USING REMOTE SENSING AND GIS TECHNIQUES FOR STUDYING IRRIGATION PERFORMANCE OF PALO VERDE IRRIGATION DISTRICT

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ABSTRACT

Managing water resources in western US has been a challenge for decision makers. In the last few decades, the rapid growth rates of population along with the alarming rates of global warming have added to the complexity of this issue. In this study, remote sensing techniques have been applied to evaluate the performance of agricultural irrigation, the largest consumptive user of water. The study area, “Palo Verde irrigation District” which is located in Riverside and Imperial counties, California, is an old irrigation district with a fairly heterogeneous cropping pattern. Landsat Thematic Mapper satellite images were used to estimate the actual ET using the SEBAL energy balance model. These estimates were integrated to obtain crop water demand for different periods throughout the growing season. The amount of diverted water was also estimated for the same periods, using flow measurements within the Palo Verde irrigation district. The results were analyzed within the ArcGIS environment in conjunction with water conveyance and field boundary layers to evaluate different performance indicators such as relative water supply, overall consumed ratio, depleted fraction, crop water deficit, and relative evapotranspiration. The results of these indicators can help irrigation managers to get a general idea of how the system performs and to identify possible ways of improving it.

INTRODUCTION AND BACKGROUND

Historically, western US has been best known for its arid climate, low precipitation, and long droughts. These inherent characteristics have made water availability a major issue in this part of the world. In recent years, some new challenges have added to the complexity of managing scarce water resources of the western states. Probably the most noticeable challenge is the rapid population growth rate. People are migrating to the west at a record rate, putting a lot of pressure on managers to supply required drinking water. Another important challenge for decision makers is that water should not only be available for human uses, but it should also protect ecosystems and critical habitat for

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flora and fauna. These issues make securing and managing water supplies far more complicated than what it was in the past.

In such a complicated situation, science plays an important role in helping resource managers to make the right decision. As authors of a recent USGS report (Anderson and Woosley, 2005) concluded: “The role of science in helping to meet water challenges will not likely involve finding undiscovered sources of water, but rather will be integral in developing a more comprehensive understanding of the consequences of each course of management action”. According to USGS, irrigated agriculture has been the biggest user of fresh water in the United States since 1950, accounting for about 65 percent of total water withdrawal – excluding thermoelectric power. Not surprisingly, 86 percent of all withdrawals and 75 percent of all irrigated lands were in the 17 conterminous western States (Hutson et al. 2004). Needless to say, a thorough management of water resources in western US is impossible without having a comprehensive knowledge of irrigation performance and the ways it can be improved.

Methods of quantifying irrigation performance have been significantly improved in last decades. A major advancement was the use of remote sensing and GIS techniques in estimating spatially distributed evapotranspiration (ET), a key input of many performance indicator models. Traditional methods of making point measurements cannot be extended to represent large irrigated areas, due to the dynamic nature of crop growth and regional variation of ET. Even if they are extended to cover large irrigation projects, the accuracy is usually low and the credibility of these studies is under question (Bastiaanssen and Bos, 1999). The advantages of space- and/or air-borne remote sensing over conventional methods are including, but not limited to: obtaining accurate and objective data, covering vast irrigated schemes with one or multiple scenes, and being able to spatially represent the results (Bastiaanssen and Bos, 1999). Nowadays, with the cost of satellite remote sensing being the lowest in its history, estimating accurate daily ET at regional scales is economically affordable by water users associations with limited financial resources. For a 15000 ha irrigation scheme, Bastiaanssen et al. (2001) estimated a cost of about US$ 1.00/ha to cover all the costs of carrying out a performance analysis using NOAA-AVHRR dataset, which is available online at no costs. Since then, Landsat high resolution imagery has also became available free of charges.

Although lots of studies have been carried out world wide, many decision makers are still not aware of the potential of remote sensing in addressing irrigation performance under different conditions. Bastiaanssen and Bos (1999) recommended more demonstration projects and pilot studies to show irrigation managers the possibilities of using remotely sensed data. This paper evaluates the performance of Palo Verde Irrigation District (PVID) in Southern California using remote sensing based indicators from satellite imagery.

