Exploring Energy Productivity for a Groundwater Dependent Irrigated Farm Using a System Dynamics Approach

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EXTENDED ABSTRACT

This paper explores the sensitivity of irrigation energy productivity to changes happening at a farm level. Energy is vital to any agricultural system, particularly in systems which depend on groundwater for irrigation. It has been estimated by Lal (2004) that over 23% of direct energy use for crop production in the US is used for on-farm pumping, with similar results found in the arid zone of India. It is therefore important to know how changes within the environment will affect irrigation energy productivity.

Energy productivity (EP) refers to the outputs derived from energy inputs into a system. EP can be further expressed in terms of physical or economic productivity. In this paper EP is defined in terms of physical output. Physical productivity is a comparison between the quantity of yield produced (kg) and the quantity of the direct energy input (kW). Physical productivity is thus expressed as kg/kW. Assessing EP can help identify pathways to ensure the sustainability of irrigation in the agricultural sector, as well as provide an opportunity to identify the major sources of energy wastage and can aid policy makers in terms of providing a basis for the efficient management of natural resources.

The Vensim™ modelling environment was used to construct a model of on-farm irrigation EP for pasture production. Sensitivity analysis was performed to examine the results of changing the values of total crop water requirement and groundwater head lift in order to predict the effect on irrigation energy productivity. In this case, parameters which affect both yield and the energy required for pumping to produce agricultural crops were included. These inputs were changes to Crop Water Requirement (CWR) and groundwater lift head (m). The sensitivity analysis of EP was performed for three different irrigation methods (Flood, Centre Pivot and Drip irrigation). It was found that in both cases the overall trend for each irrigation method was similar; however the relative level of changes were different for each method.

The sensitivity analysis for changing CWR showed that the behaviour of EP when this input was changed was markedly different from current practices. The Flood irrigation method was found to be the most sensitive, followed by the Drip irrigation and then Pivot irrigation methods. When the effect of changing groundwater lift head was explored, it was found that EP is far less sensitive to this input due to smaller level of lift needed, as the behaviour was very similar to that for current practices. A sample result for this sensitivity analysis is shown below (Figure 1). The order of sensitivity between the irrigation methods was the same as the previous case, with the Flood irrigation method being the most sensitive, followed by the Drip irrigation and Pivot irrigation methods. This model was not calibrated against field measurements.

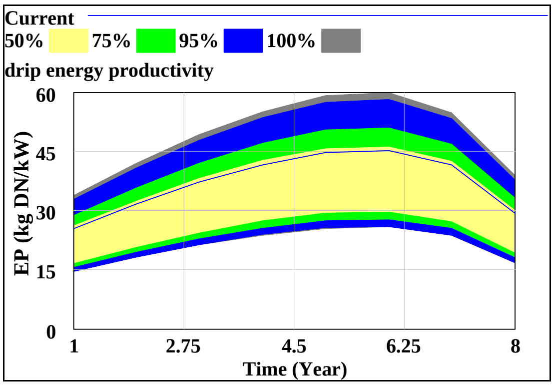

Figure 1 Sensitivity of the Drip irrigation method to changes in groundwater lift head

The system dynamic modelling framework described in this paper could be useful for determining the suitability of different irrigation methods for time varying water and energy settings affecting energy productivity.

1 INTRODUCTION

Agriculture is essentially an energy conversion process, whereby solar energy is converted to food energy for humans and animals by the action of photosynthesis (Stout 1990). Energy is an essential component of any agricultural system, whether the source is human, animal or mechanical. Energy consumption in agriculture is directly related to the development of technology and the level of production from a system (Hatirli et al. 2006). This concept is further considered by Stout (1990), who states that agricultural modernisation which requires increasing amounts of energy inputs is essential to providing enough food for growing populations. Efficient irrigation methods are important means for boosting crop productivity; however the benefits of improved yields may be at the cost of increased water and energy inputs.

