4. AI in soil and water management and irrigation

Soil and water management has a number of new challenges. Climate change has made the weather more unpredictable and, therefore, forecasting is becoming more difficult. Periods with storms and high rainfall alternate with dry periods. More crop stress, caused by higher temperatures or by excessive rain or floods, is to be expected. Heat resistant varieties are one of the options but intelligent long term (longer than one growing season) water management is another necessity. During summers with high temperatures, flooding and the submergence of crops during longer periods can be detrimental. At the same time, temperatures are higher and more droughts are expected; the crops need more water, either fed by rain or irrigation.

Challenges from a crop growth perspective are important, but the role of the agricultural land in groundwater recharge and flood reduction also needs to be optimised as an ecosystem service to society.

Using AI, we can combine real-time information from sensors, weather forecasts and crop soil modelling. In addition, spatial information from drones and satellites is accessible. In this way, climate adaptive management becomes feasible by taking into consideration the temporal and spatial variability of the soil and crop status in the field. It allows fast responses and reacts proactively to forecasts.

Finally, AI decision support should be a combination of real-time sensors feeding data and imagery into crop growth and soil water balance models for the most optimal decisions. In general, the local level focusses on the farm and crop productivity, while the water resources require a regional dimension at the level of entire river basins and aquifers.

4.1. Water budgeting at local or regional level

4.1.1. Real-time crop stress identification and prevention

A whole range of sensors can now be connected by the Internet of Things (IoT). Small solar panels and widespread internet coverage IoT has become feasible in the field, even at a distance from farmhouses and main power supplies. Although prices for the IoT are affordable, the sensors themselves are still expensive and in a dense network. AI needs to integrate this continuous stream of information into a decision support system.

There is a lot of tradition and experience with irrigation scheduling in many parts of Europe, especially in the South (e.g. Spain) (García et al., 2020). Planning irrigation applications is normally based on crop evapotranspiration (ET) estimations, rainfall measurements and soil water accounting, ideally updated by soil water sensing and weather forecasting. Farming tends to aim at the highest productivity, which often leads to supplying the average crop with more than the total water requirement. Large efficiency gains are possible. One cause is that the application of water has a degree of non-uniformity and, therefore, if the farmer wishes to give an adequate dose for the entire field, the farmer needs to over-irrigate most of the field. The higher the uniformity of an irrigation system, the less over-irrigation is needed. Crop water productivity (i.e. the amount of yield per volume of water consumed) is important. A shortage of water to about 70% to 80% of the water requirement (depending on several factors) often results in the highest crop productivity per unit of water. However convincing farmers to apply deficit irrigation, or less than 100%, remains an important challenge (Alcon et al., 2014).

The water for plant growth is taken up by the roots. The consequence is that the entire root zone needs to be considered and not just the top few centimetres. Also, the growth stage is very important. For example, pears in Belgium need careful irrigation depending on the growth stage (Janssens et al., 2011).

Measuring meteorological data by automatic weather stations connected to the internet is now reliable and low-cost. Measuring rainfall, temperature and humidity by low-cost internet-connected meteorological stations is highly reliable, provided the station is well installed and located. However, estimation of evapotranspiration (ET) by the recommended Penman Monteith method also requires proper wind-speed and radiation data. Low-cost sensors for the last two variables (wind and sunshine) are less reliable, and need to be calibrated and/or continuously cross-checked with nearby high-quality more costly stations or even research stations and advisory services. An AI-based management model should have proper data-assimilation procedures to integrate low cost meteorological stations and combine them with higher quality ones.

Soil water accounting models with rainfall and estimated crop evapotranspiration have already been used for some time. Adding AI can combine more sources of information, and check and update it by using real time soil water sensing. One particular challenge is the variability of the field in space and depth. Such sensors are to be placed in several places in the field at a minimum of two to, preferably, three depths. Therefore, a large number of low cost sensors could be preferred more than a low number of expensive but more accurate sensors. The 3D variability within the field can be captured in this way.

In agriculture, soil water monitoring (Evett et al., 2012) by in situ sensors can involve tensiometers, TDR, capacitance measurements or electrical conductivity. Measuring temperature within the same sensor is often carried out and allows a temperature correction.

The electrical conductivity-based sensors have the lowest cost and are easy to monitor. Commonly, an outer coating porous material is used around inside electrodes. The water content inside the porous material is in equilibrium with the soil water. The electrical conductivity between the electrodes relates well to the soil water content if the salt level in the soil is not too high.

