WATER BALANCE OPTIMIZATION: CASE STUDY BY THE FAO PENMAN-MONTEITH MODEL IN APPLE TREE CULTIVATION (MALUS DOMESTICA BORKH) SUPPORTED BY WEB, BIO-BIO, CHILE

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ABSTRACT

This paper proposes a framework for water resource optimization by balanced use, where a case study by the FAO Penman-Monteith model is presented in the cultivation of apple fruit (*Malus Doméstica Borkh*) in a region of Chile called "Bio-Bio". A technological support by Web is proposed for water balance in calculating the evapotranspiration (evaporation and transpiration) as an important variable in an abundant irrigation activity. The results generate recommendations to Chilean authorities in agriculture about how to care for water in these times of water shortages for rational use.

KEYWORDS

Water Optimization, Productivity Increasing, Web Technology, Apple Fruit

1. INTRODUCTION

The amount of water that a crop needs through its different stages of vegetative development, a term that is expressed as use-consumption or evapotranspiration (Sanjay & Lakshman, 2020), is a fundamental antecedent in the determination of irrigation rates, in the irrigation planning both at property and regional level, in the design of method and structures of irrigation, distribution of water, etc. However, use-consumption values determined in one place have a limited extrapolation area because this factor is strongly influenced by the place climatic characteristics for a specific crop (Tosso, 1976). On the other hand, the use-consumption measurements require several years of experimentation so that they are representative, requiring, in addition, equipment and specialized personnel. According to Xiaojie (Xiaojie et al., 2019) and (Sanjay & Lakshman, 2020), it is possible to make estimates of evapotranspiration knowing the relationship between both parameters (use-consumption and evaporation) in the different stages of the crop vegetative development. This relationship is known as evapotranspiration K coefficient.

In this paper the water resource balance for the apple tree (*Malus Doméstica Borkh*) was made, the evapotranspiration was estimated manually and with support of computational program by Web technology through the Penman-Monteith model (Penman, 1948; Monteith, 1965; Sanjay & Lakshman, 2020).

Drought, desertification and degraded soil, 76% of the country's surface is affected by drought, desertification and degraded soil. This is 57.5 million hectares. There live 11.6 million inhabitants: 65% of the national population. 22% of the country's surface shows desertification signs to some degree, 80% show soil degradation signs and 72% of drought effects. That is the diagnosis with which Chile is updating its strategy and 2016-2030 national plan before the UN Convention to combat Desertification and Drought. The combined action of the three problems affects 76% of the national territory: 57.5 million hectares where 11.6 million people live (65% of the national population) (Schneider et al., 2007; BM, 2011; CONAMA, 2010).

The ozone layer destruction is the result of that according to what is estimated in 2009 in the country generated 16.9 million waste tons, of which 6.5 million corresponded to municipal waste and 10.4 million to industrial waste, excluding the massive mining waste (CONAMA, 2010).

Climate change has caused global warming, which in some areas is causing a great water shortage for people, as well as their own crops that are their main source of food.

In Chile there are few studies on the subject. Internationally, changes are expected in temperate and tropical zones that would negatively affect, for example, wheat (*Triticum vulgare* L.) and corn cultivations (*Zea Mays* L.)

Water resources management under scarce conditions is a complex challenge and it's of vital importance for the development of crops in Chile and in the rest of the world (Schneider et al., 2007; BM, 2011, MMA, 2011). For this reason it is extremely urgent to find and develop tools that better enable us to optimize the water resource used in crops. It is here that information technologies are a perfect formula for the crop efficiency and profitability. Where management and irrigation are the ones that make a crop obtain the best results through the use of data (meteorological, crop and ground). All these data must be managed by software that manages and provides relevant information for the optimum result of the crop.