Energy consumption in any system can be categorised as either direct or indirect. In an agricultural sense, direct energy consumption is that energy used on-farm for practices such as tillage and irrigation pumping. Indirect energy consumption refers to energy that is used to produce equipment and other goods and services that are used on-farm (Pimental, 1992). Direct energy consumption by agriculture is negligible in developed countries, but if indirect energy consumption is included, the figure may more than double (Pervanchon et al. 2002). Pimental (1992) has estimated that direct energy use on farms is just one third of total energy consumption, a figure that is supported by a model developed by Fluck et al. (1991).

While accounting for energy use, irrigation can be viewed as both a direct and indirect energy input; energy is used directly for fuel for pumping water, and is also indirectly embodied in the manufacturing of equipment, construction of irrigation delivery channels and drilling of bores. The type of irrigation system used obviously has an impact on the amount of energy consumed, even within pressurised systems, as the energy required for pumping depends on total dynamic head, flow rate and system efficiency (Lal, 2004), while those systems that consist of energy intensive equipment use will necessarily contain a higher amount of embodied energy.

Most traditional irrigation energy inputs are essentially the expenditure of fossil energy to pump and apply water for crop production (Pimental et al. 2002). Given that fossil fuel reserves are declining, it is important that any long term product or industry planning for irrigated agriculture recognises that current technology will be challenged by declining resources and increasing prices (Foran 1998). For this reason, the analysis of energy use in irrigated agriculture is imperative so that areas for effective energy and water savings can be made.

This paper examines the energy productivity (EP) of three irrigation methods i.e. Flood, Drip and Centre Pivot in the ground water dependent region of the Limestone Coast, South East South Australia.

1.1 Energy productivity

Energy analysis is the objective analysis of the physical quantities of energy involved in a process. There is a general agreement on the value of energy analysis in that it allows practices to be evaluated for potential energy conservation (Fluck 1992; Stout 1990). This is useful because energy itself cannot be substituted for or recycled; it is therefore necessary to minimise its use where possible. It allows the evaluation of the sustainability of crop production methods in order to determine those with greater yields relative to resource inputs and potential environmental degradation (Martin et al. 2006).

EP refers to the benefits derived from energy inputs into a system (Fluck et al. 1991; Hatirli et al. 2006). Productivity can be calculated both in physical and economic terms. Physical productivity is a ratio of the quantity of yield produced and the quantity of the input. The yield is expressed in terms of mass (kg) and the input is represented by the amount of energy (kW) used either for a particular process or for the total crop production scenario. Physical productivity is expressed as kg/kW. Economic productivity uses valuation techniques to derive the value of energy, or income derived from energy use. Economic productivity can be measured in terms of gross value of produce or opportunity cost in the highest alternative use per unit of energy input and is generally expressed in terms of $/kW.

Assessing EP will allow the sustainability of irrigation in the agricultural sector to be evaluated, as well as providing an opportunity to identify the major sources of energy wastage (Pervanchon et al. 2002). In the event of energy shortages, it is necessary to know how scarce energy resources can be best allocated to maintain production (Fluck et al. 1991). Energy analysis can aid policy makers in terms of providing a basis for the efficient management of natural resources.

1.2 The systems dynamic approach

Systems dynamics analysis allows complex systems to be represented, explored and analysed using a theory of system structures (Khan et al. 2007 in Press). Using this approach to understand complex systems, the relationship between structure and behaviour is based on the assumption of feedback and control; that is, that the structure of any system or problem is often just as important in determining its behavior as the individual components themselves.

Systems dynamics follows a generic methodology which is identified by the Systems Dynamics Society (2007) as shown below:

1. First, a problem is identified.
2. The development of a dynamic hypothesis is established to explain the cause or contributors to the problem. This can take the form of an object flow diagram, so that the flow of any variable throughout the system can be conceptualised and traced.
3. A computer simulation model of the issues at the root of the problem is built to allow causes and links and future trends to be simulated.
4. The model is tested to ascertain that it mimics key aspects of the 'real' world.
5. The model can be used to test alternative policies that may alleviate the problem.