Study Area

The Palo Verde valley is located in Southern California, on the west bank of Colorado River. With an average elevation ranging from about 88 to 67 meters above sea level, the valley is relatively flat. Alluvial soils of this area are mostly sandy loam in texture. The Palo Verde Irrigation District (PVID) was privately developed in 1925 to serve the valley's water users. Colorado River water is diverted through Palo Verde diversion dam to irrigate growing crops of the valley year round. PVID water conveyance system consists of about 244 miles of irrigation canals (23 percent of which are lined) and 141 miles of open drainage canals. Most dominant crops of this district are alfalfa and cotton with 68 and 23 percent of total cropped area, respectively. Grasses, grains, vegetables and orchards are planted in the remaining 9 percent of the lands.

METHODS AND MATERIALS

Two major types of input data are needed in remote sensing-based irrigation performance analysis: ground and remotely sensed data. Ground data include meteorological data and flow rates of diverted water, while remotely sensed data are used in estimating potential and actual evapotranspiration. In this case study, the USGS gauging station data at the intake of the PVID main canal was used for estimating the diversions from the Colorado River to the PVID.

All required meteorological data were downloaded from the website of "The California Irrigation Management Information System" (CIMIS). The data from two CIMIS stations within the PVID were averaged and used in calculations. These two stations were "Ripley" (33.53 N, 114.63 W) with more than a 90 meter fetch of alfalfa as reference surface and "Palo Verde II" (33.39 N, 114.73 W) with the same reference surface. In addition to several meteorological parameters, CIMIS also reports reference ET for every station based on different equations. Since the dominant crop in PVID is alfalfa, alfalfa-based reference ET (ET_r) estimated by modified Penman-Monteith method was used in this study. The modified version of Penman-Monteith is basically the equation described in FAO paper No. 56 (Allen et al., 1998), with the "bulk surface resistance (C_d)" is the one suggested by ASCE Task Committee of Standardization of Reference Evapotranspiration (Walter et al., 2000):

$$ET_r = \frac{\Delta(R_n - G)}{\lambda\{\Delta + \gamma(1 + C_d u_2)\}} + \frac{\gamma \frac{66}{T_a + 273.16} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$$

where ET_r is the alfalfa reference ET, Δ is the slope of saturation vapor pressure curve at mean air temperature, R_n is the net radiation, G is soil heat flux, γ is psychrometric constant, T_a is mean air temperature, u_2 is the wind speed at two meters height, e_s and e_a are saturated and actual vapor pressure, and λ is the latent heat of vaporization. C_d is 0.25 for daytime and 1.70 for nighttime.

Landsat 5 Thematic Mapper (TM) images (Path: 38, Row: 37) were acquired for nine dates between May and September 2007. This acquisition period was selected because cotton, the second dominant crop is planted in April and harvested in October, but the farmers stop irrigating cotton in September to allow the field to dry out and facilitate the operations of the harvesting machinery. The most dominant crop, alfalfa, is a perennial crop, so it grows year around, albeit at a slower rate in the winter months. Theoretically, the month of April was also important in evaluating irrigation performance, but both Landsat overpasses in April and even the second scene of March were cloudy and impossible to be used in this study. This is the most significant drawback of the TM satellite imagery. Higher spatial resolution images are available at lower temporal resolution and lower spatial resolution images such as from the MODIS sensor are available at higher frequency. Thus it is always a trade off between spatial and temporal resolutions. Table 1 shows the dates of Landsat images used in this study.

Table 1. Dates of available, cloud free satellite images (Path: 38, Row: 37)

No.	Julian Day	Date
1	128	05/08/2007
2	144	05/24/2007
3	160	06/09/2007
4	176	06/25/2007
5	192	07/11/2007
6	224	08/12/2007
7	240	08/28/2007
8	256	09/13/2007
9	272	09/29/2007

