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ADVANCED DECISION SUPPORT AND DATA ACQUISITION SYSTEMS FOR FIELD IRRIGATION MANAGEMENT: A REVIEW

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ABSTRACT

Field irrigation operations use an impressive amount of water, scarcity of which has forced growers to irrigate with less water or even with water of lower quality and has also contributed to the drive for more precise irrigation. Irrigation managers and stakeholders continuously face difficult challenges when managing interactions between natural (crops, climate etc) and man-made systems. The capacity of farmers as regards irrigation decisions is not only dependent on their knowledge but also on accurate climate, soil and plant data acquisition. Even though the knowledge of irrigation managers is quite varied, there is an overarching need for equal access by all to the scientific knowledge needed to make the best possible decisions. The concept of transferring an ever increasing body of scientific knowledge via Decision Support Systems remains attractive. The effectiveness of irrigation decision making can be improved by integrating DSS and advanced information/communication technology techniques. This review examines the advances in decision support and data acquisition systems for field irrigation management.

Keywords: Irrigation, Decision Support System, Data Acquisition, Wireless Sensor Networks.

1. INTRODUCTION

Agriculture is the largest single user of water in nearly every country. According to FAO (2002), nearly 40% of the world's food is produced by irrigated agriculture, which covers about 250 million hectares (corresponding to 17% of the total arable land). In the developing world, water allocated to irrigation is about (or exceeds) 70% of water resources (Balendonck et al., 2007) making agriculture the major competitor for domestic and industrial users. Even greenhouse operations use an impressive amount of water. One acre of growing space would require approximately 11,000-22,000 gallons of water per day (Robbins, 2015). However, major stresses are progressively being imposed on existing water resources around the world due to increasing global population, declining groundwater availability, decreasing water quality, increasing environmental regulations, rising recreational demands, and international and interstate agreements (Evans, 2013).

Irrigation is required to provide water to meet the crop growth and evapotranspiration (ET) requirements (Zhang et al., 2015). Irrigation water use efficiency (the ratio between applied water and crop yield) must be increased drastically to secure food production for future generations. Under the condition of limited water supply, higher benefits may be achieved by adopting suitable irrigation techniques (Sharma et al., 1993) and to produce more crops per drop, growers currently explore different irrigation techniques (Wavhal et al., 2014).

Irrigation requirements differ with locations, soil types, and cultural practices. Irrigation efficiency (the amount of water stored in the crop root zone compared to the amount of applied water) depends on the type of irrigation used and also on irrigation scheduling, which is the method used to determine the amount of water to be applied to a crop and the timing for application (Pardossi et al., 2009a). Precision management of irrigation is difficult with traditional systems widely used in developing countries such as sprinkler and surface, which are designed for uniform water and nutrient delivery, but ignores the reality that demand varies across fields and between individual plants (Wavhal et al., 2014). Most often, these traditional systems employ manual control and the farmers irrigate the land at regular intervals. This process sometimes consumes more water than is necessary or sometimes the water reaches the crops late.

In addition to the use of modern irrigation system that supply the needed water to the root zone of the crops, irrigation management requires comprehensive knowledge and multiple data, which are spatially distributed (Zhang et al., 2015). The design of an irrigation system suitable for varying water application spatially, based on a series of data inputs, can be complex because of the need to address and integrate constraints imposed by the field site, irrigation system capabilities, and producer management (Kranz, 2012). Majority of the farmers in developing countries are either illiterate or do not have the expertise or experience to acquire enough data to make accurate irrigation management decisions. The application of decision support systems (DSS) provides a new, efficient, holistic and robust approach for improved irrigation management. DSS offers a framework within which complex systems can be represented in a structured way, allowing them to be more easily understood and helping to draw out additional information and new insights (Cain et al., 2003)

A number of different definitions have emerged to describe a DSS. Druzdzel and Flynn (2002) defined it as an interactive computer-based system that aid users in judgment and choice activities. Patil and Kulkarni (2014) defined it as a computer program application that analyzes data and presents it so that users can make decisions more easily. Tripathi (2006) defined DSS as an interactive computer based information system with an organized collection of models, people, procedures, software, databases, telecommunication, and devices, which helps decision makers to solve unstructured or semi-structured problems. From the definitions above, the term DSS can be considered to be quite broad because the concept of DSS varies depending on the author’s viewpoint. However, the main objective of DSS is to support and improve decision making (Taechatanasat and Armstrong, 2014).

