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On Comparison of Water and Energy Productivities in Pressurized Irrigation Systems

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Abstract: Increasing scarcity of water resources to manage climate variability and change has urged countries including Australia to adopt water saving policies for agriculture sector. These policies inevitably involve dependency on high energy demanding solutions to practice more water efficient irrigated agriculture. The energy required for installation and operation of higher water efficient irrigation systems is significantly higher than traditional systems and associated greenhouse gas emissions can be significantly higher. Efficient use of both water and energy resources is vital in terms of productivity of agriculture as well as for environmental sustainability. The energy intensive irrigation systems need to be designed and managed in such a way that delivers maximum water and energy productivity into minimum greenhouse gas emissions while optimizing economic returns. Integrated high pressure (IHP) irrigation system is a hardware and software setup that supposedly delivers savings in water, energy and costs and reduces irrigation's environmental footprints. This paper discusses a spreadsheet model of horticulture production systems in the Murrumbidgee Irrigation Area (MIA) which is a user of surface water diverted from the Murrumbidgee River. The annual water use entitlement for MIA is 1,253,000 mega litre. Horticulture (citrus and grapes) is the major high-return land use following the broad acre crops (rice and wheat) in MIA and constitutes a major portion of Australian Horticulture export. Horticulture contributes around 37% of total value of production in MIA in 2004.

This paper presents results from a spreadsheet model and compares total energy and water use of irrigation systems with or without IHP with the gravity-fed system using a case study in the MIA. It is concluded that the IHS system consumes slightly less energy and deliver more water savings than the individual high pressure and gravity furrow irrigation systems (Table A). These water, energy and cost savings are achieved through better irrigation scheduling, seepage and evaporation reductions, less operation and maintenance costs, energy price bargains, and less labor requirements for a high pressure irrigation supply system for horticulture crops. The IHP system also eliminates the need for channel pre-filling and the whole water ordering and delivery system can be automated and remotely controlled.

Table A. Comparison of water and energy productivity of the three systems.

Variable	With IHP (S1)	Without IHP (S2)	Gravity-fed Furrow (S3)
Energy Use Efficiency (kWh/kWh)	2.29	2.25	2.33
Specific Energy (kWh/kg)	0.230	0.234	0.226
Energy Productivity (kg/kWh)	4.34	4.27	4.43
Water Productivity (kg/m3)	10.01	6.93	4.29
Energy-Water Productivity (kg/m3kWh)	1.35×10^{-3}	0.921×10^{-3}	0.656×10^{-3}
Water use (ML/ha)	3.21	4.64	6.75

Keywords: *Water productivity, Energy productivity, Integrated high pressure irrigation system, Horticulture, Murrumbidgee Irrigation Area*

1. INTRODUCTION

Energy input in agriculture is directly related to the irrigation technology adopted and the level of production (Hatirli et al., 2006). The agricultural modernization which requires increasing amounts of energy inputs is, at the same time, essential to providing enough food for growing populations (Stout, 1990). 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 and associated environmental impacts. Agricultural production has a significant environmental footprint, as a result of expansion in cropland at the expense of forests, grasslands, and ecotones (Pimental et al., 2004). Crop intensification through high inputs of water, energy and macro nutrients has been articulated as the way forward, especially in land scarce regions, but this has profound implications for global water and energy budget (Khan and Hanjra, 2009).

Present and projected water scarcity has urged countries including Australia to adopt water saving policies across all sectors including irrigated agriculture. Modern agriculture production is characterized by the heavy use of fertilizers, pesticides, and labor-saving and high power consuming machines. The modern production practices including increasing inputs of agrochemicals, irrigation and the growth of more productive cultivars have led to significant increase in crop yields. However, these practices have led to a dramatic increase in the input of fossil energy (Hülsbergen et al., 2001), which has raised many concerns over sustainable use of energy resources. Pimentel et al. (1973) envisaged that dependency on fossil-fuel inputs will be a potential threat to the growth and stability of world food production. Particularly in Australia, the energy system faces a number of environmental issues that are the subject of government policy interventions. These issues include the long-term depletion of national reserves of oil, competing demands for water, and concerns over global warming due to greenhouse gas emissions (Graham and Williams, 2005).

Realizing the need to lift water use efficiency, the Australian Federal Government has launched $12.9 billion Water for the Future program (DEWHA website). This program provides grants for seeking independent professional expertise and assistance with system modernization planning including asset refurbishment and infrastructure. However, a critique on this program could be its lack of emphasis on improving energy use efficiency and undue greenhouse consequences. Given that our water resources are fully and in some places over-allocated, the only way to ensure that we have enough water for irrigation development is to use the water we have more efficiently at both farm and catchment scales. Water can be saved through better management of its delivery and application (Khan et al., 2004; Khan et al., 2005).