Potential Evapotranspiration

Almost all of the remote sensing-based methods of quantifying ET are based on simple form of energy balance equation at the surface:

$$R_n = G + H + LE$$

where R_n is the net radiation, G is the soil heat flux, H is sensible heat flux, and LE is the latent heat flux, all in W/m^2. These methods estimate R_n, G, and H from the reflectance of different spectral bands and then calculate LE as the residual of the energy balance equation. In this study it was assumed that potential evapotranspiration (ET_p) is equal to the sum of latent and sensible heat fluxes, so it was estimated by subtracting soil heat flux from net radiation. Since a well irrigated stress-free crop uses most of the available energy for ET, this assumption is valid. The results of energy partitioning models also show that the values of H are very close to zero for pixels with the mentioned characteristics. Bastiaanssen et al. (1996) used ($R_n – G$) as ET_p as well. Computed ET_p is an instantaneous value, due to the fact that the satellite image is a snapshot in time. But instantaneous ET_p can be scaled up to daily values, using ET_r values measured by CIMIS. In order to do so, instantaneous ET_r was identified, then the ratio of ET_p over ET_r was calculated and it was assumed that this ratio would be constant throughout the day. Daily ET_p can be readily estimated by multiplying this ratio by daily ET_r values. Since monthly ET_p is used in analysis of irrigation performance, daily ET_p needs to be scaled up further to longer period values. Considering that Landsat can provide two images per month (if cloud free), each month was partitioned into two periods, and it was assumed that the ratio of daily ET_p over daily ET_r for the day of satellite overpass is constant for that part of the month. The strength of this approach is that the effect of clouds or any other factor that might have an unexpected effect on evapotranspiration is reflected in ET_r value. However the weakness of this approach is that it is not taking into account the crop growth during the period. So it seems the reflectance based crop coefficient is a better method as it can be integrated in time, using the average K_{cb} curve.

Actual Evapotranspiration

Actual evapotranspiration (ET_a) was spatially estimated using the Surface Energy balance Algorithms for Land, SEBAL (Bastiaanssen et al., 1998). This model is also based on the simple form of energy balance equation at the surface. SEBAL estimates R_n by subtracting outgoing from incoming short and long wave radiation (surface radiation balance). To estimate soil heat flux, first the ratio of G/R_n is calculated empirically for every pixel, and then this ratio is multiplied by R_n of that pixel. Finally, the H is approximated by selecting two anchor points, known as the cold and hot pixels. These pixels represent the boundary condition, where the former is a wet, well irrigated vegetation surface, and the latter is a dry, bare agricultural soil. Appropriate selection of these two pixels is dependent on operator experience and judgment and can affect the accuracy of estimated evapotranspiration. After estimating three out of four components of the surface energy budget equation, the forth component (LE) can be estimated as the residual of the equation. LE is then converted to ET_a by dividing by the latent heat of vaporization. Like ET_p, estimated ET_a is instantaneous and needs to be converted to longer period values. The same methodology (the ratio of ET_a over ET_r) was utilized to obtain daily and periodic ET_a.

Performance Indicators

Five different remote sensing-based irrigation performance indicators were estimated using the ground and space borne data. These indicators are relative water supply (RWS) (Perry, 1996), overall consumed ratio (e_p) (Bos and Nugteren, 1990), depleted fraction (DF) (Molden, 1997), crop water deficit (CWD) (Bastiaanssen et al., 2001), and relative evapotranspiration (RET) (Roerink et al., 1997). The first three indicators were estimated for the entire cropped area of the district, but CWD and RET were estimated for each pixel and then averaged over every field. All these indicators are dimensionless, so they can be easily compared over the time and/or space.

Relative Water Supply (RWS): RWS evaluates if the total water (irrigation and precipitation) supplied to the fields meets the demand of the crops or not. RWS is estimated as follows:

$$\text{RWS} = \frac{V_c + P_g}{ET_p}$$

where V_c is the volume of diverted water, P_g is the gross precipitation over study area, and ET_p is the potential evapotranspiration. The target value for RWS could vary from an irrigation system to another, based on system performance. Theoretically, a RWS of unity is desired, but the value gets bigger as the losses from diversion to application point increase. For an ideal irrigation scheme, target RWS could be considered unity. An ideal irrigation scheme could be described as an area with fertile soil in appropriate physical and chemical condition, under an efficient, well designed irrigation system and operated under an on-demand delivery scheme. On the other hand, the RWS should be greater than one in an irrigation scheme like PVID, where a fraction of water will be unavailable due to evaporation and seepage during water conveyance. In addition, extra water - over the consumptive use requirements of the crops - is usually applied in order to leach the salts out and to fill the whole root zone area until the next irrigation event.