The apple tree (*Malus domestica* Borkh) (Lobos and Yuri, 2006) is one of the first trees cultivated by man, tracing its domestication to the tenth century; Its center of origin is in Asia being introduced to Europe by the Romans and brought to America by the English in the seventeenth century. In Chile apple tree is the second fruit species in planted area, with about 37,000 ha mainly in the VI and VII region. Production is estimated at 700,000 tons, and exports at about 620,000 tons (Falvey and Garreaud, 2009). The apple tree for its cultivation needs certain climatic requirements (thermal, wind and evapotranspiration and crop coefficient), being the most important evapotranspiration since it must start the crop with an abundant irrigation activity that allows the roots to begin the new season.

Evapotranspiration (ET) is a main input of the framework to estimate water consumption of a crop. The most used methodology to estimate water resource consumption in a crop is the one recommended by Allen et al. (Allen et al., 1998), where ET is estimated as a function of actual evapotranspiration (ET_r) and a crop coefficient (k_c). ET_r is calculated using the Penman-Monteith equation (Penman, 1948; Monteith, 1965; Sanjay & Lakshman, 2020) which requires simultaneous measurements of temperature, humidity, wind speed and solar radiation. In this methodology there are errors associated with the values of the crop coefficient, since they cannot be used generically and require a greater calibration, (Simonne et al., 2010).

For this reason, a model of optimization of the water resource in technified irrigation crops for the Apple tree (*Malus Doméstica* Borkh) is proposed, using a systematic framework: Web technology and the mathematical model FAO Penman-Monteith (Tosso, 1986; Lobos and Yuri, 2006) in the Region of Bío-Bío Chile.

The paper presents a section of introduction, theoretical framework, proposal framework, results, conclusions and references.

2. THEORETICAL FRAMEWORK

The main meteorological factors that determine evapotranspiration are:

2.1 Evaporation

Evaporation is the process by which liquid water turns to water vapor (vaporization) and it's removed from the evaporating surface (vapor removal) (Allen et al., 1998; Zotarelli et al., 2010). Water evaporates from a variety of surfaces such as lakes, rivers, roads, soils and wet vegetation. To change the water molecules state from liquid to vapor requires energy. Direct solar radiation and, to a lesser extent, the ambient air temperature, provide this energy. The driving force to remove water vapor from an evaporating surface is the difference between the water vapor pressure at the evaporating surface and the water vapor pressure of the surrounding atmosphere. Therefore, radiation, air temperature, atmospheric humidity and wind speed are climatic parameters to be considered when evaluating the evaporation process (Zotarelli et al., 2010).

2.2 Transpiration

Transpiration consists of the vaporization of the liquid water contained in the tissues of the plant and its subsequent removal into the atmosphere (Zotarelli et al., 2010). Crops lose water predominantly through the stomata. These are small openings in the plant leaf through which gases and water vapor flow through the plant into the atmosphere. Water, along with some nutrients, is absorbed by the roots and transported through the plant. Vaporization occurs within the leaf, in the intercellular spaces and the exchange of vapor with the atmosphere is controlled by the stomatal opening. Almost all the water absorbed from the soil is lost by transpiration and only a small fraction becomes part of the plant tissues.

2.3 Evapotranspiration

Evaporation and transpiration occur simultaneously and there is no simple way to distinguish between these two processes. Apart from water availability in the surface horizons, the evaporation of a cultivated soil is mainly determined by the fraction of solar radiation that reaches the soil surface. This fraction decreases throughout the crop cycle as the crop canopy projects more and more shade over the soil (Zotarelli et al., 2010; Allen et al., 1998). In the early stages of cultivation, water is lost mainly by the soil direct evaporation, but with the development of the crop and, finally, when it completely covers the soil, transpiration becomes the main process.