A DSS application contains five components: database, model base, knowledge base, GUI, and user. The database stores the data, model and knowledge bases store the collections of models and knowledge, respectively, and the GUI allows the user to interact with the database, model base and knowledge base. A more detailed schematic view of DSS is show in Figure 1.

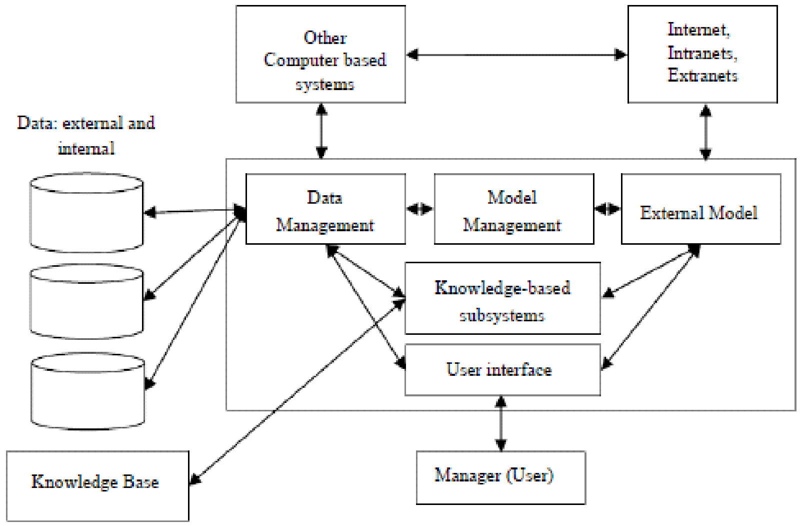

Figure 1 Schematic View a DSS (Tripathi, 2006)

DSS has been developed for waste water management (Patil and Kulkarni, 2014), identification of pests and diseases of crops (Ganesan, 2007), crop production management (Ponweera and Premaratne, 2011), food security (Wang and Chen, 2010), for farm water management in surface irrigation (Flores et al., 2010), insect management in commercial grain elevators (Flinna et al., 2007) and for large dam planning and operation (McCartney, 2007). In recent years, studies on the establishment of optimal irrigation methods and irrigation decision support system have obtained important achievements. DSS has proven to be a useful and widely applied tool for irrigation management. The main focus of this article is to explore the application of DSS for field irrigation management to include: DSS for irrigation management; advanced DSS; data acquisition systems and examples of DSS for field irrigation management.

2. IRRIGATION DSS

Decision support systems for irrigation management have been developed and utilized throughout the world to schedule water delivery on the basis of crop demand. The key point of irrigation decision includes: how thirsty the plant is and how much water should be applied. Based on cultivated crop, cropping system, the expected available water supply, weather conditions as well as crop development, DSS helps farmers to optimize their irrigation and fertilizer management on a day-to-day basis (Anastasiou et al., 2009).

Irrigation DSS incorporates a database of crops and “best practice irrigation strategies” as well as crop and ET models. Advisory modules that compute optimal irrigation and fertilization are also incorporated. Often times, a farm zoning and economic crop planning tool is added, which advises farmers on crops that yield largest gross margin under given constraints (Dominguez et al., 2008). The DSS may run either on the same local computer or on a remote host computer located at a service provider. Farmers may check irrigation system performance, crop status and water availability on a day-to-day basis. In addition, they can consult the DSS and, if needed, they may decide upon changing the irrigation scheduling strategy.

- **Architecture of Irrigation DSS**

The structure is divided into three parts (Figure. 2). The database system manages the database, which contains large number of data (such as temperature, humidity, user information, irrigation records, etc). All these data must be collected and analyzed to be useful in decision making, and available for users to retrieve at any point. The knowledge base system solves some uncertain problems. The knowledge base is classified into fact base and rule base. The inference engine draws a conclusion based on the fact and rule-based knowledge. The model base system, which includes simulation and optimization models, integrates several decision models, analyzes the internal and external data in database, and simulates the crop water requirements, to provide an irrigation decision schedule for users to choose.