The ‘balancing act’ between crop production and environmental sustainability involves boosting water productivity (Molden et al., 2007) and energy productivity (de Fraiture et al., 2007) through a range of measures. Cummins (1998) ranked horticulture second after rice, almost a decade ago, for potential water savings of up to 150 GL through adoption of irrigation technology in the Murray Darling Basin. The energy required for installation and operation of so-called hi-tech water efficient irrigation systems like drip irrigation is significantly higher than traditional systems and as a whole the associated greenhouse gas emissions are huge. Although internal and external environmental and economic benefits increase with improvement in irrigation efficiency (Beare and Heaney, 2001), a balanced use of water and energy resources is vital in terms of productivity of agriculture as well as for environmental sustainability. Unless energy requirement aspects are not considered, the improvement in irrigation efficiency is a partial solution for minimizing the environmental footprint of consumptive use of water. Irrigation conveyance losses can be caused by evaporation, seepage, leakage and operational losses but by far the greatest losses are to seepage (Meyer, 2005). Such losses may fluctuate with seasonal climate conditions and diversion volume and can be eliminated by replacement with piped system.

This paper presents an accounting of the water and energy use of a cluster of horticulture farms with and without an integrated high pressure (IHP) irrigation system in the Murrumbidgee Irrigation Area (MIA) of New South Wales, Australia. It also computes and compares the indicators of water and energy footprints of horticulture production.

2. STUDY AREA

The Murrumbidgee region is located along the Murrumbidgee River in southern New South Wales and covers 8.2% of the Murray-Darling Basin (MDB). Irrigated crops which include cereals, pasture, horticulture and hay production cover 4.9% of the region. Citrus and grapes are grown within the central areas of the Murrumbidgee Irrigation Area (MIA) and constitute 3.6% of the total irrigated area (BRS, 2005). The level of irrigation system modernization for horticulture crops in MIA is depicted by the level irrigation technology adoption as shown in Figure 1. Literature indicates that up to 4 ML/ha can be realized in water savings by high pressure drip irrigation and is being rapidly rolled out for horticulture areas of MIA. On the other hand it requires significant energy input as compared to traditional methods.

In the Murrumbidgee region it is estimated that if the recent climate (1997 to 2006) were to persist, average surface water availability would reduce by 30%, diversions by 18% and end-of-system flow by 46%. The best estimate of climate change by 2030 is less severe than the recent past. Average surface water availability would reduce by 9 percent, diversions by 2 percent and end-of-system flow by 17 percent (CSIRO, 2008).

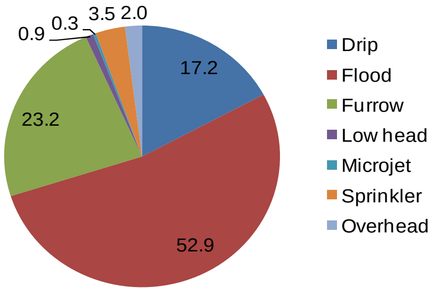

Figure 1. Irrigation application techniques adopted for horticulture crops in MIA.

The tight and heavy soils and groundwater not very deep from the surface make this area perfect for drip irrigation. It also reduces groundwater accessions and drainage requirement. More than six separate IHP systems are being installed in the Mid Murrumbidgee horticulture areas with half of them now in operation.

3. METHODOLOGY

A survey approach was adopted to collect quantitative information on water use, irrigation technology and direct and indirect energy inputs of a sample of 36 horticulture (citrus) farms in MIA. To add a degree of confidence in the information collected the random sample represented a variety of farms with various irrigation methods including irrigation by gravity flow in furrows and drip system. The irrigation water was supplied to the farms either with open channel water supply system or piped supply connected with IHP.

3.1. Integrated High Pressure (IHP) Irrigation Supply System

IHP irrigation supply system is state-of-the-art hardware and software technology that supposedly delivers savings in water, energy and economic costs and reduces irrigation's environmental footprints. The IHP is an automated irrigation supply system which consists of three components; a central pumping station, a hydrodynamically optimum supply pipe network, and pressure and flow regulators at individual farms. Schematic of a typical IHP system is shown in Figure 2. The pump station is established near the water source (canal, off-stream storage etc.) and consists of water filtration system, a number of pumps depending on command area. A specialized computer system controls the pumps duty cycle to meet the demand and maintain required pressure head and flow rate to operate the drip irrigation system of the individual horticulture farms connected with it. The system features a wireless system to enter daily demand, open and close individual farm outlets as per the water order placed and record meter readings from a central remote location. The IHP eliminated the need for individual pumps for a horticulture farm converting to high pressure irrigation. The system is operated and maintained by a central agency that holds the bulk water supply license. The operation and maintenance costs are socialized among the users of the system as per their usage. A levy can be charged to recover the capital cost of the system in an affordable way. In this study, water and energy use analysis and comparison was carried out for the three types of irrigation systems:

1. High pressure drip system connected with IHP supply system through pipe network (S1);
2. High pressure drip system connected with open channel supply system with on-farm pumping (S2);
3. Furrow irrigation by gravity flow connected with open channel supply system (S3).