2.4 Penman-Monteith Equation

Penman combined the energy balance with the mass transfer method and derived an equation to calculate the evaporation of an open surface of water from standard weather data for sun hours, temperature, atmospheric humidity and wind speed (Zotarelli et al., 2010). This method known as combined was subsequently developed by many researchers and extended to cultivated surfaces by means of the introduction of resistance factors. The nomenclature on resistance distinguishes between aerodynamic resistance and surface resistance. The surface resistance parameters are often combined in a single value, that of the total surface resistance that is combined in series with the aerodynamic drag. The surface resistance (r_s) describes the resistance to vapor flow through the stomata, the total leaf area and the soil surface. Aerodynamic drag (r_a) describes the resistance in the part immediately above the vegetation and includes the friction that the air undergoes when flowing on vegetative surfaces. Although the vegetation exchange process is too complex to be fully described by the two resistance factors mentioned above, good correlations are obtained between the measured and calculated evapotranspiration values, especially in the case of a uniform pasture surface (Zotarelli et al., 2010; Tosso, 1976; Penman, 1948; Monteith, 1965; Sanjay & Lakshman, 2020), equation 1,

$$ET_{sz} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s^0 - e_a)}{\Delta + \gamma(1 + C_d u_2)},$$

Where, ET_{sz} is standardized evapotranspiration in units over time $mm d^{-1}$ to 24 hrs of day or $mm h^{-1}$ during 1 hour. C_n is the crop type constant numerator. C_d is the constant denominator for the reference crop type. G is the density of the soil heat flux $MJ m^{-2} d^{-1}$. e_s is the saturation vapor (KPa). e_a is the current vapor pressure (KPa). R_n is the net radiation on the crop surface $MJ m^{-2} d^{-1}$. u_2 is the wind speed at 2 meters high, ms^{-1} . Δ is the slope of the vapor pressure curve, $kPa^{\circ}C^{-1}$. γ is the psychrometric constant, $kPa^{\circ}C^{-1}$. T is the air average temperature at 2 meters high, $^{\circ}C$.

3. DEVELOPMENT

3.1 Methodology

Iterative and incremental development is carried out (Sommerville, 2016), being the software base the most important, which is the calculation and estimation of variables with the model previously seen. Where it is contributed to the irrigation schedule, since it is intended to finish until the complete automation of a farm irrigation.

- Calculation of a crop evapotranspiration (Sanjay & Lakshman, 2020). This is the critical point. Although they have been investigated for years, some data and formulas are still experimental, but they are recognized by FAO (Zotarelli et al., 2010), so they have international scientific support. In addition, existing meteorological data should be used, and those calculated with moving averages
- Calculation of water volume to be applied by irrigation. At this point the crop and soil variables must be used. It is also essential that the values are correct, because with this point is delivered how much water needs the crop to not lose water by applying it unnecessarily, or to apply less water and pass the crop by water stress.
- Calculation of water scheduling to be applied by irrigation. This step is the one that generates the dates to apply the irrigation, delivering the optimal point of water application.

3.2 Design and Coding

In the case of design and coding, the following stages must be followed in software development:

3.2.1 System Requirements

Within the system functional requirements (Sepúlveda et al., 2015), there is the generation of an irrigation calendar, in which it gives the date of the next irrigations and the amount of water to be applied to the required crop with the use of climatic variables, soil and type of technical irrigation. Also within the non-functional requirements, is to facilitate the entry of data, in relation to the locality to be evaluated, the type of technified soil and irrigation, so that an untrained user can use the system functions without complications. For hardware requirements, this system must be deployed on a low-fault-tolerant infrastructure and with the minimum requirements for the use of a web server and database.

3.2.2 Use-Case Diagram

The following is the use case diagram (Figure 1), which analyzes the behavior and interaction of the user with the system.

Figure 1. Use case diagram

Description:

- Select Commune: The commune is selected to obtain weather data.
- Select Crop: The crop to be irrigated is selected.
- Type of soil: The soil type is selected to obtain estimated data of the soil physical conditions.
- Select type of irrigation: The type of irrigation is selected to obtain estimated data of the irrigation water efficiency.
- Generate schedule: daily weather data are entered.

3.2.3 Flowchart

This provides a visual description of the activities involved in a process, showing the sequential relationship between them and facilitating a quick understanding of each activity and its relationship with others. The flow diagram of the irrigation scheduling system (Figure 2) is presented below.