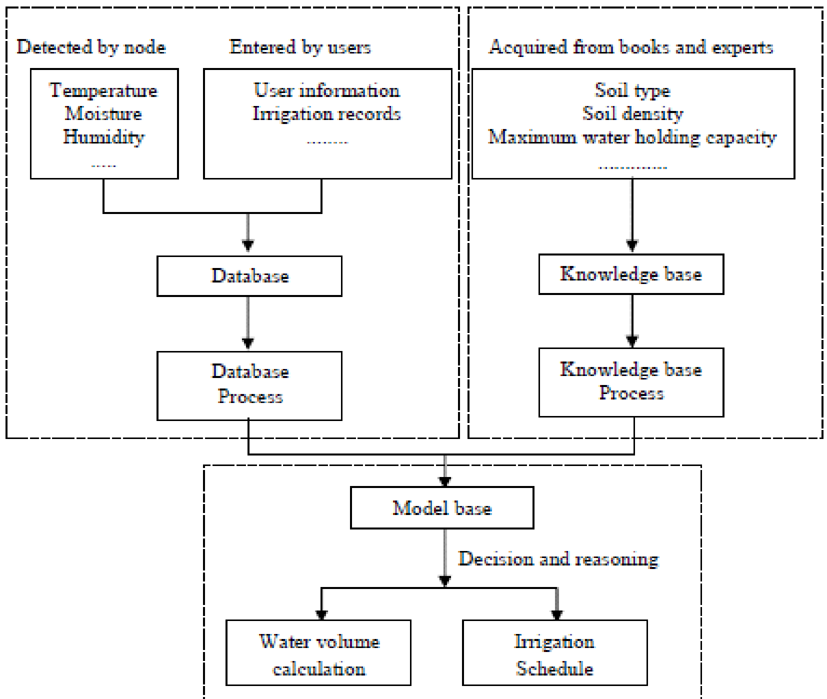

Figure 2 Architecture of Greenhouse Irrigation DSS

2.2 The Input Data

Input data include soil, climate and crop/plant data. The information about soil is usually chemical, physical, and hydrologic characteristics. For small scale applications, soil information is usually inputted manually by the user, while it is provided by regional/national database as informative layers in a geographic information system (GIS) embedded into the DSS in large-scale applications. To operate a DSS, daily information about the main climatic variables that influence crop growth and water balance is necessary. Climate data such as temperature, relative humidity, solar radiation directly affect plant growth. Each crop requires different level of temperature, relative humidity and solar radiation. The same crop at different crop growth stages requires different level of temperature, relative humidity and solar radiation. A variety of sensors are available for collection of climatic data. The DSS may also be linked to a local meteorological station that feeds it with climatic data. An important aspect is the link to a forecasting service that can broadcast weather for the next 3–10 days in order to better schedule irrigation. Examples of crop/plant data include crop growth, crop yield, stress, chlorophyll content, plant dry weight, flowering time, root biomass index etc.

2.3 The Simulation Model

Commonly, a DSS is a software package built around a model, making the model an important DSS component because ostensibly, it can predict, "What will happen if we do A instead of B?" Models used to simulate hydrologic systems are usually either mechanistic or empirical models. Calibrating these models is a process of fitting a line or surface (function) through data from two or more variables. The functions prescribed by mechanistic models are physical equations, which incorporate tunable coefficients that are adjusted by modelers to match calibration data. Linear regression is the most common empirical modeling technique. Irrigation DSS consists of crop growth simulation models for the estimation of daily biomass accumulation and crop evapotranspiration (ET), which are fundamental for the calculation of irrigation requirements. For example, Crop ET is usually calculated by means of the product, $ETc = ET_0*Kc$, where ET_0 is the reference evapotranspiration, as a function of climatic conditions, which can be estimated using different methods depending on the availability of climatic data. Crop coefficients (Kc) can be estimated by weighing lysimeters in research centers or estimated by RS images and normalized difference vegetation index (NDVI).