Overall Consumed Ratio (e_p): Overall consumed ratio represents the fraction of total supplied water that can be used by crops, in the absence of any growth-limiting factor. This indicator is calculated as follows:

$$e_p = \frac{ET_p - P_e}{V_c}$$

where P_e is effective precipitation and the rest of parameters are as described before. Like RWS, e_p can also express the adequacy of supplied water. e_p greater than unity indicate under-irrigation, while values less than one implies adequate or over-irrigation. Due to the differences in system performance and soil/climate conditions, target e_p could differ from one system to another, thus it should be established for the specific scheme under study. Overall consumed ratio is inversely proportional to RWS, and the difference between these two indicators is in utilizing effective versus gross precipitation.

Depleted Fraction (DF): Depleted fraction is the fraction of supplied water that is used up by plants and can not be reallocated to another beneficial use. The following equation is used for DF computation:

$$\text{DF} = \frac{ET_a}{V_c + P_g}$$

Depleted fraction is very similar to e_p in nature, but it is based on ET_a rather than ET_p. Therefore, comparing these two indicators can give an idea about the presence of stress factors. However, next two indicators are better representatives for addressing sub-optimal evapotranspiration conditions.

Crop Water Deficit (CWD): Crop water deficit is the difference between potential and actual evapotranspiration. This indicator can be readily quantified as follows:

$$\mathrm{CWD} = \mathrm{ET_p} - \mathrm{ET_a}$$

The optimal value of CWD is zero, which is almost unachievable under actual field condition. Thus, irrigation managers would want the CWD to be as small as possible. However, if deficit irrigation is economically viable, greater CWD's might be favorable.

Relative Evapotranspiration (RET): Relative ET identifies the fraction of potential ET that has actually happened under field condition. RET is defined as follows:

$$\mathrm{RET} = \frac{ET_a}{ET_p}$$

Spatially distributed RET can give irrigation managers a thorough understanding on where they can improve. The fact that RET is a fraction is something that should be noticed before making any decision based on the results of this indicator, because a very small, disappointing RET might be the result of dividing a tiny $\mathrm{ET_a}$ by a small $\mathrm{ET_p}$ or a big $\mathrm{ET_a}$ by a very big $\mathrm{ET_p}$. Each of these cases may require different actions to be taken. For example, at the early stages of crop growth, it is very hard to meet the crop demand when applying surface irrigation under a fixed-rotation water delivery scheme. But when the crops grow and establish good root system, it is much easier to supply most of required water. On the other hand, a farmer who takes advantage of sprinkler systems operated under on-demand delivery scheme is able to do a better job during the period right after crop emergence. Thus, a low RET at the beginning of crop growth is less surprising when surface irrigation is applied. One way to overcome the deceptiveness of RET is to look at it along with CWD.

RESULTS AND DISCUSSION

The results show that monthly actual and potential evapotranspiration values are almost constant for the first four months. The average $\mathrm{ET_a}$ and $\mathrm{ET_p}$ from May to August were 155.4 and 258.1 mm, respectively. Deviations from average are not significant during this period. But compared to August, $\mathrm{ET_a}$ and $\mathrm{ET_p}$ of the month of September showed a decrease of more than 28 and 30 percent, respectively. The reason behind this reduction in ET is the effect of atmospheric parameters such as lower average air temperature, reduced solar radiation, and higher relative humidity. Diversion of Colorado River water also dropped about 12 percent in September, mainly because farmers stop irrigating cotton in order to prepare the fields for harvest.

Performance Indicators

Relative Water Supply (RWS): The relative water supply was constantly increasing from 1.98 in May to 2.56 in September. A total average of 2.18 is reasonable for an irrigation scheme like PVID. Almost all of fields in this irrigation district are under surface irrigation systems, so a significant amount of water needs to be applied in each irrigation event in order to get the water to the end of field. In addition, a fraction of diverted water should be dedicated to leach the salts out of root zone and to account for the loss of water in conveyance (due to evaporation and seepage from irrigation canals).

Bastiaanssen et al. reported average RWS of 1.26 for Nilo Coelho irrigation scheme in Brazil, with fruits as dominant crops under pressurized irrigation system. They also defined benchmarks for different performance indicators. Based on their study, RWS values out of the acceptable range of 0.90 to 1.40 will result in more than 20 percent reduction in target yield (Bastiaanssen et al., 2001). Another recent study evaluated mean RWS of 1.10 (ranging from 0.14 to 2.77) for Lower Gediz Basin in Western Turkey (Karatas et al., 2009). Figure 1 demonstrates RWS values for each month of study during 2007 growing season. The coefficient of variation (CV) of monthly RWS was 0.10, which implies low temporal variation of this indicator.

