Predicting Irrigation Return Flows to River Systems: Conceptualisation and Model Development of an Irrigation Area Return Flow Model

[1,2]Hornbuckle, J.W. [1,2,3]E.W. Christen, [1,2]G. Podger, [1]R. White, [1,2]S. Seaton, [1,2]J.M. Perraud and [1,2]J.M. Rahman

[1]CSIRO Land and Water, [2] CRC eWater [3]CRC for Irrigation Futures, E-Mail: **John.Hornbuckle@csiro.au**

Keywords: *Return flows, Irrigation Area, Irrigation and Drainage Model.*

EXTENDED ABSTRACT

Irrigated agricultural uses 72% of total water diversions in Australia and its potential to generate returns flows to river systems in terms of both quantity and quality is significant. Increased hydraulic loading under irrigation and changes in land use has lead to high water tables and land salinisation and sodification. Drainage schemes have been implemented to reduce the consequences of land salinisation. These drainage schemes contribute large amounts of salt, nutrients and sediments into natural water courses and have lead to a decline in water quality in rivers and reduced health in riverine ecosystems.

The implications of management and interventions to drainage systems are complex and often have the potential to cause significant impacts on stakeholders in the system unless careful consideration is given to all aspects of the system. There is a need to clearly understand the tradeoffs between management options and interventions and impacts on drainage return flows, and to conduct water accounting (quantity and quality) at these scales.

Hence tools or frameworks which allow all aspects of the drainage intervention to be considered and trade-offs between stakeholders investigated allow improved decision making to safeguard against solutions which only address the symptoms of a particular problem, leading to a further different set of problems, often transferring the problem downstream.

This paper presents the conceptualisation and model development of an irrigation return flow model, called “Tiddalik”, for the prediction of drainage return flow volumes and salt loads to streams and river systems. Conceptualisation of the major drivers of return flows are presented along with the interaction of land use management variables that determine generated return flow volumes and salt loads.

The Tiddalik model can be used to look at a range of management and operational options for meeting license conditions that are applied to return flows from irrigation areas. These may include flow conditions and/or quality conditions such as salinity limits/EC credits. Various scenarios are presented from increasing irrigation efficiency to large scale land use changes (i.e. changed cropping systems, drainage implementation) for their effect on drainage volumes and salt loads.

Core building blocks of the model which include evapotranspiration, soil water balance, upflux, watertable, subsurface drainage, irrigation system and on farm storage/recycling system modules and their limitations are described and discussed.

The Tiddalik model seeks to provide a transparent framework whereby users have the ability to investigate management options and trade-offs for meeting environmental targets in relation to drainage return flow quantity and quality.

1. INTRODUCTION

While irrigation is vital to the prosperity of rural communities in the Murray Darling Basin, it has also contributed to degradation of river health. Salinity has been seen as the major threat to the health and sustainability of the basins river systems after rapid rises in river salinity were recorded in the 1980's. In addition, elevated nutrient levels from agricultural drainage have increased the frequency of algal blooms.

The current political environment means that there is increasing pressure on irrigators to use water more efficiently and reduce the associated environmental impacts. The dual pressures of increasing competition for water and declining water quality have resulted in many policy initiatives over the past 10 to 15 years. Such policies have targeted pesticides in drainage water, elevated nutrient and salinity levels and more recently, the flow regime in the river systems.

In the past 10 years there has been a large increase in awareness regarding drainage water quality from farms in irrigated areas. The main water quality aspect initially of concern was with respect to pesticides (Bowmer et al 1998). This has increased to a more widespread concern including salinity, turbidity and nutrients (Crabb, 1997). These concerns have largely been driven by State-based Environmental Protection Authorities, concerned about local impacts of drainage waters. This has led to stricter regulation and monitoring of individual irrigators (e.g. cotton and other growers along rivers) and granting of pollution permits to water delivery authorities (Irrigation Companies) managing the formal irrigation areas.

