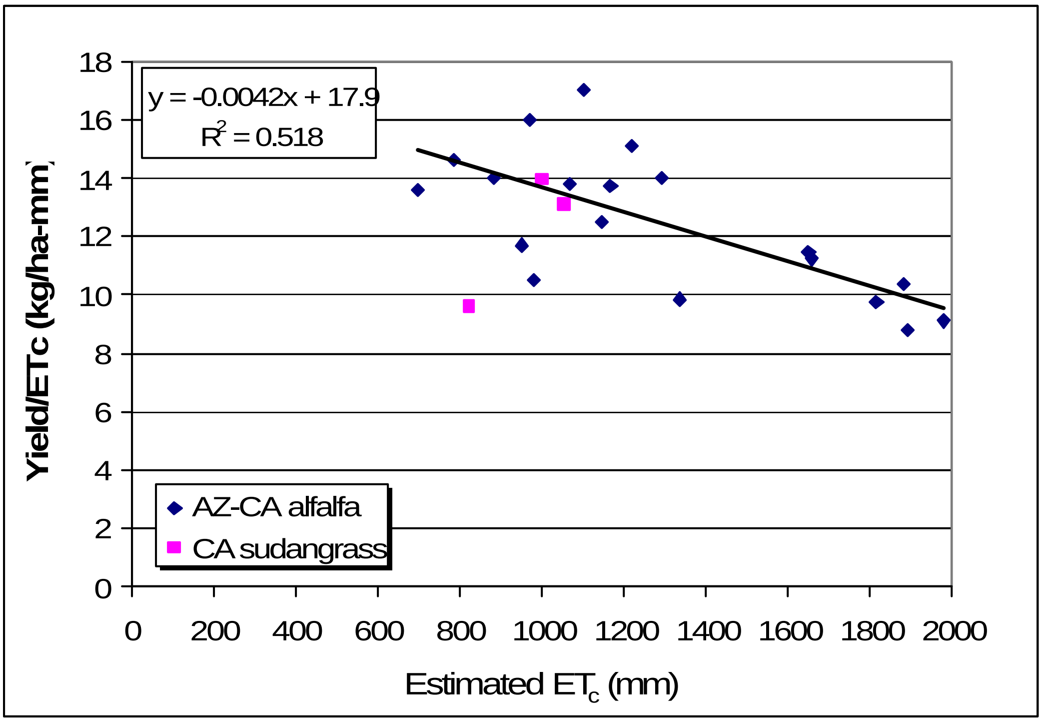

**Figure 5.** Dependence of Yield/ET$_c$ on ET$_c$ for hay production in AZ and CA.

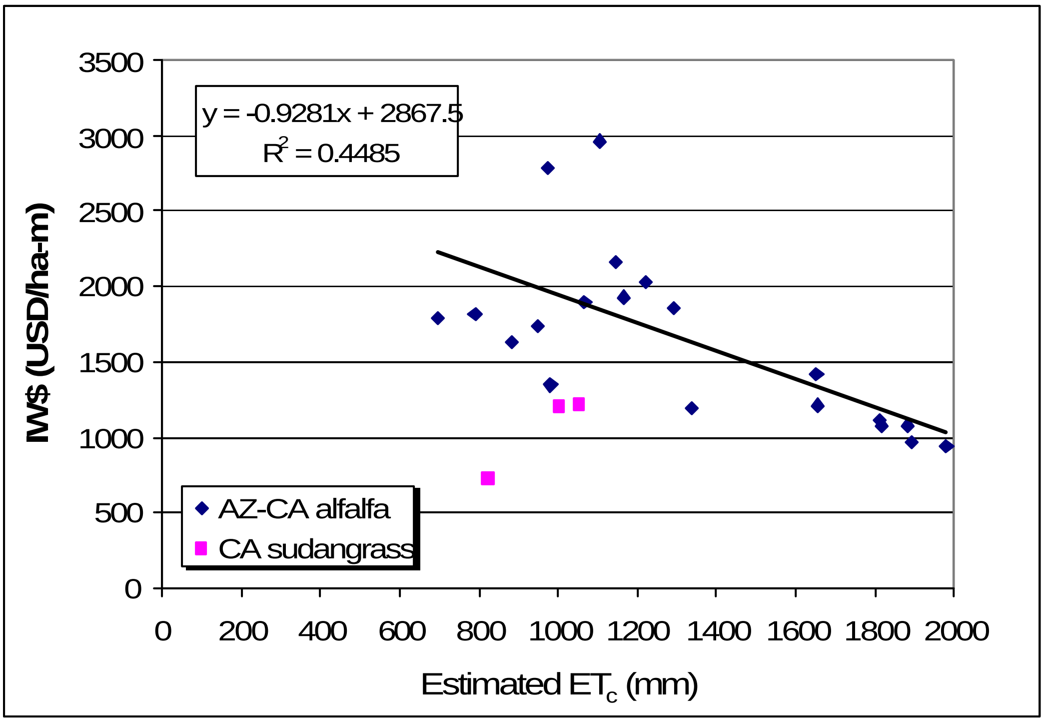

**Figure 6.** Dependence of water value on ET$_c$ for hay production in AZ and CA.

