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Review of the current understanding of irrigation mosaics

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Executive Summary

The future of northern Australia and debate about using more of the water in the north for irrigation is receiving increasing attention. Making informed decisions about the future of irrigation in the north will require greater understanding of tropical systems and whether irrigation can be designed and managed in a way that is more in harmony with the natural ecosystems.

Irrigation mosaics, involving smaller discrete patches of irrigated land dispersed across the landscape, may offer an alternative to traditional large-scale contiguous irrigation systems. This might be particularly attractive (at least at first glance) as a means of delivering improved social and economic opportunities for rural and remote (commonly indigenous) communities in northern tropical Australia. However, the longer-term environmental impacts of irrigation mosaics, and especially in tropical environments, in space and time, are still largely unknown.

Irrigation can bring many benefits to individuals, communities, and regions, but it can also lead to unwanted environmental consequences. The impacts may be local, or regional, such as in coastal zones and river basins. For example, the intensification of agriculture often results in increased use of pesticides and fertilizers. These can percolate through the soil and/or move with drainage water resulting in pollution of both groundwater and surface waters. Inappropriate and/or non-uniform on-farm irrigation can provide excess runoff and deep percolation. Runoff water can carry sediment, animal waste, and other soil surface pollutants into surface water, which may be used further for irrigation or other ecosystem services. The cumulative effect of these may impair the long-term sustainability of both an irrigation project and associated economic activities in the surrounding area. In making changes to existing irrigation systems, or designing new irrigation areas, it is necessary to determine what unwanted impacts and what compensatory benefits are likely to occur.

Existing knowledge on irrigation mosaics and implications within the context of sustainable development is very limited. However, there are some findings and lessons learned from studies of other systems, dealing with spatial patterns in the landscape, which can be used to help improve analysis and understanding of irrigation mosaics.

Ecological research has shown that patch size, shape and spatial arrangement of the patches are important characteristics in the landscape. They affect processes, patterns and organisms in different ways. Landscape ecology can track ecological processes across a range of spatial, temporal and cultural scales allowing us to understand the real or potential effects of human land use and planning.

Ecotones, which are zones of transition between adjacent ecological systems, are important characteristics of mosaics and play an important role in energy and material fluxes. Ecotones created in an agricultural mosaic play a fundamental role in minimising erosion, improving the microclimate, and in absorption of nutrients. The importance of the ecotone is particularly emphasized in restoration ecology. Ecotones are more easily manipulated than other systems such as forests or grasslands. Over the long term, ecotones are important areas for maintaining a balanced mosaic and can serve as sanctuaries for many species of plants and animals. Irrigation mosaics could be used to create or enhance ecotones in the landscape for greater biodiversity, improving the microclimate, minimising erosion, and in absorption of surplus material (nutrients, sediments, solutes) flowing from the surrounding fields, thus decreasing the discharge of the irrigation “waste” out of the irrigation area - a possible environmental off-site effect. On the other hand, fragmentation, which involves discontinuity of patches, can be detrimental for biodiversity. Fragmentation can increase the vulnerability of patches to external disturbance, for example wind storm or drought, with smaller land fragments likely to be more strongly influenced by the surrounding areas. In addition, tropical flora and fauna are often more vulnerable to fragmentation than temperate ones.

In a study of disposal basins in irrigated areas of the Riverine Plains in the Murray Darling Basin the leakage rate under the larger basins was found to be less than under the smaller basins. While we can learn about mosaic features from this work on disposal basins care is needed in drawing analogies with irrigated systems. The disposal basins involve saturated (ponded) conditions, but irrigated areas usually involve unsaturated conditions, so leakage from patches of irrigated land are likely to be much less than leakage from disposal basins (patches of ponded water).

Studies on the effect of advection on enhancing evapotranspiration and water use in irrigated mosaics indicate that evaporation can be enhanced by 10-20% in small irrigation patches compared with larger irrigation areas While further research is needed in this area, current indications are that irrigation mosaics may evaporate more and hence require more water than large scale irrigation schemes, which may not be that attractive in a dry environment, particularly in the dry tropics of northern Australia.