Tensiometers provide some of the most useful measurements because they measure the water potential, which is directly related to the ease of water extraction by roots. However, tensiometers need continuous attention. Now, they can also be monitored digitally in real time and malfunctions can be identified quickly. The digital tensiometer also extends the measurement range to -150 kPa, which is almost double the range of the manual equivalent.

Time Domain Reflectometry (TDR) and Frequency Domain (FDR) sensors are quite expensive for economic agriculture. They use more sophisticated measurements of the dielectric constant of the soil. As the dielectric of water is much larger than the mineral or organic fraction and the air, this is a very precise method which, for most applications does not require calibration. Ideally, a sensor is not impacted by the salinity of the soil water; the higher the frequency, the less the impact.

The FDR can contain the electronics inside the sensor and the minimum cost is about 150 €. The TDR works at a higher frequency and is not so affected; it can even be used to simultaneously measure soil water content and electrical conductivity. Unfortunately, TDR measurements commonly require multiplexing of the connection to a specific TDR monitor. This makes it less practical for large fields and is the most costly method.

It is important to stress that remote sensing radar or microwave techniques only measure a shallow top layer of soil, to about 1 cm, and most methods depend on modelling of the deeper layers.

The low cost amateur sensors for use in gardens are also installed in the top layer and, in most cases, they do not measure the entire root zone. They are commonly based on electrical conductivity measurements, as explained earlier in this text. As already mentioned earlier, the roots take up water. So, the entire root zone should be measured.

Depending on the rooting depth of the crop, this means that the deepest sensors need to measure the water at 60 to 90 cm below the surface.

Monitoring the above ground crop status by remote sensing has more recently been developed. Stress can be detected by thermal and multi or hyperspectral imaging. Although these methods are very useful for remote sensing and research, when water stress is detected, it is often too late for irrigation scheduling. Remote sensing by drones or by satellites (with regular passing intervals) is useful, although NDVI methods still suffer from cloudiness, they are most useful to follow the biomass growth and detect differences in growth within the field. Most irrigation managers agree that sensing stress in the vegetation as a trigger for irrigation scheduling is often too late and not as reliable. However, remote sensing is still useful. A regular follow-up of the spatial distribution of biomass within a field is necessary information for precision crop management. It is important to identify the reasons for differences in biomass production. Although the harvest can often be related to the biomass, the harvest index (harvest per biomass) is not necessarily identical within a field.

Methods following the turgor in cells and/or the sap flow in orchard trees are very useful for research but less so in the practice of commercial farming.

Irrigation scheduling, along with soil water accounting in the entire root zone, benefits from real-time in situ measurements. AI is needed to assimilate the measured online data for correction of the root soil water balance and improving the scheduling accuracy. A combination of low-cost sensors and the spatial 3D root zone monitoring, together with vegetation monitoring, is needed.

A more efficient and rational water use for crop growth is possible by a combination of modelling, soil water sensing in the root zone, remote crop biomass monitoring and weather forecasting. Irrigation scheduling requires a good follow-up of the water in the root zone of the crop. All these data sources should be integrated into the AI approach.

4.1.2. Water supply monitoring

Flow data in irrigation pipes or canals can also be monitored in real-time by IoT because of solar panel powered internet connected sensors. This allows us to follow the quantity of water at any place in the irrigation system by wireless means. Typically, for pressurised irrigation there can be continuous detection of leaks and a very quick response. The volumes of water can be administered to the crop more precisely and accidental losses avoided.

Hydraulic structures should be installed on canals. The water levels are monitored by pressure transducers or by ultra-sonic sensors.). The latter is often preferred as it is without contact with the water. Currently, they are also low cost and easy to integrate to monitor continuously. In addition, as costs have been reduced, extra sensors can be installed downstream of the hydraulic structure, to control possible backwater effects and prevent faulty interpretations. A hydraulic structure always implies a (small) loss in hydraulic head.

Similar possibilities exist for pipes. Measuring the pressure drop along a Venturi allows monitoring of the discharge in a pipe. The small pressure drop occurs in the Venturi needs to be compensated by the pump, to obtain the required pressure and discharge for the irrigation system.