2.4 The User Interface

The graphical user interface (GUI) covers all aspects of communication between a user and a DSS application. The user interface interacts with the database, model base, and knowledge base. It allows the user to enter data or update data, run the chosen model, view the results of the model, and possibly re-run the application with different data and/or model combination. The user interface is perhaps the most important component of a DSS because much of the poser, flexibility, and ease of use of a DSS are derived from this component.

2.5 The Output Data

The DSS usually can provide a plenty of information, from a simple alert of when, how much and where to irrigate, to information about soil and plant water status, crop growth, soil water deficit, daily and seasonal water use and irrigation requirement, climatic report, and so on.

3. ADVANCED DECISION SUPPORT SYSTEMS

Real time management of field irrigation is very complex due to spatial and temporal interactions among physical and biological components, and thus renders most conventional approaches to irrigation management inapplicable to real-time management of irrigation systems. Advanced decision support systems integrate advanced computer modeling, sensor systems and advanced information technology techniques to optimally guide field irrigation strategies. Predictive modeling and data mining from a variety of distributed sensor systems, as well as geoinformatics and wireless communication have proved valuable. Integration of these advanced state-of-the-art approaches into the irrigation decision-making process has allowed for enhanced irrigation decision making. Some of these state-of-the-art approaches are briefly discussed below.

3.1 Artificial Neural Networks

Artificial neural networks (ANNs), a machine learning technique from Artificial Intelligence, are information processing systems whose structure and functionality are modeled after the nervous system, especially the brain of humans and other animals (Borgelt and Rudolf, 2006). ANN sub-models are used to systematically decorrelate input variables and predict individual signal components. The sub-models are then assembled into a super-model that represents an entire system. This produces predictive models that are customized to the unique circumstances and data of a particular system.

DSS based on ANN have at least two executions of the super-model. One generates predictions using actual historical input conditions, which are used to compute prediction errors and graphically depict accuracy. The second generates "What if?" predictions using user-defined controllable inputs. The advantage of artificial neural networks is that they frequently produce the best results with respect to accuracy compared to other methods (Borgelt and Rudolf, 2006). Conrads and Roehl (1999) found that ANN models had prediction errors that were significantly lower than those of state-of-the-practice mechanistic models. Other benefits of ANN models included short development time and fast execution that allows for numerical optimization, spreadsheet integration, and integration of ANN models with mechanistic models.

3.2 Geoinformatics

Remote sensing, Geographical Information System (GIS) and Global Positioning System (GPS) are rapidly becoming important in management of natural resources (Kumbhar and Singh, 2013). Spatial Decision Support System (SDSS) deals with spatial dimension through digitized Geo-referenced spatial databases. They can organize spatial and non spatial data by applying various models, algorithms and are very useful for agricultural planning, forecasts, early warnings and decision making (Narayana and Rao, 1995). For instance, soil information is most often provided by regional/national database as informative layers in a geographic information system (GIS) which can be coupled to a DSS.

3.3 Web Support Systems

Web Support Systems (WSSs) is a multidisciplinary field that focuses on supporting human activities in specific domains based on computer science, information technology, and web technology (Yao, 2008). Web services refer to s software system designed to facilitate machine-to-machine interactions over the internet (Car et. al., 2015). Research on WSS is motivated by the challenges and opportunities of the internet and the web. The architecture of WSS can be viewed as a client/server structure. The users, including decision makers and information seekers, are clients on the top layer. They access the system with browsers via the Web. The lower layers and components encapsulated by the oval dotted line are very similar to conventional computerized support systems. The World Wide Web provides a new medium for storing, presenting, gathering, sharing, processing, and using information. WSS uses the web as a new platform for the delivery of support. In other words, a Web-based support system can be viewed as a support system with the web and internet as the interface.

Many types of web-based irrigation decision support system have been developed (Flores et. al., 2010; Inman-Bamber et al., 2007; Goncalves et al., 2011; Anastasiou et al., 2009). Web based irrigation DSS are better placed to address some of the challenges facing DSS in agriculture today, particularly the poor uptake by allowing for greater flexibility in the way data is presented and information displayed (Car et. al., 2015)

3.4 Mobile Based DSS

The proliferation and convergence of wireless communication, location technologies, information systems, the internet and mobile devices has given rise to a new set of decision support utilities for mobile environment (MDSS) (Basole and Chao, 2004). It is now possible to receive and process a vast amount of real-time data and situational information on mobile devices in a manner that was not previously possible. One main benefit that mobile technology offers to decision support systems is the ability to retrieve real-time information anywhere, anytime, as decisions have to be made at specific times and locations. This is a measure of the effectiveness and usefulness of a DSS. MDSS has been proven to save time and increase productivity for those who need to make rapid decisions in real-time (Basole and Chao, 2004).