In summary, it appears that irrigation mosaics could have negative (eg more evapotranspiration, increased operational losses) positive (eg filtering of nutrient surpluses, enhanced biodiversity, less erosional losses) effects on the environment. These potential impacts need to be studied carefully, and design criteria in terms of size, shape, density, connectivity and spatial arrangement in harmony with the landscape need to be established.

Ecological and hydrological research has also provided tools for studying landscape spatial patterns but careful study and adaptation of these to irrigation mosaics will be required.

For example, the concept of systematic regional planning which was developed for the South Australia River Murray Corridor can be used for regional planning of land use mosaics (also applicable to irrigation mosaics) once the biophysical and economic principles of mosaics are established. Systematic regional planning, based on decision theory, can be used to identify geographic priorities for NRM actions that most cost effectively meet multiple-objective regional targets.

Knowledge gained from the analysis of injection and extraction wells offer useful approximations to flow in groundwater for irrigation patches. Multiple capture wells have been used to prevent contamination of surface and groundwater systems and the design criteria for these may be useful in assessing the spacing of irrigation mosaics.

Geostatistical methods used in precision farming may also be of use in analysis of where to site irrigation in the landscape.

Numerical models that are designed specifically for analysing mosaics are scarce. However, existing process based numerical models could be adapted and applied to mosaics. The model should simulate surface and sub-surface flow at a daily time scale or finer and also process input and output in a GIS format. In addition, the models should simulate solute (salt, nutrients and agrochemicals) transport. MIKE-SHE and MODFLOW have potential to satisfy these criteria and the SWAT and HEC-GeoHMS models could be considered although they have no sub-surface component. These models have the capability to overlay map layers of soil, land use and weather and other spatial information suitable for analysing mosaics. There may be other suitable models as well that could be applied to this work and more effort is needed to explore the full range of opportunities.

This review provides a framework for further study of irrigation mosaics and their potential environmental impacts. Particular effort needs to be given to studying the effect of patch number, size, shape and connectivity on evapotranspiration from irrigated patches of land within a mosaic structure, the fate of solutes, recharge to groundwater and the surrounding land, soil and water salinisation, groundwater quality, and system losses and biodiversity.

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1. Introduction

Irrigation is a human devised process for changing the natural water and energy balance at a point in the landscape with the desire to enhance plant production. Irrigation is usually required for agriculture in regions where water is in limited supply due to lack of precipitation during some part of the growing season. In northern tropical Australia the climate is dominated by monsoonal systems with distinct wet and dry seasons. The wet season occurs through the summer to autumn period and coincides with periods of high evapotranspiration. The dry season occurs through the winter to spring period when water deficits can be substantial.

This pattern is distinctly different to that from southern Australian irrigation regions which are characterised by lower water deficits in the winter, but often high deficits at other times of the year and intermittent wetting events which can fill the soil water profile. In northern Australia, summer dominant, high intensity rainfall result in highly variable runoff and streamflow in most regions. Scarcity of rainfall and streamflow during dry winter months together with very high evaporation rates severely limit dryland cropping and necessitates use of groundwater or large above ground storages for irrigation during the dry season. In the drier regions of north Australia, high evaporation, intermittent streamflow and very low relief mean that it is seldom economically viable to build large storages that can reliably supply water through the dry season (Petheram and Bristow 2007). On-farm dams might be an alternative to larger scale storages in the north, although with short duration, high intensity flows, the opportunity to harvest water may be limited.

Most irrigation areas in Australia are characterised by large-scale contiguous irrigation systems within a region. Few, apart from market garden areas close to large cities, consist of small patches separated by larger tracts of unirrigated land. The large irrigation areas are attractive from an engineering point of view as they offer ‘economies of scale’. However, they have also resulted in environmental changes and problems associated with high water tables, salinisation, and major changes to natural river flows.