Propeller meters have traditionally been used for monitoring volumes of water. This is common practice, especially for water accounting of flow through pipes. Nowadays, they are also available with digital connections to the internet.

The transit time of an acoustic signal between two or more points in the pipe is more expensive. Such a measurement does not imply pressure loss and the need for a Venturi or an orifice restriction inside the pipe. Also, magnetic flow meters on flow pipes are possible.

In a similar way, either velocity radar sensors or acoustic dopplers can be installed on irrigation canals without the need for hydraulic structures and without loss of hydraulic head. The velocity radar sensor has the advantage of being non-contact, which is a major advantage for flow with a high sediment load.

While pressure transducers and ultra-sonic level sensors have become low cost (25 to 50€ for the sensor and approximately 100€ for the internet link), the acoustic dopplers cost at least 5000€ for one sensor. So, for a dense measurement network on pipes and canals at different levels within an irrigation system, the lower cost systems could be preferred. Precise and spatially detailed information from the irrigation system can be integrated in the management of the entire system using AI. Any malfunction and/or leak can be quickly alerted, in order to save water. Along with the real-time monitoring of flow valves and weirs, the irrigation system can be operated by IoT.

4.1.3. Reduction of water use by smart irrigation and smart micro-irrigation

In many countries in Europe, a flexible reel machine with a moving rain gun (Figure 4.1) is used. This is, however, a method requiring high pressure (energy costs are a linear function of the pressure for equal application rate) and suffers high wind-drift losses. Rain guns can be equipped with a solar-panelled GPS, pressure and spray-angle control connected to remote control over the internet. As an example, the rain gun can be stopped automatically or remotely if the wind becomes too strong.

Replacing the rain gun (Figure 4.1) by a spray boom (Figure 4.2) already allows for an important water saving, especially under windy conditions. In addition, the much lower pressure for a spray boom implies an important energy saving. The spray boom, which irrigates much more uniformly, also allows for monitoring of pressures and discharges within the system. A spray boom is, however, more expensive compared to a rain gun. If water and energy savings are not perceived as being important, farmers will not be eager to convert to the more efficient spray boom, which can also allow for differential and more precise irrigation within a field. As mentioned before, the more uniform the irrigation equipment is, the more water efficient it becomes.

Figure 4.1 Rain gun attached to a reel machine (not in the photo) (source Guido Wyseure)

Even more saving can be realised by drip-irrigation. This system supplies the root zone directly and avoids wind drift losses and soil evaporation. While a reel machine with a spray boom is highly flexible and can be used for different fields, a drip irrigation system is a permanent installation and, therefore, not as flexible. This poses more challenges for land cultivation and crop rotation. An additional advantage is that a drip irrigation system can be remotely controlled and pressures can be measured inside the system. As such, a high level of automation is possible, in conjunction with soil and water monitoring. Drip irrigation requires water quality control and allows for "fertigation". This means that a very precise, timely and more efficient demand for fertiliser is possible with less nutrient losses to the underlying aquifer. Sensing the pH and the EC of the irrigation water is important for proper functioning.

An AI system for the spray boom or the drip-irrigation that measures the water supply and combines this with the soil water monitoring, increases the efficiency and reduces excess water delivery. This should improve the management at the field, farm, and irrigation system level.

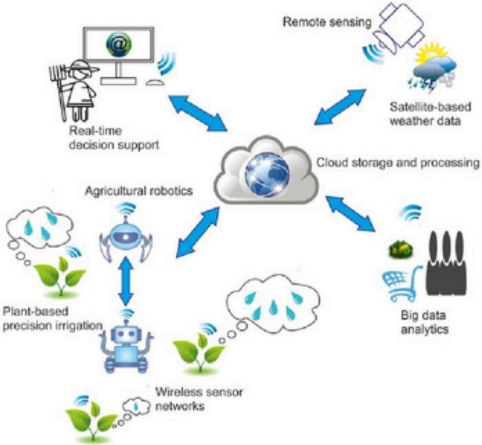
Figure 4.2 Spray boom attached to a reel machine (source Guido Wyseure)

4.1.4. Improving the efficiency of water use

Variability in soil properties and soil profiles within fields implies that there is a spatiotemporal variability in soil water content and water stress experienced by plants. This may mean that, under a uniform irrigation regime in a particular field, the crop water use efficiency can be very variable, leading to non-uniform crop growth and yields. Scheduling the timing and volume of irrigation can be improved if there is a better estimate of the forecast irrigation needs in different field locations, based on a combination of local sensing of the crop and soil indicators, as well as water loss due to evapotranspiration.