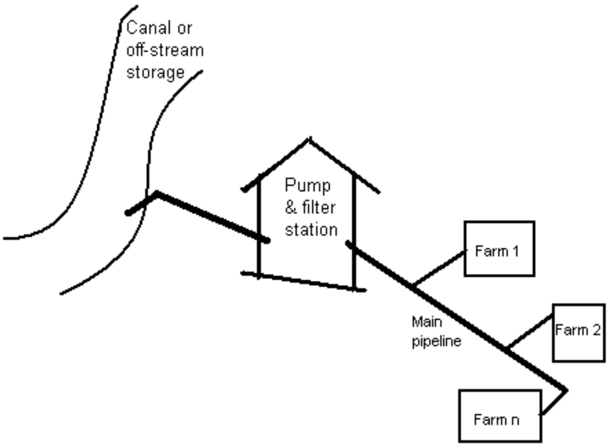

Figure 2. Schematic of a typical IHP irrigation supply system

A spreadsheet model was developed to:

- Account for various energy inputs during crop production cycle including energy required for irrigation;
- Convert all energy inputs and output into equivalent common energy unit i.e. kWh;

- Compute water and energy efficiency indicators and,
- Compare the indicators for above mentioned three irrigation systems.

The information on operation and maintenance of the IHP system was obtained from the agency responsible for controlling and operating the system. The soil and climate condition of all surveyed farms were almost identical which makes the comparison more meaningful. Table 1 lists the statistically averaged conditions of the three representative sets of irrigation systems surveyed.

Table **1**. Average conditions of the three irrigation systems

System	Description	Total No. of Pumps	System Head Loss (m)	Average Duty Flow (l/s)	Total Irrigated Area (ha)	Water Use (ML/ha)
S1	High pressure drip with IHP	5	20	18.59	150.22	3.21
S2	High pressure drip without IHP	1	7	24	20	4.5
S3	Gravity-fed furrows	1	5	7.6	20	5.5

3.2. Energy and Water Use

All forms of direct and indirect energy used were converted into a common equivalent energy unit to account for total energy use and to conduct comparisons. Energy equivalents of the inputs and outputs for the horticulture farming system were taken from various sources including Yaldiz et al., (1993); Chandra et al., (2001); Singh et al., (2002); Appl, (1997); Ozkan, et al., (2004) and Hülsbergen, et al., (2001) and are given in Table 2. Energy consumed in system manufacturing and installation is not considered in the analysis.

The following formula (Equation 1) was used to determine pump power and energy requirements.

$$GrossPower(KW) = \frac{FlowRate(l/s) \times Totalhead(m)}{102 \times Pumpefficiency(decimal) \times derating(decimal)} \tag{1}$$

Total head at the pump includes suction lift, static lift, pressure delivered and friction losses. Based on the manufacturer's specifications a pump efficiency of 80% and derating of 80% for electric motor were used for the calculations.

This paper has focused on computation and comparison of the water and energy indicators defined in Table 3 for the three systems. These indicators provide the insight of how water and energy efficient the considered systems are.

Table 2. Energy equivalents for conversion of total energy of inputs and outputs for citrus production

Input (Unit)	Energy Equivalent (KWh)
Human power (h)	0.54
Diesel & lubricants (l)	15.64
Farm Machinery (h)	17.42
Nitrogen Fertilizer (kg)	16.83
Super Phosphate (kg)	3.08
Potash Fertilizer (kg)	1.86
Farm Yard Manure (kg)	0.08
Pesticides (l)	55.27
Herbicides (kg)	66.1
Electricity (KWh)	1
Yield i.e. Orange (kg)	0.527

Energy Requirement for IHP Drip System

Data for the last three seasons shows that the IHP pump system runs at an average duty of 18.59 l/s to supply pressurized flow at 1.2 l/s with 45 m head at the farm outlet to the total irrigated area of 150.22 ha (Table 1) with an average system head loss of 20 m. The combined power requirement of the suite of pumps can be calculated as (Equation 2):

$$Pump\ Power = \frac{18.59 \times 65}{102 \times 0.8 \times 0.8} = 18.51\,KW \tag{2}$$