Tools for assisting irrigation companies to develop strategic management plans to meet these targets have not existed in the past. This paper outlines our initial efforts at creating a model which provides irrigation companies a tool to manage their drainage return flows to river systems.

2. CONCEPTUALISATION AND MODELLING APPROACH

The complexity of the land uses occurring within an irrigation area can be seen in Figure 1. In just a small area ~4 km^2 there are multiple land uses ranging from perennial horticultural crops like grapes and citrus to annual crops such as rice and pastures which have different water requirements and management regimes. Combine this with a mosaic of varying soil types for each of these and a variety of irrigation systems ranging from continuous water ponding for rice crops to subsurface drip irrigation for the higher value horticultural crops, add to this the presence of subsurface drainage systems to control water tables, a long and varied surface drainage network and the complexity of representing such a system hydrologically becomes apparent.

Figure 1. Aerial photograph of an irrigation area illustrating the complex multiple land uses

In order to simplify this complexity to a level whereby it can be represented in a modeling environment, we can conceptually represent an irrigation area as shown in Figure 2. Our representation consists of a group of sub catchments inside the irrigation area which in turn consist of a group of farms within the sub catchment. Connection of sub catchments is provided through a surface drainage channel network.

The surface drainage channel network is represented as a node-link network, allowing users to investigate what happens at a particular node in the system. This ranges from individual sub catchments to what occurs at the outlet point back to the river system, which is where point license conditions in terms of flow, load and concentration may be applied. This conceptualization has been used for the Tiddalik model to simulate drainage return flows to river systems. The Tiddalik model is powered by the E2 framework (Perraud *et al.* 2005) and relies on many of the underlying functionality available in E2.

3. NODE-LINK NETWORK MODEL

The drainage channel network is represented as a system of 'nodes' connected by 'links'. Once a sub-catchment map has been loaded the node- link network is then defined by the user with simple mouse clicks and drags to define how sub-catchment drainage channel networks are connected (Figure 2). This node link network is used for routing the drainage water generated from sub-catchments.

A number of routing methods are available for use in the model, derived from the E2 model (Perraud et al. 2005).

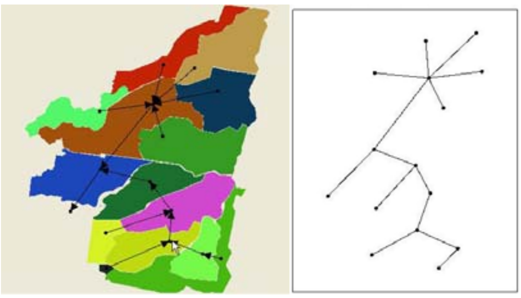

Figure 2. Node-Link network constructed from sub catchments

4. IRRIGATION FUNCTIONAL UNIT MODEL

In order to represent the hydrological processes and drainage generated from sub catchments an irrigation functional unit model is applied to the sub catchment. This represents using a 'lumped' approach the hydrological processes in the sub catchment.

The functional unit approach allows the model users to represent sub catchments as a mix of land uses with stochastic distributions of planting dates. The land use mixes describe the crop, soil, irrigation management and irrigation/drainage system. Any number of these land use mixes can be represented by a functional unit. Each of these mixes is represented by an independent water balance. These multiple water balances are then accumulated to provide an overall irrigation water demand and drainage return flow from the irrigated region.

Each functional unit consists of four key components. These are:

1. Cropping Units (CU) which represent crops, soil and irrigation and drainage systems

2. Evaporation basin component

3. Drainage recycling system component

4. Drainability component to account for the inherent topographical, drainage access and other characteristics of a functional unit that affect the rate and volume of drainage which are not represented by the node-link network (Figure 3).