The Vensim™ modelling environment (Ventana Systems, 2004) was used to construct a model of on-farm irrigation EP for pasture production. Vensim™ is a visual modelling tool for conceptualising, documenting, simulating, analysing and optimising models of dynamic systems such as farms and irrigated regions. It provides a simple and flexible way of building simulation models from causal loop or stock and flow diagrams. By connecting words with arrows, relationships among system variables can be entered and recorded as causal connections. Analyses of the causes and uses of a variable and the loops involving the variable are carried out during the building process of the Vensim™ model. Once a model is built that can be simulated, Vensim™ allows the behaviour of the model to be thoroughly explored.

Sensitivity analysis is performed to examine the results of changing the values of certain parameters in order to predict what will happen if the system changes in a certain way. In this case, parameters which affect both yield and the energy required for pumping were included.

While this paper focuses on on-farm processes, on a larger scale the problem impacts on environmental challenges such as global warming and natural resource availability, since changes in energy use also impact on the environment by directly influencing greenhouse gas emissions. The groundwater resource is affected by the amount of water extracted and returned to the system by irrigation.

2 MODEL FORMULATION

Based on regional information and data collected on-farm from irrigated farms in the Limestone Coast region of South East Australia, key data inputs were decided. The three most common irrigation methods were selected; Flood irrigation (31% of irrigated area), Pivot irrigation (40%) and Drip (18%).

EP is calculated as a ratio of yield and energy inputs. Within this model, yield is calculated separately for each method of irrigation technology. Theoretical data was used to determine the production functions for yield of pasture (Figure 1) for different irrigation technologies It was assumed that centre pivot irrigation systems were 15% more efficient than flood irrigation systems, and drip irrigation systems were 25% more efficient than flood irrigation systems (i.e. the same yield was obtained using 15% and 25% less water respectively). Personal communication with farmers has indicated that centre pivot and drip irrigation systems can significantly "out-yield" flood irrigation systems while using far less water, however for the purposes of this analysis the above assumptions were made.

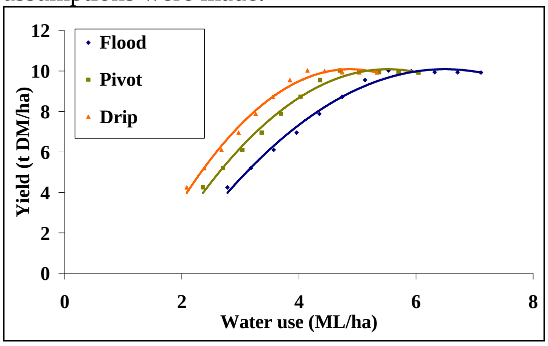

Figure 2 Yield curve for irrigated pasture

The data used to develop these yield curves (Figure 1) was processed in the Swagman Destiny model (Khan et al., 2003). Thus the equations for yield for the different irrigation methods are:

Flood:

$$y = -0.443x^2 + 5.753x - 8.5929 \quad (1)$$

Pivot:

$$y = -0.6131\, x^2 + 6.7683x - 8.5929 \quad (2)$$

Drip:

$$y = -0.7875\,x^2 + 7.6707x - 8.5929 \quad (3)$$

where y is yield (kg/ha) and x is water applied (ML/ha). The range of applicability of the data used in the yield determination equation is limited in order to obtain meaningful results; for example, the water applied must be within the range given in this data or the results are not valid (negative values obtained).

