A pragmatic water-balance based protocol for assessing water quality from agricultural lands

David Freebairn[A] Dan Rattray[B] Mark Silburn[C] and Will Higham[D]

[A]Conics Ltd, Fortitude Valley, QLD, Australia, Email david.freebairn@conics.com.au
[B]Treecrop Technologies, Toowoomba, QLD, Australia, Email dan.rattray@treecroptech.com.au
[C]Department Environment and Resource Management, Toowoomba, QLD, Email Mark.Silburn@derm.qld.gov.au
[D]Reef Catchments, Mackay, QLD, Email will.higham@reefcatchments.com.au

Abstract
Poor water quality from agricultural lands has come into focus worldwide as the pressure for increased food production has pushed production to less stable environments and community attitudes demand more environmental accountability. Even in a dry continent like Australia, water quality attracts community attention when algal blooms occur in ephemeral streams and iconic natural assets such as the Great Barrier Reef (GBR) are threatened by poor water quality. In order to better allocate resources toward improved natural resource management, there is a need to quantify water quality signatures of alternative land use and management practices, along with impacts on receiving environments. A pragmatic approach to quantifying water quality is described. Application of water balance models support the merging of expertise from a range of disciplines and literature.

Key Words
Runoff, drainage, model, erosion, sediment, nutrient, pesticide, natural resources.

Introduction
Deterioration in water quality entering freshwater and marine systems has been attributed to agricultural worldwide. In most cases, agricultural practices have resulted in soil disturbance, exposure of bare soil and changes in water use patterns which increase loss of water as surface runoff and deep drainage. Changes in erosion rates and water quality have in many cases resulted in an order of magnitude increases in sediment and agri-chemical loads compared to natural systems.

A common feature of reports of field experiments dealing with water quality is that data are either incomplete (e.g. only some elements of water quality are reported), constrained by a short record or insufficient site descriptions are available to generalise results. Literature, while reporting detailed results at a range of temporal and spatial scales, often presents conclusions from experiments with disclaimers such as the experimental period being drier or wetter than the long term average. It is uncommon in NRM literature that simple annual averages of water balance and pollutant load are reported, making it difficult for quantitative evaluation of management options across locations, soil types and management options. In short, empirical studies are limited by the narrow range of conditions that have been observed, yet they can be used to inform more generalised relationships. Water balance models adapted to consider soil erosion, sediment, nutrient and pesticide losses offers a pathway to deal with these constraints.

The need for quantification
Evaluations of large public NRM investments in Australia have struggled to demonstrate impact after decades of investment by public and private sectors. In some cases this “lack of evidence” is a result of a variable climate making it difficult to observe changes in attributes such as water quality or it might be argued that investments were either misguided or inefficient, resulting in little change. This situation is unacceptable for investors who are seeking a quantitative basis for allocating resources and evaluating impacts.

While management practices have been developed that reduce the impact of agriculture on soil and water resources, allocation of investment in natural resource management (NRM) is often based on qualitative evaluations of alternatives. From an economic viewpoint it stands to reason that we should know the impact of intervention options and costs associated with implementing changes. NRM agencies are being asked to quantify improvements in natural resource attributes such as water quality, beyond the traditional reporting of activities such as attendance at field days or number of farmers adopting “best practice”.

This paper describes a relatively pragmatic approach, in that: it is physically based; uses best available information; can capture information from a range of disciplines; and is sufficiently rigorous to support decision making.

The approach

The principle behind a water balance driven approach is that pollutants are moved by water and an estimate of water flow is a basis for estimating water quality. Water balance models deal with water flows explicitly and when combined with descriptions of soil, vegetation and landscape features provide a physical basis for estimating water quality (Figure 1). Models can act as collections of summaries from experimental studies.