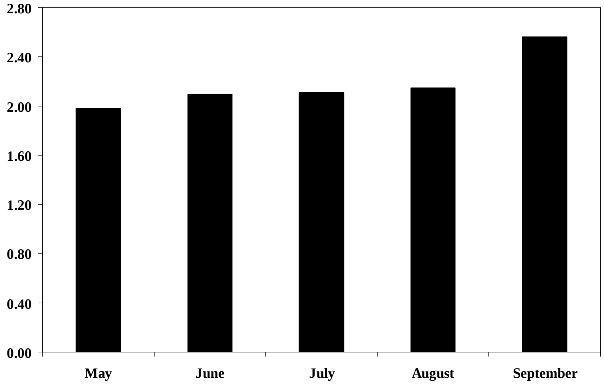

Figure 1. Monthly values of relative water supply (RWS) for PVID.

Overall Consumed Ratio (e_p): Overall consumed ratio is reversely proportional to RWS. As expected, this indicator showed decrease with the time, from 0.50 in May to 0.39 in September. The average e_p for the entire period of study was 0.46 with the CV of 0.09, which is a sign of low temporal variability of this performance indicator. The maximum e_p of 0.50 implies that even under an optimal agricultural condition, PVID crops will not be able to use more than 50 percent of diverted water. In other words, diversion of water is about two times larger than maximum crops water requirements. Hutson et al. (2004) mentioned that the risk of over-irrigating is greater in the arid West and the Mountain States, where surface irrigation is predominant and application rates are greatest. However, it is hard to conclude that PVID crops are over-irrigated, because part of diverted water spills back to the river at the end of canals. In addition, extra water is required to account for losses and leaching.

The range of 0.60 to 1.10 was considered as the benchmark for Nilo Coelho Scheme, and the average e_p (0.78) showed that irrigation managers have supplied adequate water to the crops (Bastiaanssen et al., 2001). In their study, Karatas et al. multiplied conveyance and application efficiencies of Lower Gediz Basin and defined 0.51 as the target value for e_p. The main crops of Lower Gediz Basin are cotton and grapes with some maize, vegetable, and fruits. In addition, the dominant irrigation system is furrows and borders, so this irrigation scheme is more comparable with PVID than Nilo Coelho. The researchers estimated an average e_p of 1.01, which indicates an overall under-irrigation in this case (Karatas et al., 2009). Figure 2 shows the estimated monthly e_p for Palo Verde irrigation district.

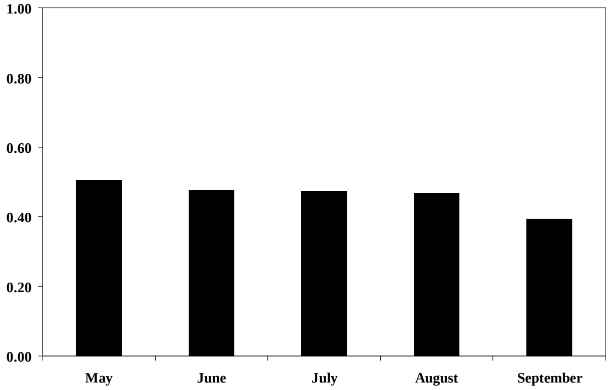

Figure 2. Monthly values of overall consumed ratio (e_p) for PVID.

Depleted Fraction (DF): Figure 3 presents the monthly variation in depleted fraction. Low temporal variation in DF can be seen in this figure, and a CV of 0.10 also confirms that. DF, in general, follows a pattern very similar to that of e_p. This is not surprising, since the main difference between these two indicators is the use of ET_a instead of ET_p as crop water demand in DF equation. ET_a can never exceed ET_p, so the values of DF are always lower than e_p values. The DF ranged from 0.37 in May to 0.28 in September, with the total average of 0.34. This is about half of the average DF estimated for Gediz basin, which was 0.69 (Karatas et al., 2009). However, it should be noticed that for Gediz basin, DF was highly variable among different months and different sub-basins (ranging from 0.28 to 3.79), so the estimated average may not be an appropriate statistical summary for comparison with DF values of PVID. Bastiaanssen et al. reported 0.61 as the average DF for pressurized irrigation system of Nilo Coelho scheme in Brazil (Bastiaanssen et al., 2001).