4. DATA ACQUISITION SYSTEMS

Precision and accuracy of information is not only related to ways in which data is acquired, but also related to the frequency of data collection (Malaverri & Medeiros, 2012). In agriculture, there are substantial numbers of methods for acquiring data for decision making. Data acquisition in agriculture can be summarized based on the following criteria (Chenghai et al., 2013; ICT International, 2013; Lopes et al., 2011; Pask, 2011; Primicerio et al., 2012): Location, method and tools. Location borders on whether data is collected in the field or for research trials. Method of data collection borders on whether the data is collected manually, automatically or an integration of the two. Tools are the instruments used for collecting data. This section will focus only on tools for data collection.

There are various tools for collecting data in agriculture which can be categorized into: specialized instruments, ICT tools and weather instruments. Examples of specialized instruments in agriculture include penetrometers, soil moisture probes, chlorophyll meters, tensiometer, near infrared (NIR) machines and normalized difference vegetation index (NDVI) meters. Example of ICT tools in agriculture are sensor networks technologies (Yin et al., 2013).

One technology that has encouraged smart agriculture is the Wireless Sensor Networks (WSNs). Wireless sensor networks are a new technology that promises fine grain monitoring in time and space, and at a lower cost, than is currently possible (Coates et al., 2008). Wireless networks refer to a standardized set of digital radio technologies that allow computers and other electronic devices to communicate and access each other and the internet without being physically connected via a cable, while a sensor network is a computer network composed of a large number of sensors. WSN emerged from advancements in the areas of micro-electro-mechanical system (MEMS) technology, wireless communication, and digital electronics. A WSN usually consists of tens to thousands of sensor nodes that communicate through wireless channels for information sharing and cooperative processing. Wireless Sensor Networks (WSN) plays an important role in data collection and transmission function.

WSN can operate in a wide range of environments and provide advantages in cost, size, power, flexibility and distributed intelligence, compared to wired ones. In a network, when a node cannot directly contact the base station, the message may be forwarded over multiple hops. By auto configuration set up, the network could continue to operate as nodes are moved, introduced or removed. WSN have similar architectures to general computers and can be divided into two main parts: hardware and software. The main hardware in a wireless sensor network is called the sensor node or mote. It consists of six components: micro-controller unit, memory modules, power supply component, input-output component, radio module and antenna.

Figure 5 A WET-sensor (Delta-T-Devices, UK) and a 5TE (Decagon, US) to measure water content, EC and temperature (left); a wireless sensor network (eKo,Crossbow, US) and irrigation controller (GP1, Delta-T Devices, UK) (Balendonck et. al., 2010).

There are a number of challenges and constraints in developing wireless sensor networks such as reducing energy consumption, self–management, design issues and security (Dargie & Poellabauer, 2010). Wireless sensor network has been developed to monitor and control system for greenhouses (Phuja, et al., 2013). Research by Paventhan et al., (2012) utilized sensor and wireless sensors for soil property monitoring. Both systems reported high quality of collected data.

5. EXAMPLES OF DSS APPLIED FOR FIELD IRRIGATION

FLOW-AID system (www.flow-aid.eu) (Anastasiou et al., 2009; Balendonck et. al., 2010). The system was developed through a close partnership between research institutes, universities and SME's; mainly funded by the European Union under the contract 036958 in the 6th Framework Project (Balendonck et. al., 2007). This market-ready precision irrigation management system consists of an array of irrigation controllers distributed over the farm zones to be irrigated (Figure 6). The system is scalable from one to many zones and consists of a data gathering tool that uploads agronomic data, from monitored crops around the world that have internet connectivity, to a central web DB, and a web based DSS that processes intelligently (Crop

