Distributed Water Demand Computation Using Remote Sensing Techniques

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ABSTRACT

The Arenal-Tempisque irrigation district is located in the lower part of the Tempisque and Bebedero basins. It is the major irrigation project of Costa Rica (59960 ha) and is divided into eight sub-districts. It has extensive agricultural activity (sugarcane, rice, watermelon and tilapia) with a high water consumption. Systematization of information is a priority issue to increase water distribution efficiency and enhance decision making during the dry season. An example has been developed in Cañas sub-district to analyze various hydro-geospatial variables related to water demand in order to determine the water status of the region for January, February and March, corresponding to the driest months in Guanacaste. Using GIS and remote sensing techniques, it was possible to obtain distributed water balance and water demand on farms, taking into account precipitation, temperature, evapotranspiration and runoff. Normalized difference vegetation index (NDVI) was calculated using information extracted from LANDSAT 8 satellite images available for the study area. These were used to evaluate kc and evapotranspiration to a resolution of 30 meters. Distributed runoff was computed with the SCS method. The curve number was obtained from impermeable, vegetation and soil proportions using LandSat images and the lineal spectrum unmixing technique for the separation. Results showed a total water deficit of 416.53 L/m2 with a standard deviation (SD) of 157.64 L/m2 during the 3 dry months.

Keywords: Geographic information systems, Water resources, Water balance, Water demand, Irrigation, Linear spectral mixture analysis, NDVI, Costa Rica.

1. INTRODUCTION

Irrigation is a way to solve the water shortages to which a crop is naturally subject, whether because of unsuitability to the particular zone or deficits in precipitation. Another important reason to irrigate is to increase productivity. In several cases a crop cannot be grown year-round, so watering can help in some way to circumvent the effect of climate on the viability of agriculture (James, 1988). However, in some places the hydric resource is already scarce, so even this practice becomes impossible at a certain point.

One evident case of shortage of water resources for irrigation is that of the province of Guanacaste, Costa Rica, located in the Northern Pacific region of the country. Due to recurring water shortages, an initiative to run an irrigation project in Guanacaste was conceived in the 1950s, though the first investigations and feasibility studies were not conducted until 1995 by the Inter-American Institute of Agricultural Sciences of the Bureau of Reclamation of the United States. Nevertheless, in the 1970s, with the financing and construction of the Arenal

Hydroelectric Project that the Arenal-Tempisque Irrigation District Project (DRAT, in Spanish) the idea got a decisive boost, when it was first considered that the residual waters from the power generators could be used to irrigate the lower parts of the watershed to enhance agricultural productivity (Villalta, 1994; Zúñiga, 1993).

Currently water diverted to the Pacific from the Arenal watershed is initially used in power generation through a series of hydroelectric plants. The construction of the infrastructure - Arenal reservoir and drainage channels - has substantially increased the availability of hydric resources for irrigation in Guanacaste, especially in times of drought (Villalta, 1994). The existence of these volumes of liquid enables the transformation of a province with very high livestock exploitation into a potential farming region, as this area has a series of technical disadvantages - for example, a system of poorly distributed rainfall and frequent droughts - that have hindered its full development throughout history, having turned it into a zone of population emigration in the past (Morales, 2010).

The main uses that have been given to the land since the beginning of the first phase of the project are: rice (45.79%), sugarcane (30.2%), grass (12.19%), vegetables (0.4%), fruits (0.13%), aquaculture (0.17%) coconut (0.12%), investigation (5.18%) and others (5.82%). An economic study shows that the average annual income per hectare ascends to 85134,34 CRC, while the benefit-cost ratio is 1.46 (Zúñiga, 1993). This demonstrates that the project is able to generate wealth and increase the flow of capital in the province; all of this even without taking into account the possibility of industrial exploitation of the raw material.