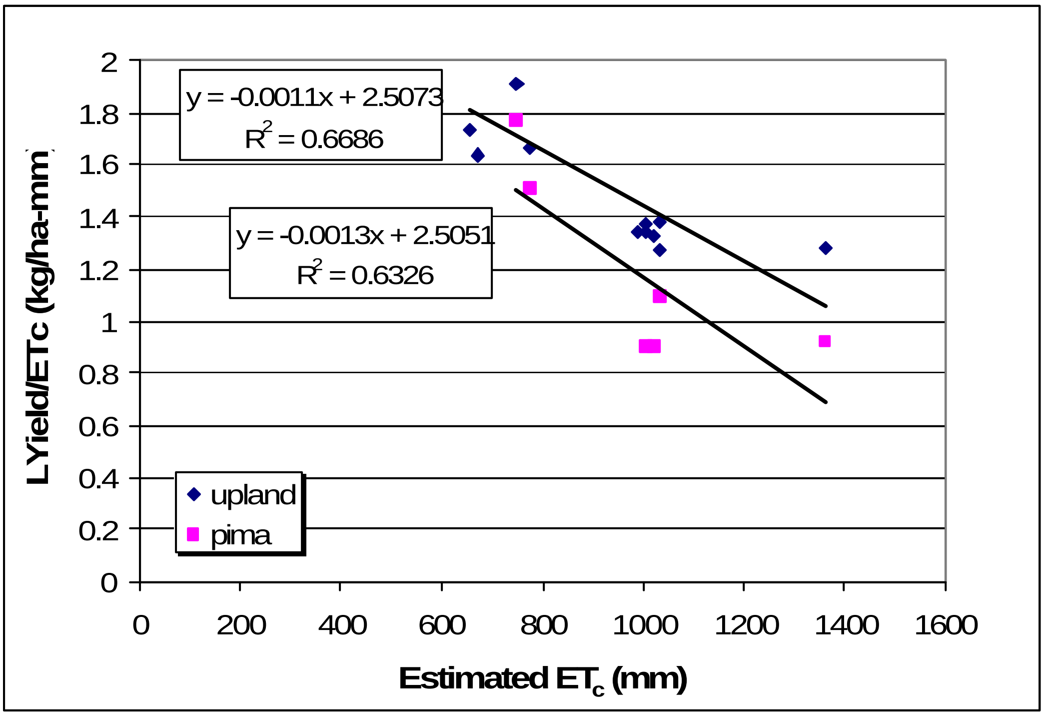

**Figure 7.** Dependence of Yield/$ET_c$ on $ET_c$ for cotton lint production in AZ and CA.

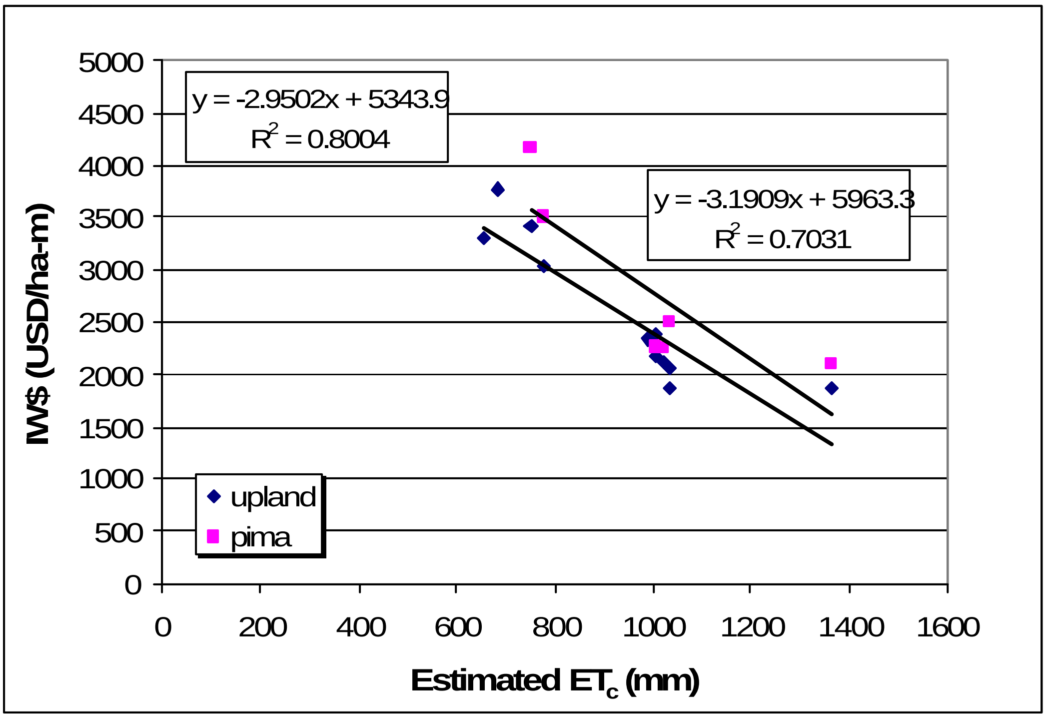