Response Models, Nutrient Uptake Models, Water Uptake Models) the data of the crop and downloads to the irrigation and fertigation controller a command file containing water scheduling and nutrient supply guidelines. (Anastasiou et al., 2009)

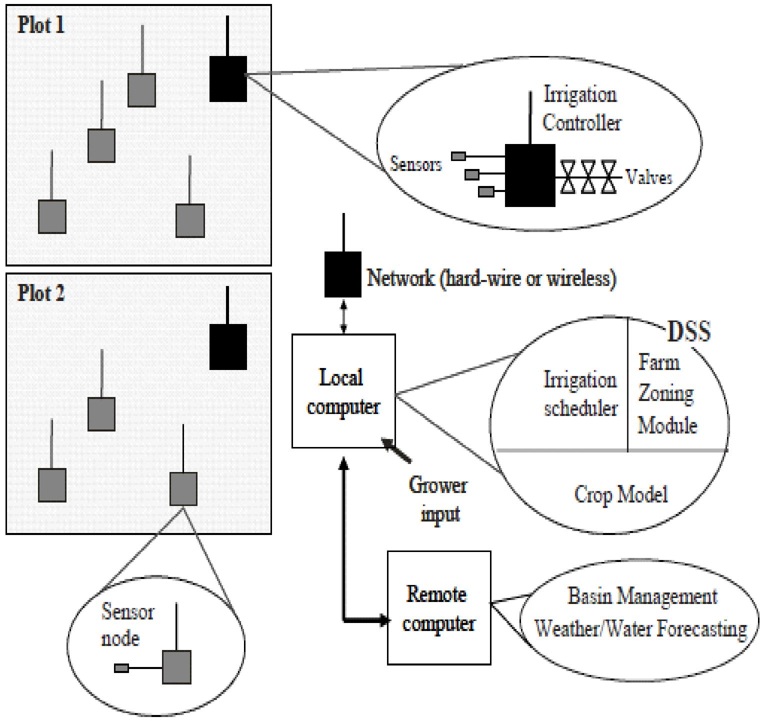

Figure 6 Schematic representation of the FLOW-AID system (Pardossi et al., 2009b)

The irrigation controller monitors in each farm plot all relevant weather and soil parameters such as soil moisture (available amount of water in soil), soil water matrix potential (extractability of water from soil by plant roots), soil temperature and electrical conductivity (water quality), and activates an irrigation or fertigation event through valves (Balendonck et. al., 2007). The controllers are connected via a wireless communication link to a local computer, which retrieves regularly the data from root zones and weather station, and updates the irrigation scheduling programs running autonomously in the controllers (Pardossi et al., 2009b). A DSS running on the local computer and partly on a remote computer (connected via the Internet) assists the grower in the optimization of the scheduler programs for the irrigation controllers on a long-term as well as on a short-term basis. The system can assist farmers with farm zoning by dividing the farm into zones and each zone into manageable plots which allows for proper planning with respect to long term (months or even years) expectation of the water availability in terms of amount, quality and timing. Further the irrigation scheduler optimizes the water scheduling for each plot, based upon the actual weather and available water on a short term basis (i.e. weekly or daily, in terms of amount and quality) and the crop plan.

CropIrri (Zhang and Feng, 2010) is a field crop irrigation management decision-making system designed for dryland crops (wheat, maize and soybean) to provide a practical decision tool for irrigation management. The flowchart of CropIrri is shown in figure 7.