2. MATERIALS AND METHODS

2.1 Description of Study Area

The irrigation district covers a total area of approximately 61.026 ha, which is divided into two sub-districts, namely: Arenal, with an area of 41.126 ha; and Zapandí, with 19.900 ha. This project was limited to sub-district Cañas - because of the size of the whole DRAT - and comprises a total of 6.006 ha. The latter is watered by the South Channel, which has a maximum capacity of 30 m^3/s (Zúñiga, 1993). The location of the area is shown in Figure 1; the elevation was determined using the ASTER satellite raster (ASTER GDEM is a product of METI and NASA), and it was noted that the slope is insignificant throughout the area. The soils are mainly of two types: In the northern part of the district there are Vertisols (Usterts suborder, typic haplusterts subgroup), with a very uniform silty-loam texture through 1.02 meters of depth - except for particularly high proportions of iron in the first 9 cm. Apparent density varies from 1.17 kg/L to 1.30 kg/L, and real density from 2.41 kg/L to 2.58 kg/L. In the rest of the district, the soils are Mollisols (Ustolls suborder, Fluventic Haplustolls subgroup) with a uniform sandy texture through 2 meters of depth - except for a sandy loam texture through the first 15 cm - apparent density that varies from 1.16 kg/L to 1.28 kg/L, and real density from 1.96 kg/L to 2.59 kg/L (Sandoval Chacón & Mata Chinchilla, 2014). Temperatures can vary from 22°C to 33°C during the year, with a mean value of 29°C. However, the period of interest (January to March) tends to be the driest during the year. The precipitation data used was obtained from the National Meteorological Institute (IMN, in Spanish), and due to a lack of direct information from Cañas, data available from Liberia and Nicoya stations (stations "La Ceiba" and "Daniel Oduber" respectively) were averaged. The cumulative average rainfall in the area for the months of study, according to these sources is 11.15 mm. Furthermore, the average temperature is 28.33 °C.

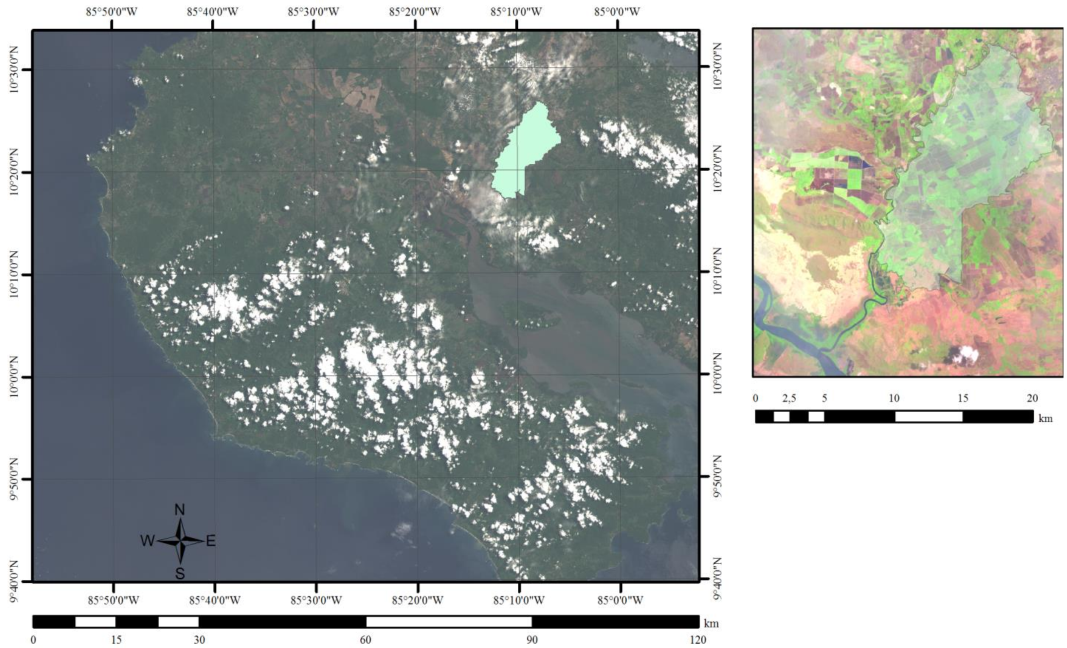

Figure 1. Location of study area. Left image is real color and right image is false color.