Figure 2. System Flowchart

Figure 3. System Sequence Diagram

3.2.4 Sequence Diagram

A sequence diagram shows an interaction, which represents the sequence of messages between instances of classes, components, subsystems, or actors. The following diagram analyzes the interaction that occurs between the user, the system and the database (Figure 3).

3.2.5 Design and Data Model

The development of the system has data from the Meteorological Station of the Agriculture and Forestry High School “El Huertón” from Los Ángeles city of Bio-Bio Region in Chile, which since January 1, 2002 have stored the data obtained daily. From the beginning they have the following data: date, 9 o'clock temperature, 21 o'clock temperature, minimum daily temperature, maximum daily temperature, cold hours, rainfall, sunshine hours, minimum relative humidity, maximum relative humidity.

Since February 6, 2003, the evaporation value of the tray has been used, which is a necessary value for the calculation of the crop evapotranspiration.

The variables of temperature, precipitation and radiation are the critical variables to work with. This is mainly due to that field to field; city to city; region to region are changing, and in some cases are significant figures, so having the most real data to the area where the schedule is intended helps to generate accurate and reliable information.

In the following database model (Figure 4) the data mentioned above are presented as data for each culture. It also takes into account the communes and regions of Chile and the the soil physical and chemical characteristics.

Figure 4. Database Model

3.2.6 Web System

The dialog structure diagram represents the windows and dialogs that the end user needs to complete all the tasks, and the necessary selections to move from one window to another. In the case of the web system would be as shown in figure 5.

Figure 5. Web portal Diagram

4. RESULTS

The FAO Penman-Monteith equation that models evapotranspiration is more accurate to measure the water balance of a crop which gives us more accurate data. Calculations made with the water amount to be added to crops were consistent with the reality of traditional crops in Los Angeles city, Chile. We compared the risk data of a real plantation of Apple tree (*Malus Doméstica* Borkh) of 2014, in addition to the differences of irrigation obtained by the developed web system with the real data calculated by agronomists in the same way but with monthly averages and in a traditional way are very low, arriving at 10 days of differences between irrigations.

Figure 6 shows the comparison of the water resources applied in cubic meters calculated manually and with the software (web system). Observing the curves it is clear that manual calculation gives an irrigation every 5 days, which leads to the use of 28,000 cubic meters of water to the crop, instead the web system delivers a wide difference of days, applying four irrigations per month, being 19800 cubic meters of applied water. Saving 30% of water per month.

Without the help of soil samples at the moment of irrigation, it would not be possible to know exactly which of the two methods has a greater efficiency in the irrigation scheduling of the apple tree. With the help of agronomist engineers there is an instance of conducting studies in the experimental field and testing in situ the veracity of the data made using the water amount and the periodicity delivered by the web system. In order to complete the only data needed to perform a crop irrigation schedule are: soil type, drip irrigation and a watering threshold.

Figure 6. Comparison of irrigation manually and with the web system

5. CONCLUSIONS

The use of the web system in which the agricultural irrigation scheduling can be generated using real data, mainly favors the use of resources in an optimal way, such as irrigation, water, nutritional and human equipment.

The obtained results cannot be compared to irrigations carried out in a crop with manual calculations and monthly, unless experiments be carried out, since soil samples must be taken at the moment of irrigation, to know if it is necessary to do so or if the values delivered are far from reality.

There are few projects of this type in Chile, which contradicts the messages of the authorities, such that water must be care for in these times of water scarcity, since agriculture is where the waste of this vital resource is mostly produced (MMA, 2011), therefore, it is necessary to take advantage of the social interest in the area of care of water resources and to present a tool that is an aid to the farmer, in addition to the use of qualified personnel that show users the potential that the framework has for them to choose according to their growing needs.

The research centered on proof of concept and with the knowledge provided by computer engineering and agronomics, generates a tool, which at a first stage wants to reach all farmers to improve their way of irrigation, giving you fast, timely and accurate information, in addition, will be a teaching tool for future agricultural technicians of the country.

Dealing with computer technology today as support system allow the technicality scale traceability of measuring behavior of using water as the apple tree plantations.