In order to determine the amount of water applied for each irrigation method, the following procedure was used. The crop water requirement (CWR) for pasture was determined from regional ET_0 and crop factor information (Skewes 2006). This then resulted in the calculation of net CWR.

$$\text{net CWR} = \text{CWR} - \text{Pe} \quad (4)$$

where Pe is equal to effective rainfall (Skewes, 2006). The amount of water required for any given year was given by

$$\text{water applied} = (\text{net CWR} - (\text{DD}*\text{net CWR}) \quad (5)$$

where DD is equal to the degree of deficit irrigation. This relates to the fraction of CWR that is applied in any one year. For example, if DD is 10%, then 90% of CWR is applied in that year. A range of DD from 0 to 0.7 values of deficit over eight years was assumed for stochastic analysis.

Finally, to calculate the amount of water applied using each irrigation method, the amount of water applied was divided by the given efficiency of the irrigation method, resulting in a total amount of water applied by each method (ML/ha).

The energy component for the purposes of this paper relates only to direct energy used for irrigation pumping. It is assumed in this case that other energy inputs would remain constant, as the purpose of this paper is to investigate irrigation energy productivity.

When calculating energy requirements for pumping, the energy used in ground water pumping is calculated by the following equation:

$$\text{kW} = (Q*h*g*\rho) \div 1000 \quad (6)$$

where Q is flow rate (m^3/s), h is total head (m), g is the specific gravity of water (9.806) and ρ is the fluid density of water (assumed to be 1000 kg/m^3).

Average flow rates were determined using local data for Flood, Drip and Pivot irrigation systems.

Total head is the sum of groundwater lift head and discharge head. The groundwater lift head is the depth from which water is pumped. Discharge head is equal to the operating pressure of the irrigation system in metres. Average discharge head for each irrigation method was taken from local data.

The total energy used for pumping depends on the number of hours that the pump is operating in any one season. Thus, total energy for a given irrigation method is given by:

$$\text{Total kW} = ((Q*h*g*\rho) \div 1000)*\text{PH} \quad (7)$$

where PH is equal to the total pumping hours over the season.

PH is given by the following:

$$\text{PH} = \text{water applied}/(Q*3.6) \quad (8)$$

where water applied is given in ML/ha and flow rate (Q) is given in m^3/s and converted to ML/hr using a factor of 3.6.

3 EXPLORING THE CAUSE-EFFECT RELATIONSHIP

It has been established that EP is a function of yield and energy use. Using a system dynamic approach, the relationships between these variables have been explored.

Figure 3 shows how water applied changes for each irrigation method over time. Degree of deficit irrigation increases with time; as DD increases, the fraction of CWR applied is reduced, causing water applied to decrease therefore a resultant decline in yield. The difference between the irrigation methods can also be seen, with the Flood irrigation method applying more water than the Pivot irrigation and Drip irrigation methods respectively.

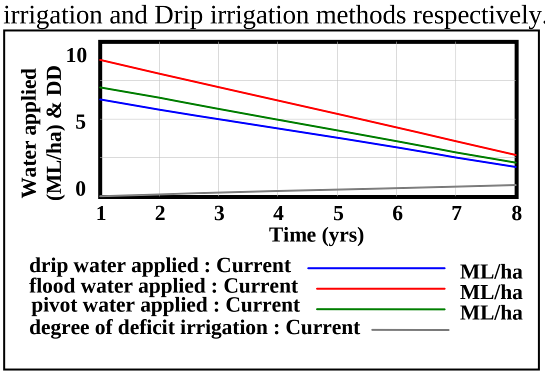

Figure 3 Water use and degree of deficit irrigation over time

Figure 4 shows how yield changes over time. It was assumed that water was the sole determinant of crop yield as other conditions were held constant. The yield for the Pivot irrigation method and the Drip irrigation method is very similar, resulting in the yield curve for the Pivot irrigation method being hidden. This shows that DD can have a positive effect on yield up to a point, before yield starts to decline. This indicates that optimum yield is achieved in years three and four, when DD is 0.2 and 0.3; optimum yields can therefore be achieved with 70-80% of CWR. This has implications not only for saving water, but also for reducing energy use in a groundwater dependent irrigation region.