2.2 Soil Properties and Runoff.

Based on the work of the SCS (Soil Conservation Service) a curve number was associated with each soil and land use combination, and runoff was calculated. To obtain the CN, information from soil type, slope and land use is needed; then data is consulted on CN tables, like that published by Mockus (2004). Because the predominant soil type of the area is clay loam in the upper layers, the group to which it belongs in the SCS classification is "C" (Mockus, 2004). As no information on the hydrological condition of the farms is handled, an average between "poor" (CN = 84) and "good" (CN = 82) is used, which would return a value of curve number for the area of 83. Given that the distribution of rainfall in the area is not known, a rain event uniformly distributed over the 3 months, which would not allow the soil to return to an unsaturated condition, is assumed. However, Fan et al.,2013 propose to relate the proportions of vegetation, soil and waterproof to obtain curve numbers from factors proposed on their project. Then, based on that methodology, the number of curve can be calculated as follows:

$$CN_C = ISA * CN_{ISA} + V * CN_V + S * CN_S \qquad (1)$$

Where *ISA*, *V* and *S* are the proportions of impervious surface, vegetation and soil respectively, and due to the fact that they have to be normalized, the sum of *ISA*, *V* and *S* has to be 1.

To obtain the factors mentioned above, the statistical technique of linear spectrum mixture analysis was performed using the ENVI software to separate vegetation, soil and impervious subpixels - VIS model proposed originally by Ridd (1995). To achieve that, LANDSAT 8 satellite images of the three visible colors, in addition to near infrared, far infrared and shortwave were used. Principal components were computed using the program mentioned before and pixels were plotted on their respective PCs and representative endpoints of *ISA* (high albedo and low albedo), *V* and *S* were chosen (Fan et al., 2013). Endpoint analysis states that each value of a pixel on a set of bands can be represented by the sum of the product of every representative reflectance (endpoint) and its relative proportion of that particular endpoint. The mathematical representation of this analysis would be:

$$R_i = \sum R_{ik} f_k + ER \tag{2}$$

Where R_i is the value of the pixel, R_{ik} the value of the endmember, f_k the proportion of endmember in that pixel and ER an error. A different way to see it would be to compare the whole hyperspace of bands with the textural triangle; sand, silt and clay being the endmembers. Although this comparison would be a simplification of what the endmember analysis is, the PC computation helps to reduce the amount of dimensions of the hyperspace, simplifying the methodology while reducing the error to the minimum. Endmembers can be selected manually or by using different selection methods; for this particular case manual selection was performed. The rasters obtained through this methodology need to be normalized in order to apply equation 1. To achieve this, each image had to be divided by the sum of the three:

$$L_{N_a} = \frac{L_a}{\sum L_i} \tag{3}$$

Where: $L_{N,a}$: Normalized layer, C_a: Corresponding original layer, C_i: Each of *ISA*, V and S.

According to Fan et al., (2013), CN_{ISA} = 98, and for group "C" of soil CN_S = 91. Moreover, the value of CN_v varies depending on NDVI value (Equation 4) for each pixel, and the initial values as shown on Fan et al., (2013). As vegetation vigor is not known, mean values of each condition where used. After obtaining CN_c, runoff can be calculated using the SCS equation (5 and 6). Where Q is runoff (mm).

$$NDVI = {}^{NIR - VIS}/_{NIR + VIS} \tag{4}$$

$$Q = (I - 0.2S)^2/(I + 0.8S) \tag{5}$$

$$S = {}^{25400}/_{CN} - 254 \tag{6}$$

2.3 Evapotranspiration

First it is necessary to calculate potential evapotranspiration, for which the equation of Heargraves and Samani will be used (Samani, 2000):

$$ET_0 = 0.0135\,(T_{med} + 17.78)\,R_S \quad (7)$$

Where ET_0: potential evapotranspiration, T_{med}: average temperature (°C), R_S: Incident solar radiation. R_S will be calculated using the "Solar Radiation Area" tool of ArcGIS. This program returns values in W-h/m^2, so it is needed to apply a correction. Considering that 2.45 MJ/m^2 equals 1 mm, after some calculations it can be concluded that 1 W-h/m2 equals 0.00147 mm of evapotranspiration (Allen et al, 1998). Thus, knowing that T_{med} is 28.33 ° C:

$$ET_{0,mm} = 0.000913\,R_S \quad (8)$$

Crop coefficient can be estimated using the following relation according to Rocha et al, (2012):

$$k_C = 1.2246\,NDVI + 0.2203 \quad (9)$$

And then, from these results we obtain total evapotranspiration:

$$ET = ET_0 k_c \quad (10)$$

2.4 Water Deficit

A water balance will be computed considering precipitation, infiltration and evapotranspiration of crops. Hydric resource demand may be calculated through:

$$Deficit = ET + Q - Precipitation \quad (11)$$

Deep percolation will be considered null since precipitation during this period tends to be very low, and most soils are clays which tend to accumulate more water and have low conductivity. Actually, according to Sandoval Chacón & Mata Chinchilla (2014), the soil present on the southern part of Cañas stores up to 44.11%, whereas that on the northern part stores up to 61.16% when at field capacity. It is important to consider that this deficiency is not for the exact water consumption because it depends on irrigation management, so we might rather consider the need for crop irrigation as separate from actual water demand. The efficiency of each particular system in every farm has to be taken into account.