The system takes almost 14.94 hours to deliver 1 ML at its average flow rate. Therefore, the total power required to irrigate 1 ha at the rate of 3.21 ML/ha/season will be given by (Equation 3):

$$Gross\ \ Power\ (to\ Irrigate\,1\,ha) = 18.51 \times 14.94 \times 3.21 = 887.7\ KWh/ha \tag{3}$$

Energy Requirement for On-farm High Pressure Drip System

Table 3. Indicators of water and energy use

Indicator	Unit	Definition	Description
Water productivity	Kg/m^3	$\frac{Yield(kg)}{Water\ applied\ (m^3)}$	Yield of marketable produce per unit of water used.
Energy productivity	Kg/kWh	$\frac{Yield(kg)}{Total\ energy\ input\ (kWh)}$	Yield of marketable produce per unit of energy input.
Specific energy	kWh/kg	$\frac{Total\ energy\ input\ (kWh)}{Yield(kg)}$	Energy input per unit of marketable yield.
Water and energy productivity	Kg/ m3kWh	$\frac{Yield(kg)}{Waterapplied(m^3)\times Energyapplied(kWh}$	Yield per unit of energy and water inputs. It captures the effect of these inputs on yield. Lower values may indicate lower efficiency and higher environmental impacts.

Table 1 gives specifications for a typical 20 ha citrus representative farm with average conditions in the study area. The farm has its own heavy duty pump installed to supply pressured irrigation water to the drip irrigation system. An average rate of irrigation supply of 1.2 l/s/ha with 45 m discharge head was taken from the collected data. The capacity of the pump (average flow rate) is calculated as (Equation 4):

$$PumpCapacity = 1.2 \times 20 = 24 l/s \quad (4)$$

The friction loss in the mainline and pump was 5 m and water is being lifted 2 m. the required pump power is computed as (Equation 5):

$$Pump\ Power = \frac{24 \times 52}{102 \times 0.8 \times 0.8} = 19.12\ KW \quad (5)$$

The irrigation application rate in this category of farms in the study area ranges from 4 ML/ha to 5 ML/ha. Therefore an average irrigation rate of 4.5 ML/has been assumed. This pump takes almost 11.57 hours to pump 1ML. Therefore, the total power required to irrigate 1 ha is given as (Equation 6):

$$Gross\ \ Power(to\ Irrigate 1\ ha) = 19.12 \times 11.57 \times 4.5 = 995.5\ KWh / ha \quad (6)$$

Energy Requirement for Furrow Irrigation System

The same approach was applied to compute energy requirement of the gravity-based furrow irrigation system (S3) for irrigating a typical 20 ha citrus farm. This system operates without energy use for irrigation pumping thus consumes lesser energy; however the irrigation application efficiency is also reduced due to higher conveyance and irrigation application losses including deep drainage.

Water Savings

The major feature of an IHP system is the water delivery infrastructure. In case of open channel supply system, conveyance losses are caused through seepage from the walls and floor of a channel, evaporation, leakage from physical breaks in the channels and operational losses. Seepage and channel evaporation losses were used from previous studies in the area (Khan et al., 2004; Khan et al., 2005) concluded that up to 12.5 GL/yr is lost in evaporation and 42 GL/yr of water is lost in seepage from some 500 km of main supply channels in the MIA. The same study has estimated that around 2% of the on-farm water supply is lost in seepage from and 1% in evaporation from the farm supply channels. Also the irrigation application efficiency of the gravity-fed furrow irrigation system is lower than the high pressure drip system.

Table 4. Inventory of input and output energy from citrus production with high pressure drip irrigation connected with IHP (all values for unit area i.e. ha).

Input (unit)	Total Quantity Used	Total Equivalent Energy (kWh)	Percentage of Total Energy Input (%)
Fertilizer (kg)		4847.40	65.42
Urea (kg)	266.67	4488.06	60.57
DAP (kg)	116.67	359.34	4.85
Potash (kg)	10	18.60	0.25
Machinery (h)	89.84	1565.01	21.12
Human Labor (hr)	170	91.80	1.24
Electricity (KWh)	887.7	887.7	11.97
System operation (man-hours/ha)	0.06	0.03	0.00
Total Energy Input (kWh/ha)		7409.84	
Output (Citrus) (kg/ha)	32142.86	16939.29	

4. CONCLUSIONS

The water and energy use analysis of the three systems under consideration was conducted in two steps. First, energy and water inputs and outputs of the three systems were calculated and converted to a common unit; KWh. then the water and energy use indicators which are defined in Table 3 were computed and compared to find the most water and energy efficient system. Table 4 gives the quantities and equivalent energy of various inputs and outputs for S1. All values are expressed per unit area (ha) of the citrus crop. It is worth noting that electricity input is the third highest energy input after machinery and fertilizers. The machinery includes tractor use for various farm operations. Human labor includes man hours spent in tractor operations in addition to pruning and thinning etc.