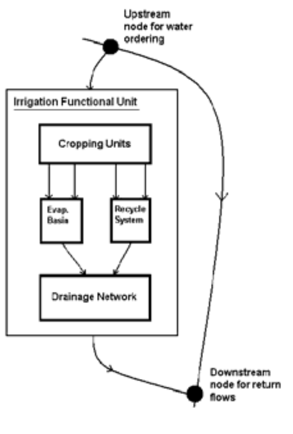

Figure 3. Irrigation Functional Unit and subcomponents

Return flows generated by the cropping units are then passed to either evaporation basin and/or recycling system modules, these have their own waterbalance. If they reach maximum capacity any return flows which are generated by the cropping units are passed directly to the drainage channel network.

Modelling approaches taken to represent these individual components were selected based on two criteria. These were:

1. That input data requirements where likely to be available to model users

2. That where possible standard or well understood/validated approaches were used

This was undertaken to ensure that the model could be utilized by end users with data that they would typically have available or could easily collect.

4.1. Cropping Unit

Cropping Units (CU) are used to represent the irrigated land uses. The CU represents a discreet land use within the sub catchment which has the potential to generate return flows. CUs dictate the make up of various components of crop, soil and irrigation system parameters that form a water balance. Each CU has a unique combination of crop type, soil type and irrigation/subsurface drainage system. This determines the behavior of the water balance of the CU and ultimately the drainage return flows, either through surface runoff or subsurface drainage. Salinity values are assigned to the surface and subsurface drainage of each CU. The module allows a very large number (hundreds) of CUs.

In applying the model to an irrigation area the first step involves developing a set of cropping units which adequately represent the cropping systems which are present in the sub catchments. In practice this would most likely be accomplished with 10-20 CUs.

Although each CU represents a major land use inside the irrigation area, it does not take into account the various individual land use units (i.e. individual paddocks) which make up the cropping unit. For example there could be 50 paddocks within an irrigation area that all have rice grown on clay soil using ponded water. The water balance for each of these 50 paddocks will not be identical, due to a range of factors, different crop planting dates are particularly important. In order to capture this complexity the user can define the number of paddocks which form a subset of the CU and a planting duration over which paddocks have been sown. The model then constructs a series of water balances for each of these paddocks and assigns a random planting date (stochastic distribution - within user defined limits) to each of the water balances. This accounts for multiple paddocks being represented by the CU. So while there may only be 10 CUs representing an irrigation area each cropping unit may consist of 50 similar paddocks so 500 individual water balances will be run to simulate the individual paddocks which make up the CU. Figure 4 shows an example where for 3 cropping units a total of 14 individual water balances are being modeled.

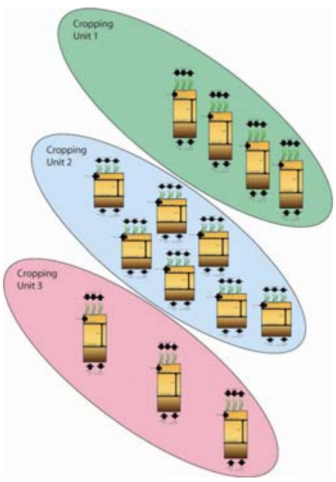

Figure 4. Cropping Units consisting of multiple waterbalances

Soils

Soils are characterised by drained upper limit, lower limit and saturation volumetric soil contents, saturated hydraulic conductivity, surface storage and infiltration properties. These are specified for each layer.

Soil layering is user defined and can be any number of layers and depths depending on available data. Infiltration into the soil profile uses a time to ponding approach outlined by Broadbridge and White (1987). Drainage through the layers uses a cascading tipping bucket concept. Upflow from wet soil layers to drier layers is determined from an internally calculated diffusivity gradient (Meyer *et al.* 1997).

This approach has been used extensively in irrigated cropping models and found to adequately represent the water balance under numerous field conditions. The approach is also typically more robust than numerical models based on the Richards equation and requires less input data.

Crops

Crop water demand is calculated using the FAO 56 Methodology (Allen et al. 1998). This approach was taken due to the large user base and knowledge of crop coefficient which has been developed throughout the world ensuring input data is readily available to represent most crops typically found in irrigation areas.