An alternative to the large contiguous irrigated systems would be to have a number of small, localised irrigated areas dispersed as a mosaic across the landscape. Trying to improve understanding of mosaics and what benefits they may deliver over traditional large scale contiguous irrigation systems is of particular interest in trying to help work out what role irrigation may play in the future of northern tropical Australia. In the north, land ownership is different than in the south with indigenous Australian communities managing large proportions of the land. Mosaic style irrigation development may present an opportunity to some communities for sustainable development enterprises. Small-scale mosaic irrigation may also offer opportunities for existing large-scale cattle stations to diversify and integrate sustainable irrigation with other enterprises (Petheram and Bristow 2007). A key question in thinking about mosaics is would they be an advantage or not? In this report we examine some of the issues associated with irrigation mosaics. We focus in particular on the bio-physical effects of irrigation mosaics compared to large scale contiguous irrigation systems.

This report also provides a framework for further work on irrigation mosaics. Our search of existing literature has shown that there is little information on irrigation mosaics per se, and none from tropical regions, so we draw mostly on information from studies on mosaics in natural and other systems.

1.1. Definition of mosaics

Mosaics or patchiness is referred to as spatial variation of some factor in the landscape. Spatial heterogeneity due to patchiness in the landscape characteristics can be due to climatic, geomorphological or landuse patterns imposed by humans. These patterns are often termed mosaics and various attempts at characterising these have been used (Gardner et al, 1987; Milne, 1992; Wiens et al. 1997; Nikora et al. 1999; Hoffman and Greef, 2004). Patchiness can be continuous or discrete, and patches can vary in size, shape, intensity, spatial configuration, and interconnectedness. The patches in any fluvial landscape are linked by hydrological connectivity. This hydrological connectivity is an important aspect of mosaics response to external changes such as landuse, climate, or irrigation.

Irrigation mosaics refer to irrigation schemes where smaller discrete patches of land dispersed across the landscape are irrigated as compared to large scale contiguous irrigation systems (see Figure 1).