Table 5 provides the balance sheet of energy equivalents of inputs and outputs for the system S2 for unit area (ha) of the citrus crop. There was no significant change in the yield as compared to S1. This is due to the fact that irrigation system operates with almost the same rate and pressure as the one connected with IHP. However, electric energy use for pumping was higher due to different irrigation scheduling. Also more time is consumed in management, operation and maintenance of the irrigation system. Also this option involved higher capital costs due to the requirement for individual farmers to upgrade electricity service and purchase of their own pumps.

On average, the gravity-fed system farms were irrigating at 6.75 ML/ha. Although no energy is required in irrigation, yet more than double man-hours are spent in irrigation application and maintenance as compared to S2. The total energy use of the system was computed to be 6536.31 KWh which is 11% to 13% less than what is required for the other two systems. The average yield of these farms was 10% less than the other two systems. The lower water use and lower yield are attributed to the lower distribution uniformity (DU) and lower mean application rate (MAR) of the gravity furrow system.

By applying the seepage and evaporation loss rates mentioned in the methodology section, it was estimated that on average, the total water use was 4.64 ML/ha for the farms with open channel supply. Thus the total water conveyance saving realized from converting open channel supply to pressurized pipe network service by IHP system was 1.425 ML/ha. A comparison of water and energy productivity indicators for the three systems is given in Table 6.

Table 5. Inventory of input and output energy from citrus production with drip irrigation using on-farm pumping (all values for unit area i.e. 1 ha).

Input (unit)	Total Quantity Used	Total Equivalent Energy (kWh)	Percentage of Total Energy Input (%)
Fertilizer (kg)		4847.40	64.43
Urea (kg)	266.67	4488.06	59.65
DAP (kg)	116.67	359.34	4.78
Potash (kg)	10	18.60	0.25
Machinery (h)	89.84	1565.01	20.80
Human Labor (hr)	170	91.80	1.22
Electricity (KWh)	995.5	995.50	13.23
Irrigation (man-hours/ha)	10	5.40	0.07
Total Energy Input (kWh/ha)		7523.71	
Output (Citrus) (kg/ha)	32142.86	16939.29	

The water productivity of IHP system (S1) is as high as 10.01 kg/m3 , consistent with what was found in literature, for example, as reported by Skewes and Meisner, (1997). This is mainly owed to the least water use than the other two systems. The gravity system (S3) has slightly higher energy efficiency than the other two systems and hence supposedly contributes a lesser level of greenhouse gas emissions. But it has least water productivity due to relatively higher water use and lesser yield. The energy-water productivity which combines both water and energy efficiencies is has the highest value for IHP. The higher value of this indicator reflects that it leaves lesser environmental footprints.

Table 6. Comparison of water and energy productivity of the three systems.

Variable	With IHP (S1)	Without IHP (S2)	Gravity-fed Furrow (S3)
Energy Use Efficiency (kWh/kWh)	2.29	2.25	2.33
Specific Energy (kWh/kg)	0.230	0.234	0.226
Energy Productivity (kg/kWh)	4.34	4.27	4.43
Water Productivity (kg/m3)	10.01	6.93	4.29
Energy-Water Productivity (kg/m3kWh)	1.35×10^{-3}	0.921×10^{-3}	0.656×10^{-3}
Water use (ML/ha)	3.21	4.64	6.75

The piped irrigation water supply system is an effective solution for achieving real water savings and for providing high pressure supply to horticulture areas. Real water savings can be achieved through reduced seepage and reduced evaporation from open channels. The cost and energy required to install piped system can ultimately be repaid by the water savings and yield improvement. The environmental gains in terms of reduced greenhouse gas emissions and recharge to saline groundwater are on top of these benefits. The reliability of supply of the piped irrigation system is currently being investigated through simulation of the irrigation demand and supply network at diurnal scale.

The high pressure drip irrigation requires lesser water application rate to achieve required moisture levels because it has highest DU among the pressurized systems. This result into savings of water and pumping time thus reducing energy costs. The energy-water productivity is an integrated indicator of water and energy use in agricultural production systems. It captures the efficiency of systems which are energy intensive as well as water scarce. The IHP is one of such systems and has highest value of energy-water productivity.

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