Crop water use is directly related to reference evapotranspiration (ETo). The crop's water use is determined by multiplying the ETo by a crop coefficient (Kc). The crop coefficient adjusts the calculated reference ETo to obtain the crop evapotranspiration (ETc). Different crops will have a different crop coefficient and resulting water use.

$$ET_c = ET_o \times K_c$$

Where

ETc = crop evapotranspiration/crop water use (mm)

ETo = calculated reference ET for grass (mm)

Kc = crop coefficient

There are four crop coefficients used for each crop through the growing season depending on the crop's stage of development. Crop growth periods are divided into four distinct growth stages; initial, crop development, mid season and late season (Figure 5). The length of each of these stages depends on the climate, latitude, elevation and planting date.

Local observations are recommended for determining the growth stage of the crop and which Kc values to use, however failing this generic crop coefficients can be obtained from Allen *et al.* 1998 which lists crop factors and stage development days for the commonly irrigated crops.

A coefficient is also used to represent bare soil evaporation during the non-crop period. Therefore in order to model the crop water requirements a total of five parameters are used for each crop. These are four crop coefficients values representing initial, mid and end crop coefficients and a non-cropped period coefficient.

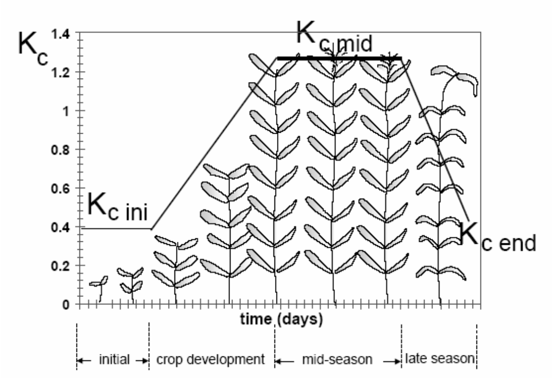

Figure 5. Crop coefficient curve showing crop growth stages (Allen *et al.* 1998)

Root Depth

Root depth is modelled using an algorithm developed by Borg and Grimes (1986) and was chosen due to its simplicity and readily available data requirement of maximum rooting depth. The model was validated on 48 irrigated crop species under various field conditions and found to adequately represented root depth development in irrigation conditions (Borg and Grimes 1986). This model describes root depth by a sigmoidal development of the roots from planting date until maturity. The empirical model is given by:

$$RD = RD_{\max}\left[0.5 + 0.5 \times Sin\left(3.03\frac{DAP}{DTM} - 1.47\right)\right]$$

Where

RD = Root Depth (m)

RDmax = Maximum Root Depth (m)

DAP = Day after Planting (Day)

DTM = Days to Maturity (Days)

The variable DTM is assumed to be equal to the initial + crop development period. The roots are then assumed to stay at a constant depth until the crop finishes. Therefore the only additional parameter which needs to be defined is the maximum rooting depth of the crop.

<u>Irrigation and Drainage Systems</u>

Irrigation is modeled using two methods of scheduling. These methods are irrigation determined by soil water deficit or irrigation determined by accumulated ETc. A description of each of these methods and there functionality is given below:

Soil Water Deficit Irrigation

Using this method irrigations are scheduled by the soil water deficit determined from the soil water balance. A trigger level is set by the user which determines the soil water deficit at which irrigation will occur. Once the soil water balance determines that the trigger water deficit has occurred, then an irrigation occurs at the end of that day. The irrigation amount is determined by the trigger deficit level and refill %. The refill % is set by the user and determines how much of the soil water deficit is replenished by irrigation. This determines the total volume of water applied for a given irrigation amount.

Irrigation Amount (mm) = Trigger (mm) x Refill (%)

This method allows excess (>100%) or deficit irrigation (<100%) to occur.

ET Irrigation

This irrigation method schedules irrigation based on an accumulation of ETc. This method does not take into account the soil water balance. Irrigation amounts are determined in the same manner described above for soil water deficit irrigation. This method is more representative of irrigators that schedule by observation of climatic conditions or gut feel, whilst the soil water deficit method obviously is representative of irrigators who use soil moisture monitoring devices to schedule irrigations.