**Figure 8.** Dependence of water value on $ET_c$ for cotton lint production in AZ and CA.

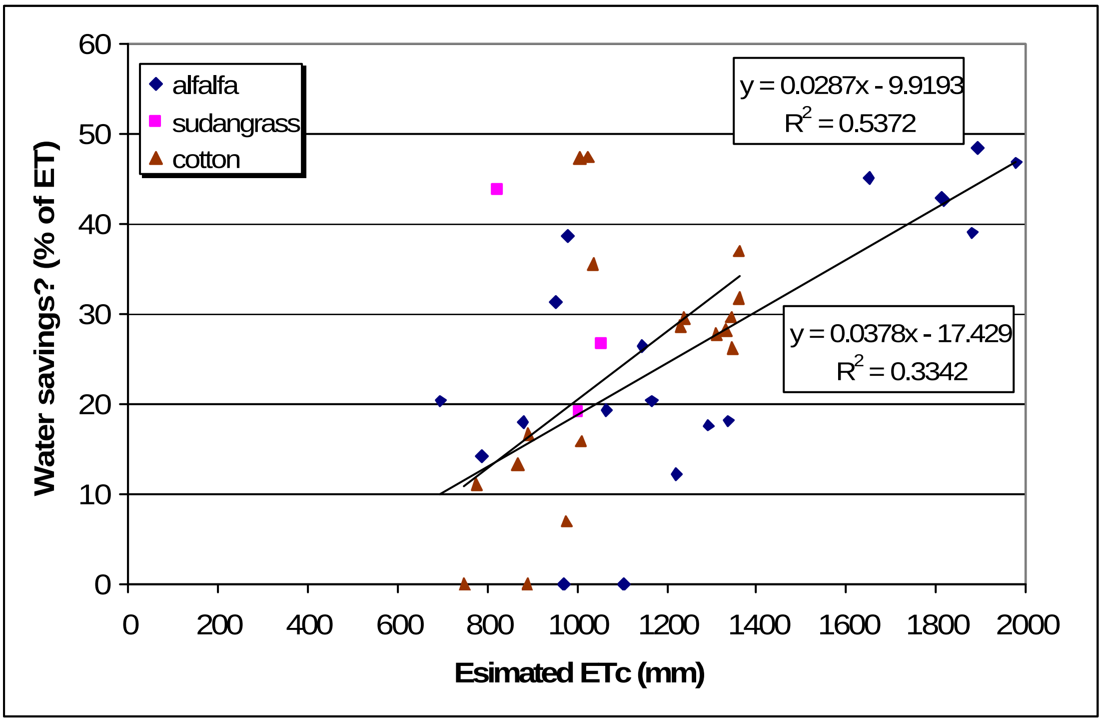

**Figure 9.** Dependence of possible water savings on $ET_c$ for hay and cotton lint production in AZ and CA.