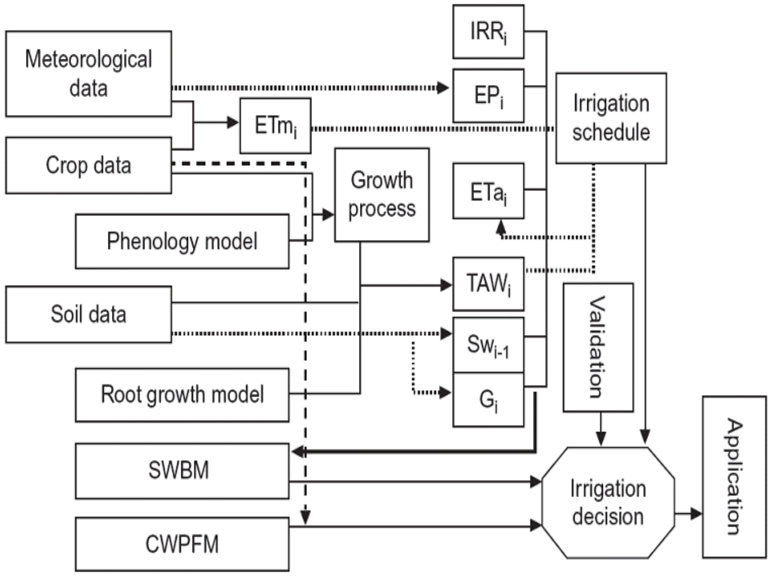

Figure 7 Irrigation flowchart of CropIrri (Zhang and Feng, 2010).

The irrigation plan is made by predicating of soil water content in root zone and daily crop water requirement using historical and forecasting weather data and measured real time soil moisture data. CropIrri has four decision modes for non-limiting irrigation, water-saving irrigation, irrigation with experience and user custom irrigation. The main functions include: 1) Irrigation decision services, evaluation of crop water requirements, and making of pre-sowing and real-time irrigation plans based on the historical weather data and weather forecast information. 2) To simulate daily change of soil moisture content in the root zone. 3) To evaluate a given irrigation schedule, and to develop optimal irrigation schedule in addition. 4) To modify the planned results according to the measured actual soil moisture content during crop growth period to enhance the forecasting accuracy. 5) Database management capability.

PVIDSS (Zhang et al., 2015) is a WSN-based Irrigation Decision Support System for Viticulture in Protected Area. PVIDSS is a decision support system for use in planning and scheduling of irrigation operations. The system can monitor the data, in combination with farm-specific information about fields, crops, and actual irrigation practices provided by irrigators, to estimate soil moisture conditions and to forecast irrigation schedules. The water requirements for individual fields are aggregated to estimate the potential command area water requirement, and then summed up to determine the potential irrigation system demand. A queuing system is used to allocate available water to command areas and fields. Irrigation decision and management module is the key component and is responsible for collecting field data and making irrigation decisions. This module consists of data collection module, which collect and stores data in the database using Crossbow's WSN suite transmitting based on ZigBee protocol and decision making module, which estimates the vine's water tension, calculate the irrigation water volume and schedules irrigation.

SIMIS (Scheme irrigation management information system) Mateos *et al*. (2002) is a DSS for managing irrigation schemes. SIMIS uses a coherent modeling approach based on the water balance, with two management modules (the first for water management and the second for financial management). The water management module in SIMIS deals with four key issues: crop water requirements, seasonal irrigation planning, water delivery scheduling, and recording water consumption, whereas the financial management deals with the incomes and costs viabilities. SIMIS also contain a geographic information system, giving the option to visualize geo-referenced information.

6. CONCLUSION

Limited water availability has become a great challenge for farmers. Scarce water should be applied with the highest possible efficiency, which means irrigation has to be precise. Irrigation management is the ultimate determinant of water use efficiency. The main objective of irrigation management is to control the irrigation dose or frequency such that the amount of water applied is enough and only enough to maintain the required root zone water content necessary for plant development. Farmers when faced with the complexity of optimal irrigation management need systems that will augment their own experience and judgment. Such systems should facilitate integrating and analyzing more extensive field data, analytical tools and other diverse information quickly and efficiently and make recommendations tailored to the specific circumstances of individual fields and farms. By making the best possible operational decisions, yields will increase, which will result to better income. New technology based on innovative tools can help farmers to meet the challenges of the future. DSS provides a means to effectively transform databases and models into information that is equally accessible to all stakeholders for informed decision-making. In spite of the large number of DSSs that have been developed and the substantial interest in reducing uncertainty in decision making, DSSs have contributed little to practical agriculture. There is need to raise the awareness of farmers as regards the potential benefits of employing DSS for irrigation management. Adoption of DSS will hinge on systems that fully engage individual producers in management decisions in order to adequately address their objectives, experiences, and constraints. Future perspectives of DSS evolution will be more about the compromise between simplicity of use and results reliability.

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