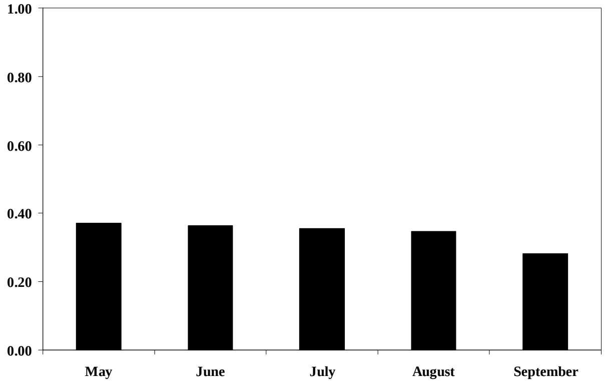

Figure 3. Monthly values of depleted fraction (DF) for PVID.

Crop Water Deficit (CWD): As it was mentioned before, CWD was estimated on a pixel by pixel basis and then it was averaged over every field in PVID. Figure 4 represents box plots of field's mean CWD for every month of the study. Ideally, irrigation managers want CWD to be as small as possible, unless deficit irrigation is selected as common irrigation practice. Studies carried out over Nilo Coelho and Gediz Basin show an average CWD of 30.30 and 41.50, respectively. Compared to these numbers, an average of 53.16 mm for PVID is not very high. The lowest CWD was 43.67 mm, belonging to the month of September. However, the decrease of CWD in September cannot be attributed to any improvement in water management or eliminating growth-limiting factors, but it is simply a result of lowered ET-deriving atmospheric parameters and biophysical changes of the crops (especially cotton) during final periods of growth. The temporal coefficient of variation was 0.12, which implies a low variability, but the mean spatial CV was higher (0.43), which is very close to the CV of 0.45, estimated for Nilo Coelho (Bastiaanssen et al., 2001).

The maximum observed CWD (60.31) is equal to about 2 mm/day difference between ET_a and ET_p. This difference could be due to the existence of stress factors such as elevated levels of soil salinity or inappropriate practice of irrigation (amount or timing). Some unofficial studies done in mid 1970’s revealed that the water discharged from PVID back to the Colorado River (drains and canal spills) is about half in volume and twice in salt concentration of diverted water. So the system is approximately salt balanced (Henning, 2009). The fact that the overall average of DF is 0.34 implies that the system is still successful in removing introduced salts. Therefore, salinity does not seem to be affecting crop growth, unless the initial salt level of the PVID soils was high, but this will not be clear without looking at the results of a thorough soil analysis. However, it should be noticed that a CWD of less than 2.00 mm/day is not really concerning. In addition, the median (47.95) may be a better representative than the mean, because the data distribution is skewed and median is more resilient to skewness and outliers. The maximum median CWD is about 1.8 mm/day.

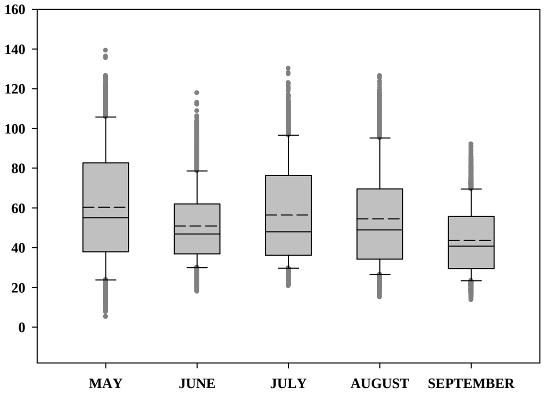

Figure 4. Monthly values of crop water deficit (CWD) in mm for PVID fields.