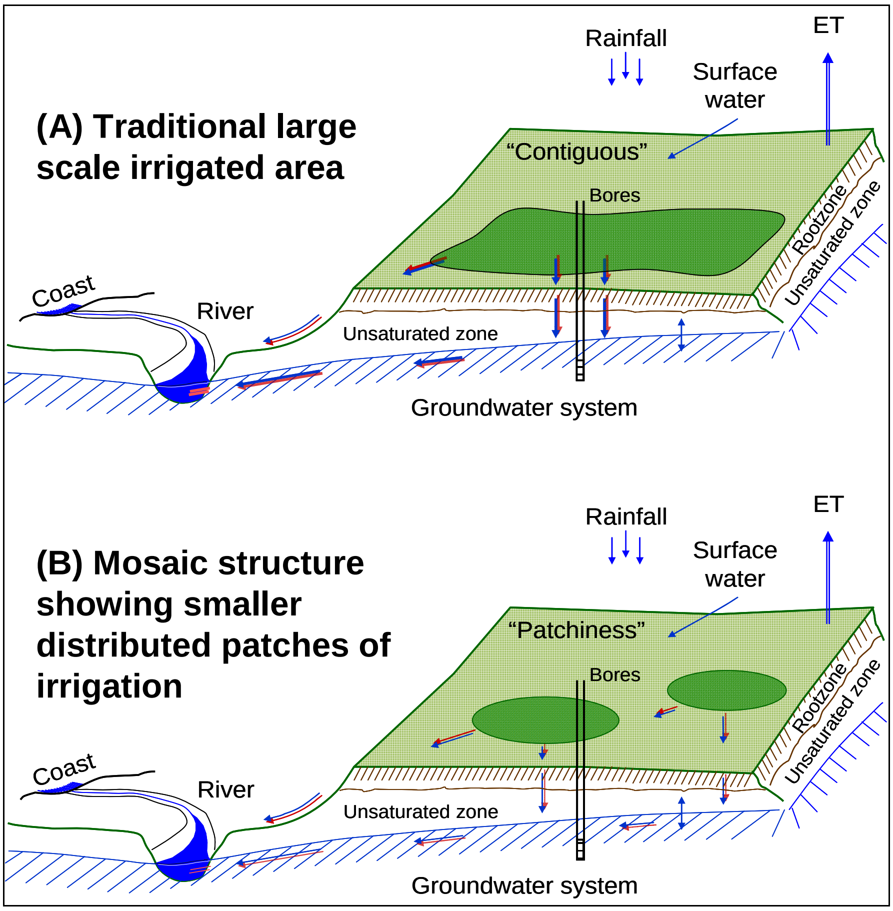

Figure 1. Schematic showing basic features of large contiguous irrigation compared with irrigation mosaics involving smaller patches of irrigation distributed across the landscape.

In this report we are more interested in the effects to the hydrology of a region if a man-made pattern with regard to irrigation is imposed on the existing natural system.

Under these conditions we can characterise the system in terms of some length scale that allows us to examine the effects of the size of the mosaics on the hydrological properties. We can consider the characteristics of the spatial extent of most mosaics as being described approximately by an ellipse (Figure 2). The perimeter (P) and area (A) of an ellipse are given by:

$$P = 4a\int_0^{\pi/2}\sqrt{1-\left(\frac{a^2-b^2}{a^2}\right)\sin^2\theta}\; d\theta \approx 2\pi\sqrt{1/2(a^2+b^2}$$ [1]

$$A = \pi a.b$$

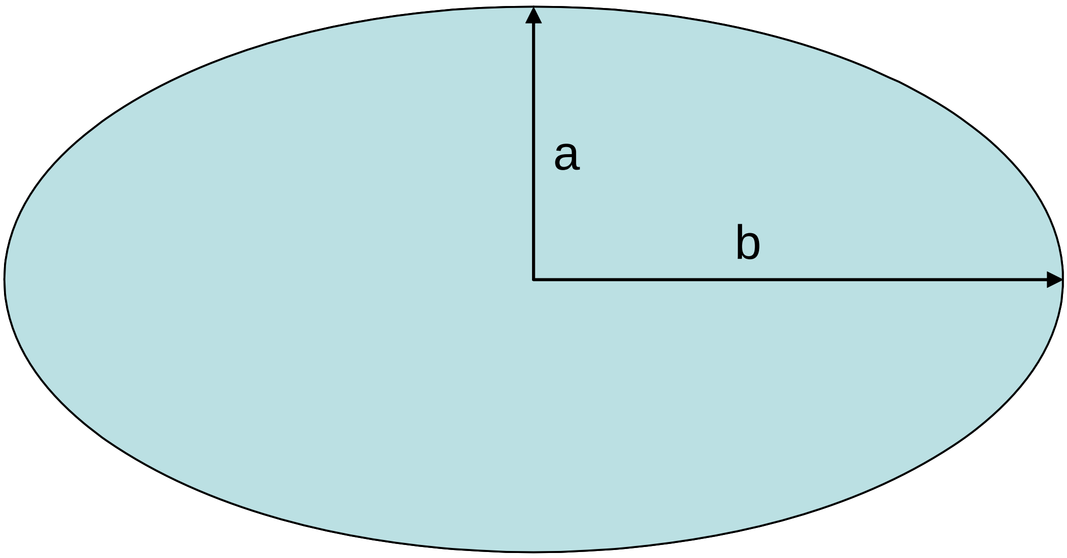

Figure 2. Ellipse with characteristic major axis, a and b.

We have chosen an ellipse, as when the axis lengths are the same it becomes a circle (special case of an ellipse) and it avoids the problems with corners associated with rectangles. The scaling that can be done using such idealised objects will be explored in more depth in a subsequent report and for a circle has been partially explored by Cook *et al.* (2006). In Cook *et al*. (2006) they used the concept of a marginal cost or benefit associated with the area irrigated and showed that for a power law scaling rule, the benefit or dis-benefit of mosaics depended on the value of the power. These and the associated ellipse shapes will be presented in more depth in a subsequent report (Cook *et al*., 2007). In a mosaic we will have patches spread throughout a region and the total area will then be the sum of each patch. If an irrigation scheme was implemented such that it consisted of a number of smaller patches that will make up an irrigation mosaic rather than one contiguous irrigated area, then there maybe consequences in terms of the impact of the irrigation scheme in having a mosaic arrangement compared to a contiguous area. Here we will not explore these ideas further but will do so in later publications.