A monitoring system that captures several plant, soil and weather parameters can feed enhanced models for the dynamics of water use and water needs. These can be physics models enhanced by AI with data processing of all the available data and their temporal, as well as spatial, variability. Such a system ensures that most local disturbances are incorporated for predictive accuracy. A novel irrigation control strategy, based on a hybrid model of predictive control can, after suitable field evaluation, results in improved water use efficiency and water productivity (Bwambale et al., 2022). Efforts have been made to include rooting depth in the irrigation technology, thereby changing the depth in the soil where water is delivered, to have the best uptake efficiency (Liao et al., 2021). Much of the stress and burden of irrigation can be reduced for farmers and users. In some cases, farmers can also remotely visualise and monitor their cultivation environment, to see the performance and state of their plant and soil conditions, as well as control the status of actuators using mobile phones and computers (Abioye et al., 2022). Reducing water consumption will have to consider the soil variability and the response of the plants to make a more efficient use of every applied drop of water. Plant-level sensors can give individual plants or plant monitoring units the ability to communicate their needs in real time. After all, the best-placed entity to answer the question "how much water is too much water" is the individual plant, communicating its needs. real time and determining when it wishes to be watered, how much water it requires, and how much thirst it can take before compromising the final expected yield (Owino & Söffker, 2022). Artificial intelligence combining plant and soil and weather data with accurate, dynamic growth models can look at specific scenarios in the management of the available water as well as the expectations of yield quantity and yield timing (Figure 4.3). Efficient precision irrigation technology supplies the water to each field or part thereof according to the growing season and these expectations. In the next step, improvements of the irrigation management can be expected from the use of digital twins. This also opens opportunities for precision "fertigation".

Figure 4.3 The future of precision irrigation control, with cloud-based data storage and processing, real-time communication between plant-based sensors, intelligent agents (including robots), supported by weather data and market analytics. (Owino and Söffker, 2022)



4.2. Management of aquifers and river catchments

Integrating the local management at a regional scale is important in managing the water resources in aquifers and river catchments.

4.2.1. Monitoring water level in soils and rivers

Most countries in Europe have a network of river and aquifer monitoring. We do not elaborate this detail here but the measurement of water resources is fairly standard in most member states. Several existing water information systems allow real time access to data by the public including the farmers, especially to river and canal levels and discharges.

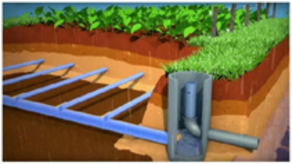
Real-time access to groundwater levels is less common and those levels change more slowly. But more real time sensors connected to the internet would also be very useful for following the groundwater reserves in real-time.

The integration of regional water resource levels and the forecast of water resources availability into irrigation and drainage management opens up new possibilities for intelligent proactive management under drought conditions.

4.2.2. Information on phreatic water table for run-off management and groundwater recharge

Some water managers blame the draining of agricultural fields in many parts of Europe for water shortages. It is important to understand that most agricultural drainage systems are meant for workability and trafficability during early spring, to allow field operations and grazing, but not for summer conditions. Also, during harvest in the autumn and early winter, machinery might damage the soil structure of very wet soil. At the same time, it should be well understood that roots for almost all crops (rice is an exception) grow in aerobic conditions and not in saturated conditions. Crops with shallow roots will suffer more severely during dry periods. Also, during the summer, the excess of evapotranspiration over rainfall reduces the groundwater recharge to zero, regardless of whether there is a pipe or ditch drainage system or not.

Figure 4.4 Level controlled drainage with higher water level and lower outflow. The manhole on the collector drain is blocked (courtesy of https://www.boerennatuur.be/peilgestuurde-drainage-en-subirrigatie/).



Shallow phreatic water can contribute to root zone water supply by capillary action. Therefore, level-controlled drainage (Figure 4.4) lowers the water table when needed for workability/trafficability and keeps water levels higher during the growing season in the summer. This is often done manually by controlling the water level in the manhole of the collector before discharge into the ditch.

It is important to stress that level-controlled drainage is only feasible in flat low lying areas with shallow groundwater. In sandy areas, the control of the water level by ditches is sufficient and there is no need for the installation of tile drains. In medium textured soil with shallow phreatic water, drainpipes have added value. The fine textures, like heavy clay, have too low a conductivity for effective drainage.