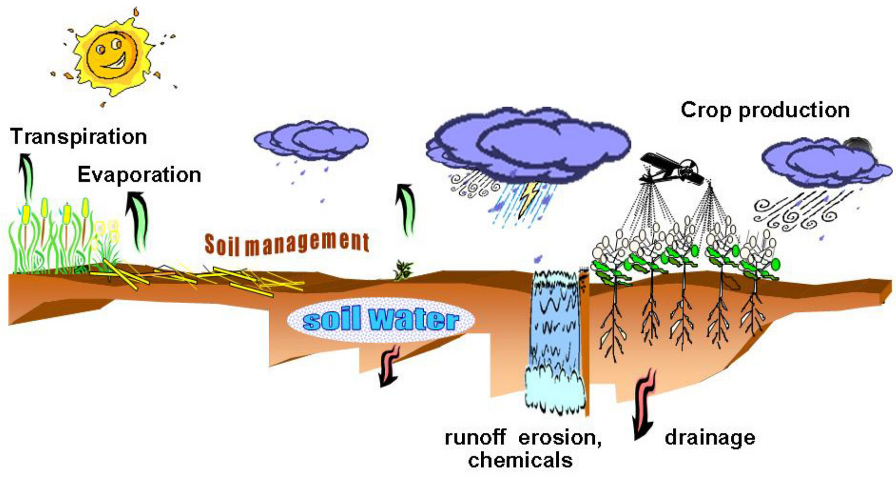

Figure 1. Schematic of an agricultural system showing some dynamics of vegetation cover, evapotranspiration, soil water, runoff and deep drainage.

A time series of water flows can be combined with relationships from the literature and local empirical studies to provide estimates of soil, nutrient and pesticide movement. Figure 2 is a simple representation of the main factors involved in determining water quality from a specified land use and environment.

$$WQ = f\left(\text{runoff, slope, cover, cohesion, concentration}\right)$$

Figure 2 A function describing the main factors controlling water quality (WQ) at a paddock scale. Runoff and slope are the driving forces for movement while cover describes the exposure and hydraulic roughness of the surface. Cohesion describes the ease with which material can be dislodged while concentration describes the amount of chemical available in the soil.

Water balance accounting is intrinsically conservative in that mass balance must be preserved. In most cases there are natural resets (saturated or completely dry) in a time series which adds stability through time. Well understood limits to estimates of water store sizes and rates provide further checks to simulation based estimates. For example, plant available water capacity (PAWC) of a soil is known with reasonable accuracy. When water inputs exceed PAWC, water must become either runoff or deep drainage. The allocation of water excess to runoff or drainage can be assessed based on soil properties, stream flow patterns and field observations. Typically, models operate on a daily time step, being the period of most common weather observation, although there are no intrinsic limitations to the length of time step (from seconds to weeks or months).

Understanding how agricultural and pastoral systems function in a landscape is the domain of many disciplines. This requires an approach that can bring a breadth of knowledge to bear on solutions. Models provide a mechanism to bring together knowledge from a range of sources. For example, the processes presented in Figures 1 and 2 require an understanding of soil-climate-management interactions, pesticide and nutrient processes, hydrology and erosion.

The process

In order to apply water balance models to estimating water quality signatures, the following steps have been applied:

- Develop conceptual models of water quality-management interactions based on experience from literature and experts. This ensures the main management options are identified and provides an interface for discussion between land managers, scientists and modeller;
- Using subset of climate, soil and crop system combinations, apply model(s) to generate a 1st pass estimate of water quality signatures;
- Engage local experts (soil scientist, agronomist, water quality specialist, economists) to better describe systems, bring local data and experience to the Table and build local ownership (ask - are the water balance and water quality estimates sensible? Why not?)
- Refine model estimates based on local data and knowledge and summarise outputs
- Summarise management options in terms of effectiveness in reducing pollutant loads and costs to implement ($/reduction in load from baseline condition).

Note that there is no requirement for collating detailed experimental data typical of most modelling exercises where intensive model tuning would occur; with statistics describing goodness of fit for several physical attributes e.g. biomass, hydrology and water quality. Model calibration is a necessary requirement for complete analysis of key datasets but it is impractical when best bet estimates of water quality are required for a number of management options in a short time frame with limited resources. Skills derived from detailed modelling are a preferred requirement for the process described here but the key requirement is the ability to synthesise data with a wide range of quality (sensibility testing), informed by water balance estimates and known relationships between land conditions, hydrology and water quality.

For this exercise we used the Howleaky? model (Freebairn *et al.* 2003, McClymont *et al.* 2008), a derivative of PERFECT (Littleboy *et al.* 1992) and similar to APSIM (McCown *et al.* 1996). Howleaky? was chosen as the modelling environment as the authors were familiar with the model which is well informed by extensive field and laboratory studies of agri-chemical behaviour in the Queensland environment (e.g. Freebairn and Wockner 1986, Silburn 2003, Rattray *et al.* 2007).