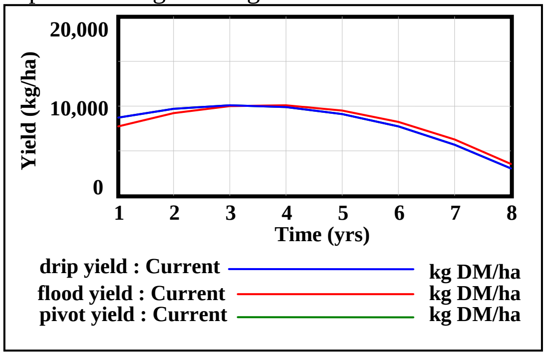

Figure 4 Yield changes over time

As is illustrated in Figure 5, energy required for irrigation pumping declines over time, following the trend of decreasing water application. Since energy is a function of flow rate and total water applied, it is to be expected that reducing the volume of water applied will also require less energy to pump that water.

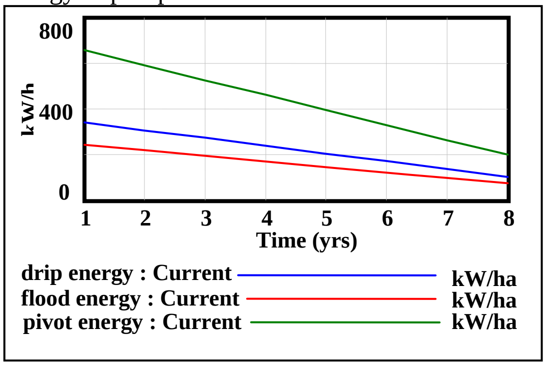

Figure 5 Energy for irrigation over time

EP is a combination of the above factors. Figure 6 shows the trend of EP for each irrigation method over time. As less water is applied over time (see Figure 3), EP increases; this is due to a combination of a reduction in water applied increasing yield up to years 3 and 4 while simultaneously reducing energy use. EP continues to increase until yield starts to decline, indicating that a reduction in energy has more effect on EP than an increase in yield. However, there is a point where EP starts to decline, which coincides with a rapid decline in yield.

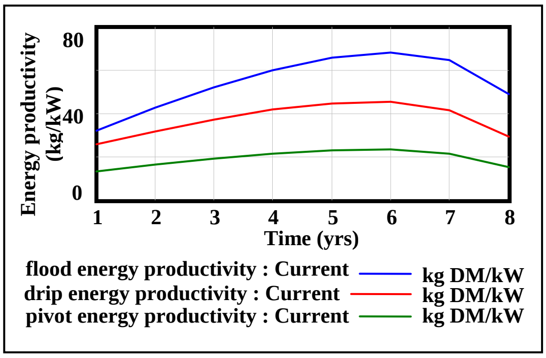

Figure 6 Energy productivity over time

4 SENSITIVITY ANALYSIS

In order to determine whether energy or yield has a bigger impact on EP, sensitivity simulations on factors affecting these variables can be explored.

4.1 Changing groundwater lift head

Changing the groundwater lift head will impact on irrigation energy use alone, as this has no impact on total water applied for each system and hence no effect on yield. The range of values used for groundwater lift head was 5 – 25m. Similarly to the results for sensitivity to changes in CWR, the parameters all display the same behaviour over time in this case, as can be seen in Figures 9, 10 and 11. Unlike the previous situation however, the behaviour of EP is similar to the graph of EP over time, indicating that EP is relatively insensitive to changes in this parameter.

The Flood irrigation method is again the most sensitive to changes to groundwater lift head, as shown by Figure 7. This is due to the fact that groundwater lift head is the only component of total dynamic head for this system, thus as it increases energy use will also increase. This irrigation method is also applying the greatest volume of water, and pumping it from a greater depth will therefore increase the energy required for this.