Measuring groundwater levels in a drainage system allows us to adjust the groundwater level automatically in a climate adaptive way. In combination with distance controlled, adjustable weirs and levels in the manholes, climate adapted drainage is possible.

Higher demands of ET during the dry and hot periods can steer a rise in water so that more capillary rise can reach the bottom of the root zone.

Alternatively, forecasts of heavy rain can be a signal to lower the table in order to create an extra buffer in the root zone to store more rain and to reduce runoff. Immediately after, storm levels can rise again. AI can contribute to climate-intelligent groundwater level management with advantages for local crop growth and regional water management at the same time.

4.2.3. AI based weather forecasts for drought or water excess

Weather forecasting has been improved by the use of supercomputers and cooperation between weather services. In general, predictions for the next 5 to 7 days are accurate, especially for temperature and general weather conditions. However, the amount of rainfall is still more difficult to predict. Therefore, local weather stations are still useful and should be integrated.

For agricultural drought, it is important to stress that it is the storage of soil water in the root zone that matters.

4.3. Challenges for AI in soil and water applications

4.3.1. Macro-management of the water supply

The AI will allow the integration of several sources and a large quantity of data to proactively and quickly react to multipurpose management of the crop, along with the conservation of water resources. The online connection through the IoT of a large and diverse sensor network is important for soil water balance models that drive irrigation and drainage scheduling. It leads to the climate adaptive control of phreatic water levels for sustainable and economic crop growth. At the same time, the water supply and phreatic level control can be monitored and integrated within the local water balance models. Data assimilation algorithms need to update the models with the observed variables. With a high number of sensors, monitored simultaneously by IoT and with a very short time interval, a continuous automatic data check and correction is essential. In addition, spatial images of crop biomass from satellites or drones can be integrated. Ideally, the models can consider the status and forecasts of regional water resources, to preserve the quality and quantity of the resources.

Careful regional and local water table management in low lying areas, by AI-steered phreatic water level control, should replace the former simplistic view of agricultural drainage.

4.3.2. When and how to irrigate

AI based management of aquifers and all water supply sources and precision irrigation systems that incorporate crop soil and weather information allows farmers to increase water-use efficiency.

Variable irrigation within a single crop or field must be achieved based on models for forecasting water needs and data analysis from previous seasons. A major challenge here is the integration of crop-soil-water models with real-time data-acquisition and weather forecasting. Capturing the monitored spatial variability of the available water in the entire root zone is important for managing the water supply to the crops. Also, providing irrigation appropriate to the growth stage of the crop is paramount.

In the foreseeable future, irrigation decisions will be based on ever smaller sections of a field, perhaps down to a single plant. In these operations, the seed selection and the root development potential of varieties is an important decision for farmers. With increasing problems of water scarcity and environmental impact, a policy leading to high water productivity (maximum yield per unit of water) and minimal environmental impact should be implemented. This means maintaining low-cost water, up to the maximum productivity, but substantial incremental costs for over-irrigating. With AI, a lot of water can be saved by more precisely targeting the maximum water productivity, rather than the maximum yield, which includes attention for the growth stage. The irrigation timing and the use of water only when required can increase the water productivity and the crop yield resulting in 'more crop per drop'.

4.3.3. Storing surface water for long dry spells

In recent years, there has been the phenomenon of periods with heavy rains, alternating with long dry and hot spells. This can be within a single year or it may be that wet and dry years alternate on an irregular basis. Not all the excessive rain can percolate into the soil but should be captured in reservoirs. Deciding on the size and location of these reservoirs can best be done based on all the information about water storage capacity of the soils, the types of crops planted and the crop rotation, as well as the long-term weather forecasts. AI can be a useful tool in preparing such plans.

Weather forecasts, in combination with water levels in storage basins, can alleviate the risk of floods and may also offer opportunities to divert water to other regions where expected rainfall is lower. Such dynamic use of storage capacity can reduce flood risks and also avoid much water going into rivers (in the short term) while there may be a shortage (in the long term). The regional topography has to be taken into account in such management strategies.

In addition, soil water levels can also be dynamically changed through drainage control. This is another component of dynamic water storage management, in combination with reservoirs and basins. Artificial intelligence is a useful tool for such management.