Subsurface Drainage

The Hooghoudt drainage equation is used for the calculation of subsurface drainage volumes from pipe or open drains. This model has been used extensively for the design of subsurface drainage systems throughout the world and has been field validated under a number of conditions on various soil types (Talsma and Haskew 1959). The Hooghoudt model is given by:

$$q = \frac{8K_2 dh}{L^2} + \frac{4K_1 h^2}{L^2}$$

Where:

q: drainage rate (mm/day)

L: subsurface drain spacing (m)

K_1: saturated hydraulic conductivity of soil above drains (m/day)

K_2: saturated hydraulic conductivity of soil below drains (m/day)

d: equivalent depth above the impermeable base

h: water table height above drains (m)

Hydraulic conductivities are calculated from the input soil parameters with a depth weighted average for hydraulic conductivity above and below the drains. Watertable height is calculated from the soil water balance. The depth and spacing of the drains are user defined parameters.

4.2. Evaporation basins and Recycling systems

Evaporation basins and drainage recycling systems are modeled using a simplified approach based on BASINMAN (Wu *et al.* 1999). A relationship is specified between surface area and storage volume to calculate evaporation based on defined evaporation factors for storages given by Morton (1986). A waterbalance with the basin or storage acting as a single bucket is then undertaken. Gains are associated with rainfall and inflow from the cropping units and losses from evaporation and extraction in the case of recycling systems.

4.3. Drainage Network

The drainage network which is lumped inside the irrigation functional unit (i.e. not represented by the node-link network) is represented by a simple waterbalance on the network. Using the same principles defined for evaporation basins. This requires knowledge of the extent of the network.

5. MODEL OUTPUTS

Outputs from the Tiddalik model include the flow, salinity and salt load over time for any node or irrigation functional unit in the system. Model outputs can be compared with field measured data or monitoring stations for calibration and model testing. For example, flow and salinity data measured at gauging stations can be directly compared to those predicted by the model at node junctions.

Various scenarios can then be modelled and results saved to compare alternative management and interventions to meet license conditions imposed on the system. A broad range of alternative scenarios from single point interventions to broad scale changes in land use and irrigation efficiency can be investigated for their impact on drainage flows.

Figure 5 shows typical output from the GUI for modeled drainage flows for selected nodes in the Coleambally Irrigation Area.

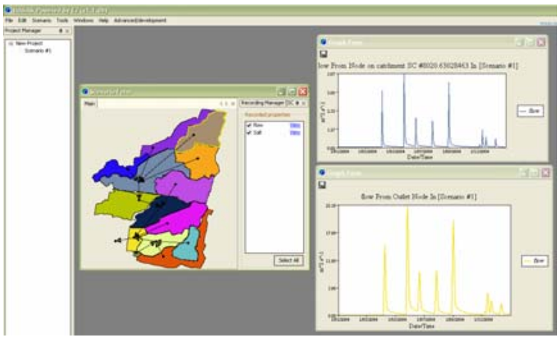

Figure 5. Node and Functional Unit outputs of drainage flows from the network

6. POTENTIAL APPLICATIONS OF THE MODEL

A number of potential applications for the model exist. Potential applications of the model include but are not limited to:

- Assessing the impact (EC limits/credits) of system efficiency gains. i.e. Improving irrigation efficiency across a region or district
- Assessing impacts of land use management change i.e. change in cropping systems from rice to maize due to lower water availability
- Assessing magnitude of impacts of new subsurface drainage programs
- Investigating options such as Serial Biological Concentration schemes, regional evaporation basins and storages and strategic location of these features
- Identifying problem regions so that investment/grants can be targeted for more impact per $ spent
- Assessing the effectiveness of potential strategies/management plans i.e. crystal balling
- Communicating and reporting on return flows for meeting environmental license conditions and communicating impact of actions taken to irrigators and the community.