<u>Relative Evapotranspiration (RET):</u> With the temporal CV of 0.02, RET is the most uniform indicator over study period. Spatial variation of RET over PVID fields was about 0.26, which is two times the CV of RET over Nilo Coelho (Bastiaanssen et al., 2001). It should be noticed that the irrigated area of Nilo Coelho scheme is less than half of PVID in size, and achieving a uniform spatial distribution is more difficult as the area expands. In addition, water is applied through pressurized systems, which gives farmers more flexibility in meeting crop’s water demands. The average RET was 0.70 for all PVID

fields over all five months. As mentioned before, the median (0.76) is statistically a better representative of the RET, due to the skewness of data distribution. In general, both numerical summaries indicate that on average, PVID crops transpire more than 70 percent of their potential. The results of other studies are highly comparable with our findings. Bastiaanssen et al. reported 0.76 as the mean RET for Nilo Coelho (Bastiaanssen et al., 2001). The value was 0.70 for Gediz basin with surface irrigation system (Karatas et al., 2009). Figure 5 illustrates box plots of monthly values of RET.

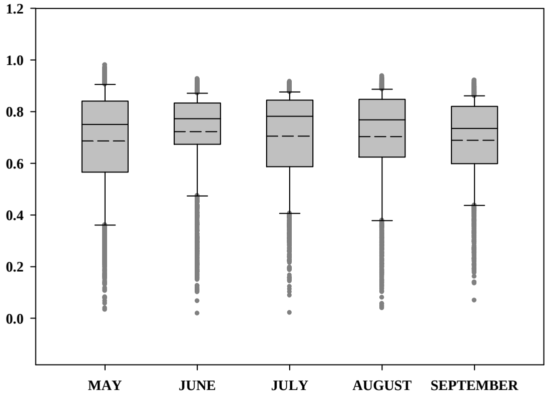

Figure 5. Monthly values of relative ET (RET) for PVID fields.

CONCLUSION

Different remote sensing-based performance indicators were studied over Palo Verde irrigation district in southern California. The relative water supply, an appropriate indicator for addressing irrigation water sufficiency, showed an average of 2.18 for the period of study (May to September). Since the surface irrigation method is widely practiced in PVID and only less than a quarter of the district's canals are lined, a value of more than 2 does not seem unrealistically high for PVID. However, irrigation managers may not be interested in reducing diversions. The main reason behind this lack of interest is financial issues. PVID farmers pay about US$ 55.00 per acre-feet, to cover operation and maintenance expenses. This fee is applicable just to the water they beneficially use, because the water that is not used goes back to river through canal spills. Therefore, a more accurate control on water diversion, which requires more staff and higher fees, is not really supported. The overall consumed ratio with an average of 0.46 also implies that demanded amount of water is most probably supplied. However, a target e_p should be defined before making any judgment about sufficiency of water diversion. Identifying such a target value is not possible without quantifying the efficiencies of irrigation sub-sections (conveyance, application, etc.), something which is not known for PVID. Average depleted fraction was 0.34, about 74 percent of mean overall consumed ratio. Mean and median RET of all fields in PVID were 0.70 and 0.76, confirming the observed difference between e_p and DF. These values indicate that PVID crops' evapotranspiration is more than 70 percent of their potential. Mean crop water deficit was 53.16 mm/month, or about 1.77 mm/day. Based on these indicators, it can be concluded that the overall performance of Palo Verde irrigation district is acceptable. Some of the indicators can be further improved by more accurately controlling water delivery, but the modifications are probably not economically viable.

REFERENCES

Ahmad M.D., Turral H., and Nazeer A. (2009) "Diagnosing irrigation performance and water productivity through satellite remote sensing and secondary data in a large irrigation system of Pakistan" Agricultural Water Management 96: 551 – 564.

Allen R.G., Pereira L.S., Raes D., and Smith M. (1998) "Crop evapotranspiration: Guidelines for computing crop requirements" Irrigation and Drainage Paper No. 56, FAO, Rome, Italy.

Ambast S.K., A.K. Keshari, and A.K. Gosain (2002) "Satellite remote sensing to support management of irrigation systems: concepts and approaches" Irrigation and Drainage 51: 25 – 39.

Anderson M.T. and Woosley Jr. L.H. (2005) "Water availability for the Western United States - Key scientific challenges" U.S. Geological Survey Circular 1261, 85 pp.

Bandara K.M.P.S. (2003) "Monitoring irrigation performance in Sri Lanka with high-frequency satellite measurement during the dry season" Agricultural Water Management 58: 159 – 170.