ACKNOWLEDGEMENT

In the process of making this paper, I would like to thank the support from Vice-Rectorcy for Research and Postgraduate of the Catholic University of Temuco, by the project 2019EM-ML-08.

REFERENCES

- Allen, R.G., L.S.Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and Drainage Paper No. 56, Food and Agriculture Organization of the United Nations, Rome, Italy.
- BM, Banco Mundial. (2011). Diagnóstico de la gestión de los recursos hídricos. Departamento de Medio Ambiente y Desarrollo Sostenible Región para América Latina y el Caribe.

- CONAMA: Comisión Nacional del Medio Ambiente, 2010. Primer reporte sobre manejo de residuos sólidos en Chile. Santiago, Chile: CONAMA.
- Falvey, M. and Garreaud, R., 2009. Regional cooling in a warming world: Recent temperature trends in the southeast Pacific and along the west coast of subtropical South America (1979-2006). *Journal Geophysical Research*, 114. doi:10.1029/2008JD010519.
- Ian Sommerville Ian: *IEEE Software and Professional Development*. *IEEE Software* 33(2): 90-92 (2016).
- Lobos, G. A. and Yuri, J. A. (2006). Flower induction and differentiation of four Apple cultivars in Chile. *Agricultura Técnica (Chile)* 66(2): 141-150.
- MMA: Ministerio del Medio Ambiente, 2011. Catastro de sitios con presencia de dioxinas y furanos asociados al uso de pentaclorofenol en aserraderos fase II. Metodología de investigación confirmatoria y estimación preliminar de riesgos ambientales. Preparado por Ingeniería Alemana. Santiago: MMA.
- Monteith, J. L. 1965. Evaporation and Environment. In: *The state and movement of water in living organism*. 19th Symp. Soc. Exptl. Biol. P. 205-234.
- Penman, H. L. 1948. Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, Vol. 193, No. 1032, p. 120-145.
- Sanjay Shekar N C & Lakshman Nandagiri (2020) A Penman-Monteith evapotranspiration model with bulk surface conductance derived from remotely sensed spatial contextual information, *International Journal of Remote Sensing*, 41:4, 1486-1511.
- Schneider S. H. et al. (2007). Assessing key vulnerabilities and the risk from climate change. Contribution of working group II to the Fourth Assessment Report (AR4) of the IPCC. <http://www.ipcc.ch/publicationsanddata/>.
- Sepúlveda S., Cravero A., Bustamante M. Identification of non-functional requirements for electronic voting systems: a systematic mapping. *IEEE Latin America Transactions*, vol.13, 1577-1583, 2015.
- Simonne, E.H., M.D. Dukes, and L. Zotarelli. 2010. "Principles and Practices of Irrigation Management for Vegetables," p. 17-26, In: S. M. Olson and E. Simonne. eds. *Vegetable Production Handbook for Florida 2010-2011*. IFAS, Gainesville, FL.
- Tosso J. and Torres Juan. (1986). Plant - water relations in grapevines, under different irrigation levels, using drip, sprinkler and furrow irrigation. II. Effect on vegetative growth and production. *Agricultura Técnica (Chile)* 46(3): 283-289, Chile.
- Tosso, Juan. (1975). A new formula to determine evapotranspiration in Chile. *Agricultura Técnica, RESEARCH ARTICLES*, Volume 35, Issue 3, Pages 139-147, Chile.
- Tosso, Juan. (1976). Determination of Evapotranspiration and K Coefficients for Several Crops. *Agricultura Técnica (Chile)* 36(4): 151-155.
- Xiaojie Li, Shaozhong Kang, Jun Niu, Zailin Huo, Junzhou Liu, Improving the representation of stomatal responses to CO₂ within the Penman-Monteith model to better estimate evapotranspiration responses to climate change, *Journal of Hydrology*, Volume 572, 2019, Pages 692-705.
- Zotarelli L., Dukes M, Romero C., Migliaccio K., and Morgan K. (2010). Step by Step Calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method). Agricultural and Biological Engineering Department, UF/IFAS Extension. U.S.