7. MODEL LIMITATIONS AND FUTURE DIRECTIONS

There are a number of simplifying assumptions and limitations with the Tiddalik model. General limitations include:

- Regional groundwater systems in irrigation areas are not represented. While the model does account for groundwater extraction through subsurface drainage it does not include a regional groundwater model.

- Crop rotations are not represented at a point scale. Waterbalances are conducted by repeating a particular crop. The mix of crop waterbalances and their associated area provide the broad representation of the mix of crops at any one time. The mix of crops in irrigated areas does not change rapidly and hence is assumed to be static.
- Salt loads are modeled by applying a concentration to the flow volumes. Hence the model does not track salt stores in the soil.

Future development of the model will include a crop growth model for yield prediction and a solute transport component for tracking soil salt stores and investigating effects on yield. Interaction of the node-link network representing the surface water drainage network with groundwater interactions on the network will also be incorporated in future versions of the model.

8. CONCLUSIONS

The implications of land use change, irrigation drainage management and other interventions on drainage flows form irrigated areas are complex and often have the potential to cause significant impacts on stakeholders in the system unless careful consideration is given to all aspects of the system. There is a need to clearly understand the tradeoffs between management options and interventions and impacts on drainage return flows, and to conduct water accounting (quantity and quality) at these scales.

Hence tools or frameworks which allow all aspects of the drainage intervention to be considered and trade-offs between stakeholders investigated will provide improved decision making.,

The Tiddalik model which has been developed seeks to provide a tool whereby users have the ability to investigate management options and trade-offs for meeting environmental targets in relation to drainage return flow quantity and quality.

9. ACKNOWLEDGMENTS

We would like to thank the following organisations for providing reports and data for this study:

Coleambally Irrigation Co-Operative Ltd, Goulburn-Murray Water, Murrumbidgee Irrigation Ltd, Sunraysia Rural Water Authority, Murray Irrigation Ltd,

Particular thanks are extended Matthew Linnegar, Sigrid Tijis, Derek Poulton, Arun Tawari, Andrew Sinn, Penne Sloane, Ken Smith and Monique Aucote who provided feedback on the functionality of the module and/or test data.

10. REFERENCES

Allen, R.G., Pereira, L.S., Raes, D. & Smith, M. 1998, Crop evapotranspiration – Guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56, FAO, Rome

Borg, H. & Grimes, D.W. 1986, Depth Development of Roots with Time: An Empirical Description, Trans. ASAE, 29(1), 194-197

Broadbridge, P. and White, I. 1987. Time to Ponding: Comparison of Analytic, Quasi-Analytic and Approximate Predictions, *Water Resources Res*. 23: 2302-2310

Crabb, P. (1997) Murray-Darling Basin Resources. Murray Darling Basin Commission: Canberra, Australia.

Meyer, W., Godwin, D. and White, R. (1997). SWAGMAN Destiny: A tool to predict productivity change due to salinity, waterlogging and irrigation management. In: Role of Computer Modelling in the Development and Implementation of Land and Water Management Plans for Irrigated Catchments. Murray-Darling Basin Commission Drainage Program Technical Report, No. 5. May 1997. pp 139-142.

Morton, F.I. (1986) Practical estimates of lake evaporation, *Journal of Climate and Applied Meteorology*, 25(3), 371-387.

Perraud, J.-M., Seaton, S. P., et al. (2005), The architecture of the E2 modelling framework, Proceedings of MODSIM 2005

Smedema, L.K. & Rycroft, D.W. 1983. Land Drainage: Planning and Design of Agricultural Drainage Systems, Cornell University Press, Ithaca, New York

Talsma, T. & Haskew H. (1959) Investigation of water-table response to Tile Drains in comparison with theory, *Journal of Geophysical Research 64:11: 1933-1944*

Wu, Q., Christen, E.W., and Enever, D. (1999). "Basinman - A water balance model for farms with subsurface pipe drainage and on-farm evaporation basin". CSIRO Land and Water, Griffith, NSW, Australia. Technical Report 1/99