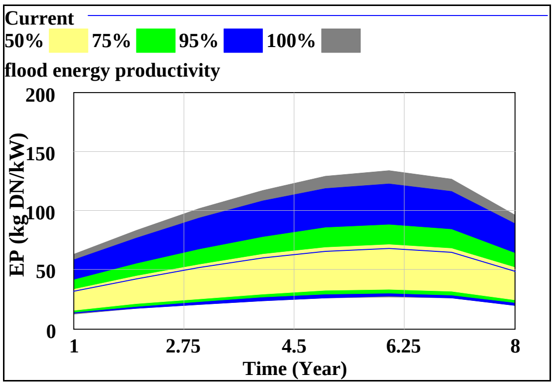

Figure 7 Sensitivity of the Flood irrigation method to changes in groundwater lift head

Figure 8 shows the sensitivity of the Pivot irrigation method to changes in groundwater lift head. As previously mentioned, energy use by Pivot irrigation systems is mostly influenced by discharge head; therefore it is less sensitive to changes in groundwater lift head. This is clear by the relatively low range of values in Figure 8.

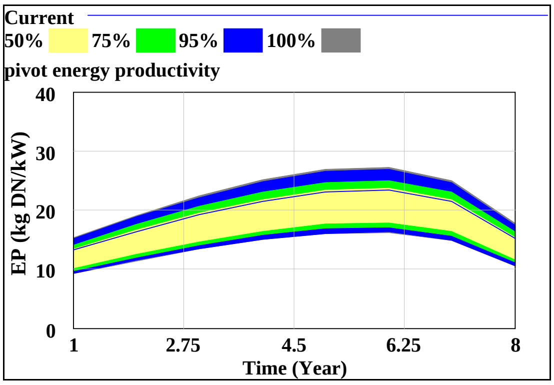

Figure 8 Sensitivity of the Pivot irrigation method to changes in groundwater lift head

Figure 9 shows the sensitivity of the Drip irrigation method to changes in groundwater lift head. As Drip irrigation systems generally operate at a lower pressure than Pivot irrigation systems, it is affected by changing groundwater lift head more than the Pivot irrigation method but less than the Flood irrigation method.

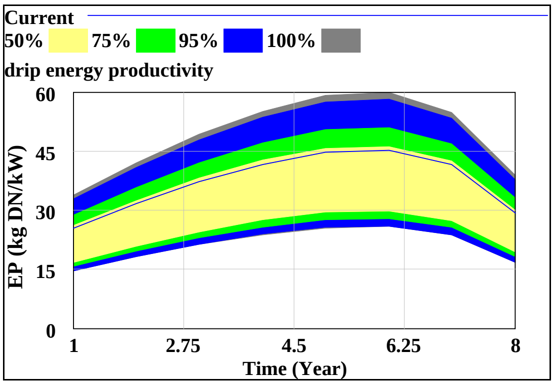

Figure 9 Sensitivity of the Drip irrigation method to changes in groundwater lift head

4.2 Changing Crop Water Requirement

Changing CWR allows the sensitivity of EP to changes in yield and energy to be assessed. Figures 10, 11 and 12 show the results for sensitivity analysis of EP to changes in CWR for the Flood irrigation method, Pivot irrigation method and Drip irrigation method respectively. The range of values used for CWR was 6 – 8 ML/ha. It is immediately obvious that modifying this parameter has changed the behaviour of EP. However, the behaviour of all three parameters is similar, with sensitivity increasing up to a point; after this point a further decline in the amount of water applied has a negative impact on EP. There appears to be a point at which EP is insensitive.

The Flood irrigation method is the most sensitive to changes in CWR, as shown by Figure 10. This is due to the fact that energy for this irrigation method is influenced primarily by the amount of water applied and flow rate, as the total dynamic head is relatively low since the discharge head component of this is 0. Sensitivity becomes greater when increasing DD causes water applied to decrease and yields to decline.