In summary, runoff and deep drainage are modelled essentially the same as in most water balance models. Transpiration is dealt with in a simpler manner than many models by describing a Leaf Area or green cover distribution through time rather than a fully dynamic crop growth model. This allowed us to efficiently capture expert opinion on growth habits of a wide range of vegetations while not compromising the basic elements of water balance accounting. Predictions of pesticide losses are based on concentration of pesticide in the soil which is a function of chemical half life. The amount of pesticide in soluble and sediment phases is dependent on the sorption coefficient of the chemical. Groundwater losses were not explicitly considered beyond estimates of accession to groundwater associated with deep drainage at the paddock scale. Risks of pesticide and nitrate accession to groundwater associated with deep drainage are described qualitatively based on estimates of chemical loads in the soil through time. Qualitative assessment of environmental toxicity can be made based on chemical properties, chemical loads and concentrations. A combination of load/concentration probabilities and toxicities provide an assessment of the relative performance of a range of land uses and management practices. Current practice is used as a benchmark for environmental performance.

In practice, a water balance analysis requires accessing climate, soil and land use and management descriptions that are compatible with the model. Figure 3 provides a graphical view of inputs and outputs for a typical water balance analysis. One feature of any synthesis activity is that there will be many uncertainties and model output should not be viewed literally – it is a “best bet” estimate informed by water flows. Data is brought together from a range of sources. For example, soil descriptions may come from soil surveys from related landscapes, hydrological data from local or adjacent stream monitoring networks, descriptions of relationships between soil conditions and water quality from controlled plot studies or models such as the USLE (Wischmeier and Smith 1978), vegetation patterns from agronomists and farmers, and climate records from public databases. The quality and local relevance of inputs will be varied, yet together can provide a picture of site conditions, hydrologic and water quality responses. A water balance analysis adds value to these disparate data sources.

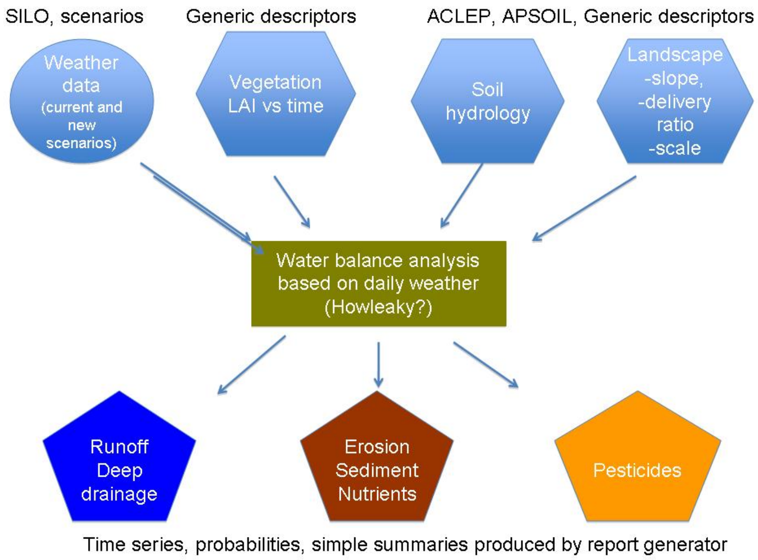

Figure 3. Schematic of linkages in a water quality modelling environment between inputs (weather, vegetation cover, soil hydrology and landscape), water balance and water quality outputs.

Conclusion

Water balance models provide a well tested approach to bring data together from a wide range of sources in order to provide a credible set of estimates of water quality for a specified land use when little empirical data are available. Where empirical studies are limited in terms environmental conditions and land conditions, models are an efficient tool for "stretching" data and knowledge in time and space. To date, the application of water balance simulation has been in the hands of a few specialist "modellers". The protocol presented here has been tested in the GBR catchments of eastern Australia, and while estimates of water quality are open for discussion and disagreement, the resulting estimates provide a defendable basis for assessing the efficiency of alternative management options for improving water quality at the farm scale. The process is relatively efficient and confidence in estimates will improve as more data and experience is brought to the Table.

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