Bastiaanssen W.G.M. and Bos M.G. (1999) "Irrigation performance indicators based on remotely sensed data: a review of literature" Irrigation and Drainage Systems 13: 291–311.

Bastiaanssen W.G.M., Brito R.A.L., Bos M.G., Souza R.A., Cavalcanti E.B., and Bakker M.M. (2001) "Low cost satellite data for monthly irrigation performance monitoring: benchmarks from Nilo Coelho, Brazil" Irrigation and Drainage Systems 15: 53 – 79.

Bastiaanssen W.G.M., Menenti M., Feddes R.A., Holtslag A.A.M. (1998) "A remote sensing surface energy balance algorithm for land (SEBAL), Part 1. Formulation" Journal of Hydrology 212-213: 198–212.

Bastiaanssen W.G.M, Molden D.J., and Makin I.W. (2000) "Remote sensing for irrigated agriculture: examples from research and possible applications" Agricultural Water Management 46: 137 – 155.

Bastiaanssen W.G.M., Noordman E.J.M., Pelgrum H., Davids G., Thoreson B.P., and Allen R.G. (2005) "SEBAL model with remotely sensed data to improve water-resources management under actual field condition" Journal of Irrigation and Drainage Engineering 131 (1): 85 – 93.

Bos M.G. and Nugteren J. (1990) "On irrigation efficiencies" In: International Institute for Land Reclamation and Improvement (ILRI), ILRI Publication 19, Wageningen, The Netherlands, 138 pp.

Henning R. (2009) Personal Communication, May 19, 2009.

Hutson S.S., Barber N.L., Kenny J.F., Linsey K.S., Lumia D.S., and Maupin M.A. (2004) “Estimated use of water in the United States in 2000” Reston, VA., U.S. Geological Survey Circular 1268, 46 pp.

Israelsen, O.W. (1932) “Irrigation Principles and Practices” John Wiley and Sons, New York. 418 pp.

Karatas B.S., Akkuzu E., Unal H.B., Asik S., Avci M. (2009) “Using satellite remote sensing to assess irrigation performance in Water User Associations in the Lower Gediz Basin, Turkey” Agricultural Water Management 96: 982 – 990.

Molden D.J. (1997) “Accounting for water use and productivity” SWIM paper 1, International Water Management Institute (IWMI), Colombo, Sri Lanka: 16 pp.

Moran M.S., Inoue Y., and Barnes E.M. (1997) “Opportunities and limitations for image-based remote sensing in precision crop management” Remote Sensing of Environment 61:319 – 346.

Perry C.J. (1996) “Quantification and Measurement of a Minimum Set of Indicators of the Performance of Irrigation Systems” International Irrigation Management Institute, Colombo, Sri Lanka.

Perry C.J. (2007) “Efficient irrigation; inefficient communication; flawed recommendations” Irrigation and Drainage 56: 367 – 378.

Priestley C.H.B. and Taylor R.J. (1972) “On the assessment of surface flux and evapotranspiration using large-scale parameters” Monthly Weather Review 100 (2): 81 – 92.

Ramos J.G., Cratchley C.R., Kay J.A., Casterad M.A., Martinez-Cob A., Dominguez R. (2009) “Evaluation of satellite evapotranspiration estimates using ground-meteorological data available for the Flumen District into the Ebro Valley of N.E. Spain” Agricultural Water Management 96: 638 – 652.

Ray S.S., Dadhwal V.K., and Navalgund R.R. (2002) “Performance evaluation of an irrigation command area using remote sensing: a case study of Mahi command, Gujarat, India” Agricultural Water Management 56: 81 – 91.

Roerink G.J., Bastiaanssen W.G.M., Chambouleyron J., Menenti M. (1997) “Relating crop water consumption to irrigation water supply by remote sensing” Water Resources Management 11 (6): 445–465.

Walter I.A., Allen R.G., Elliott R., Jensen M.E., Itenfisu D., Mecham B., Howell T.A., Snyder R., Brown P., Eching S., Spofford T., Hattendorf M., Cuenca R.H., Wright J.L., and Martin D. (2000) "ASCE's Standardized Reference Evapotranspiration Equation" Proc. of the Watershed Management 2000 Conference, June 2000, Ft. Collins, CO, American Society of Civil Engineers, St. Joseph, MI.