3. RESULTS AND DISCUSSION

3.1 Soil Propierties and Runoff

As a result of PC analysis and subpixel unmixing three images were obtained, corresponding to pure pixels of each vegetation, soil and impervious surfaces (low albedo). It was not possible to get high albedo because the amount of pixels corresponding to actual urban areas was not statistically significant enough for an endmember to be recognized manually. Cañas subdistrict is still rural and high albedo corresponds to concrete, while low albedo corresponds to water and shades (Weng, Hu, & Lu, 2008). Resulting rasters are shown on Figure 2 along with the result of runoff. As was probably expected, values for total runoff were very low due to a lack of proper precipitation, which was initially the reason for the construction of the DRAT. The highest value for the whole 3 month period is 0.61 mm inside the polygon. The arithmetical mean is 0.06 mm with a standard deviation of 0.15 mm.

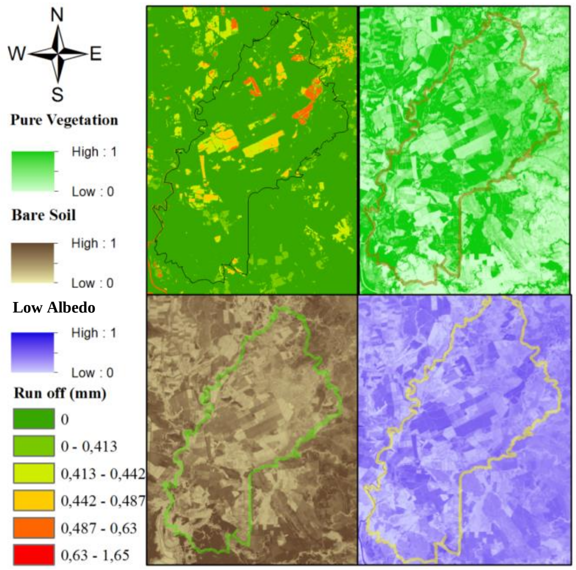

Figure 2. Resulting rasters from LMSA analysis. Image corresponds to total runoff and the ones below, from left to right, to pure vegetation, bare soil and low albedo, respectively.

3.2 Evapotranspiration

In Figure 3, it can be seen that both potential and actual evapotranspiration as crop coefficient vary. Results show that evapotranspiration ranges from 0 to 1.247 mm, but most values are below 672 mm for the three months. Even so, values corresponding to this depth are much greater than those obtained for runoff, so evapotranspiration practically defines water demand in Cañas. Actually, frequency distribution is almost the same as that for water demand. The arithmetical mean for ET during the study time (3 months) is 427.58 mm with a standard deviation of 157.65 mm.

3.3 Water Deficit.

Water deficit was obtained using equation 11, knowing that precipitation is 11.15 mm; then, a results table from pixel values on the raster was created. The whole image was analyzed and each value for water demand on every pixel was plotted on a histogram, as shown on Figure 4. Moreover, arithmetic mean value for all pixels on Cañas was 416.53 mm - or more practically 416,53 L/m^2 - with a standard deviation of 157.64 mm. Total polygon area ascended to 110.24 km^2, so total amount of water needed to supply water demand for three months is 45.92 hm^3, and the total flow needed is 17.11 m^3/s for the three months or an average of 5.91 m^3/s for each month. According to the Irrigation and Drainage National Service (SENARA in Spanish) required water for January, February and March is 5.68 m^3/s, 6.73 m^3/s and 8.61 m^3/s respectively, for a mean value of 7 m^3/s (Servicio Nacional de Riego Aguas Subterraneas y Avenamiento, 2012). The amounts obtained by this entity are greater probably because they considered irrigation method and conduction efficiency, which is an important value to account for in superficial irrigation systems, mainly in Cañas.