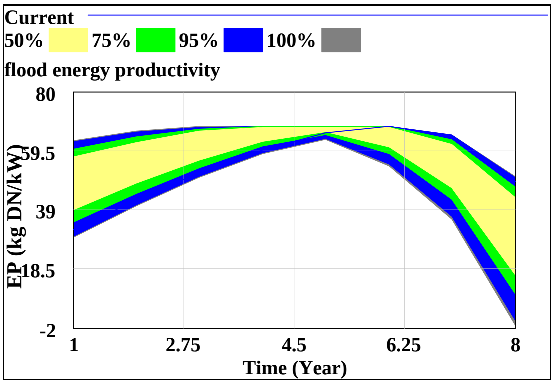

Figure 10 Sensitivity of the Flood irrigation method to changes in CWR

Figure 11 shows that the Pivot irrigation method has the lowest sensitivity to changing CWR. This is due to the fact that total dynamic head, and in particular discharge head, has the biggest impact on energy use by this method, which masks the impact of changing CWR.

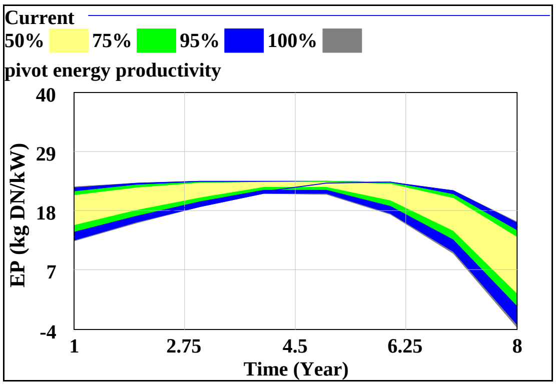

Figure 11 Sensitivity of the Pivot irrigation method to changes in CWR

The Drip irrigation method is also relatively sensitive to changes to CWR, as illustrated by Figure 12. As Drip irrigation systems generally operate at a lower pressure than Pivot irrigation systems, it is affected by changing water application rates more than the Pivot irrigation method but less than the Flood irrigation method.

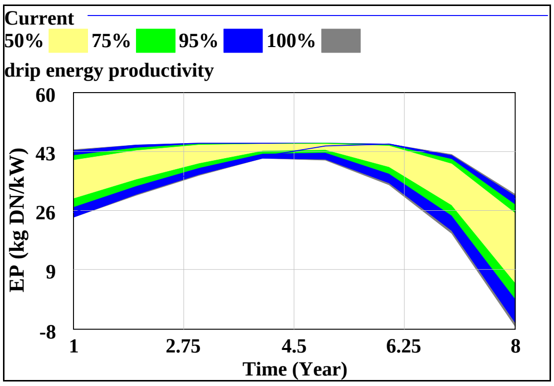

Figure 12 Sensitivity of the Drip irrigation method to changes in CWR

5 KEY CONCLUSIONS

The Vensim™ model was found to be a useful tool for investigating the effects of different parameters on on-farm irrigation EP. Sensitivity analysis provided insights into parameters which can greatly influence behaviour of EP.

In this paper, two different inputs affecting the parameters of yield and energy use were explored in order to investigate the sensitivity of EP for three different irrigation methods. It was found in both cases that the overall trend for each irrigation method was similar; however the relative magnitudes changed for each method.

The sensitivity analysis for changing CWR showed that the behaviour of EP when this input was changed was markedly different from the current practices. The Flood irrigation method was found to be the most sensitive, followed by the Drip and Pivot irrigation methods respectively.

When the effect of changing groundwater lift head was explored, it was found that EP is far less sensitive to this input due to smaller level of lift needed, as the behaviour was very similar to the base line graph. The order of sensitivity between the irrigation methods was the same as the previous case, with the Flood irrigation method being the most sensitive, followed by the Drip and Pivot irrigation methods.

This analysis could be a useful framework for determining the suitability of different irrigation methods for time varying water and energy settings affecting energy productivity.

6 ACKNOWLEDGEMENTS

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