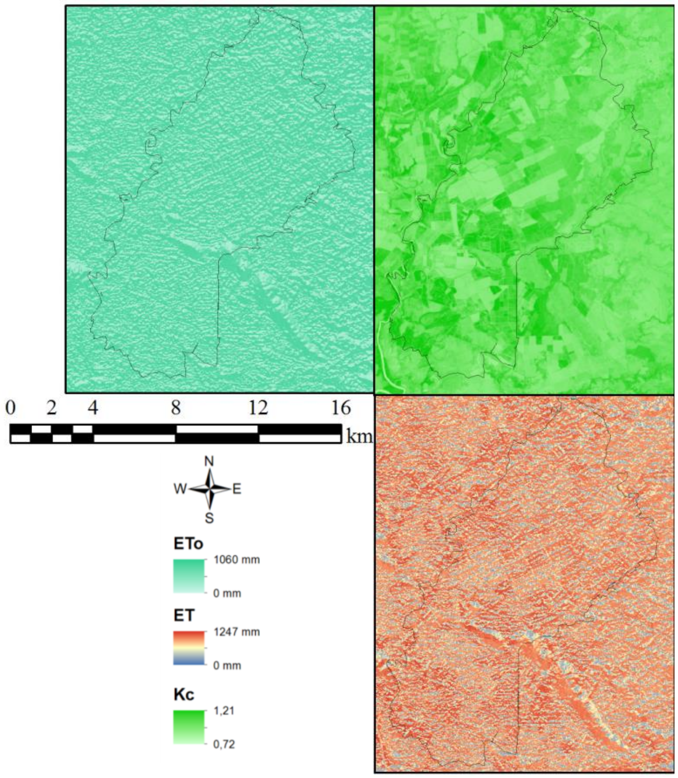

Figure 3. Results of evapotranspiration analysis. Potential evapotranspiration (Top left), crop coefficient (top right) and real evapotranspiration (bottom) (1:250000)

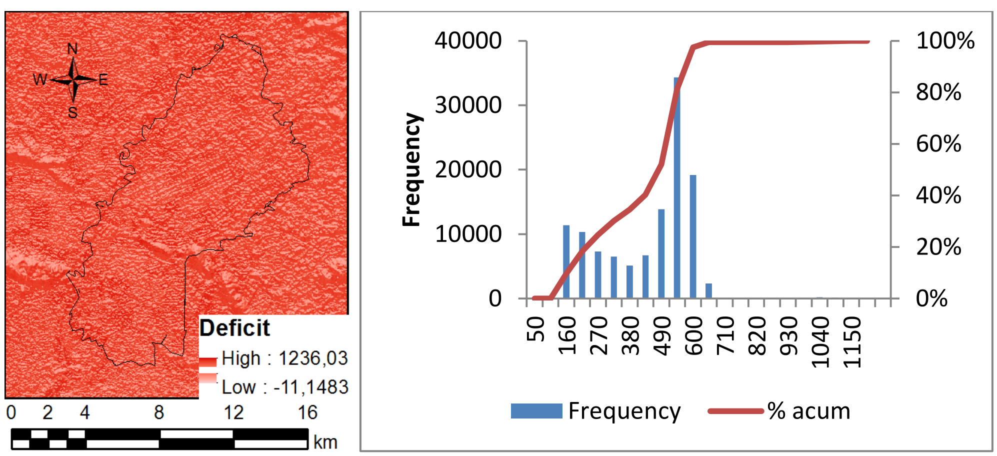

Figure 4. Water demand results. Left an image of the resulting raster, and right the corresponding histogram for water demand on each pixel.

4. CONCLUSIONS

Total hydric requirement for Cañas is 5.91 m^3/s for the three months, not accounting for irrigation efficiency methods and losses by conductions. Total runoff is 0.06 mm (standard deviation (SD) = 0.15 mm), evapotranspiration is 427.58 mm (SD = 157.65 mm), and water demand 416.53 mm (SD = 154.64 mm). V-I-S model using LMSA is applicable to Costa Rican dry regions, but should be validated on the rest of the country. Methodology proposed tended to underestimate actual water requirements due to the effect of efficiency of irrigation and conduction. This represents a difficult constraint to overcome using solely satellite imagery because it needs data obtained from the field, like leaks on the channel, or agricultural practices in every farm.

5. BIBLIOGRAPHY

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