Patch shapes are often described by area, perimeter, long axis or short axis. As patch shapes are dictated by natural or artificial interventions, they are more likely to be compact-shaped on plains and convoluted on slopes. Inter-patch variability is also more pronounced on slopes than plains. Skidmore (1987) indicated that mass flow is strongly affected by lobes of convoluted patches. There are several measures used to characterise patch shape.

Measures based on lengths of axes

Form (Davis, 1986) $F = \frac{l}{w}$

Elongation (Davis, 1986) $E = \frac{w}{l}$

Measures based on Perimeter and Area

Compactness (Bosch, 1978; Davis,1986) $K = \frac{2A\sqrt{\pi}}{P}$

Circularity (Griffith, 1982; Davis, 1986) $C = \frac{4A}{P^2}$

Measures based on area

Circularity (Unwin, 1981; Davis 1986) $C = \sqrt{\frac{A}{A_c}}$

Circularity ratio (Stoddart, 1965; Unwin, 1981) $C_r = \frac{A}{A_c}$

Measures based on radii

Mean radius (Boyce & Clark 1964) $\overline{R} = \frac{\sum R_j}{n}$

Measures based on area and length

Form ratio (Horton 1945; Stoddart, 1965) $FR = \frac{A}{l^2}$

Ellipticity Index (Stoddart,1965; Davis 1986) $EI = \frac{0.5\pi l^2}{A}$

Measures based on perimeter

Shape factor (Bosch 1978; Davis 1986) $SF = \frac{P_c}{\mathrm{P}}$

where

A = area of patch

A_c = area of smallest circle enclosing a patch

l = length of long axis

n = number of sides, considered as a polygon

P = perimeter of patch

P_c = perimeter of circle having same area as patch

R_j = jth radius of patch, measured from centroid to margin

w = width of patch perpendicular to long axis.

It is to be noted that no single measurement or index can completely describe a given shape as a particular index value can result from different shapes. However, these indices are amenable to numerical and analytical solutions involving patch geometries.

1.2. Why study mosaics: Context and expected benefits/ impacts

The consequences of adopting a mosaic pattern for an irrigation scheme compared to a large contiguous area are largely unknown. Irrigation of landscapes has consequences in altering the water balance of the region. This leads to different cropping patterns, income structures, local industry and social patterns. Here we will concentrate on the biophysical aspects of the change that occur from irrigation.

One aspect of changing the water balance is to change the drainage patterns and the solutes carried in the drainage water. The lack of water stress means that higher plant production rates occur and with this is a change in fertilizer and other agrochemical usage, with generally an increase in the total amount as well as the number of products used. This and the requirement for leaching of the soil profile to remove the salts added in the irrigation water (Cook et al., 2006) will result in increased input of solutes into the surface and/or groundwater. These increased loadings of surface and groundwater can lead to detrimental environmental impacts of irrigation systems on aquatic ecosystems.

Irrigation brings many benefits to individuals, communities, and region, but it also brings some form of degradation and concerns. It is necessary to determine the acceptable level of degradation and the compensatory benefits. This degradation may extend both upstream and downstream of the irrigated area. The impacts may be both to the natural, physical environment and to the human environment. Many environmental concerns are local, but some are larger in scope: such as coastal zones, river basins, and regional. Irrigation planners and decision makers need to have a basic understanding of the general processes by which irrigation can affect soil, water, air, plant, animal and human resources. For example, large areas of irrigated cropland in arid areas can affect local climate, such as increased humidity. Irrigated cropland creates a green oasis in an otherwise barren desert. Green irrigated areas attract people and wildlife in both an urban and rural environment.

Irrigation water conveyance systems (open channels) provide open water and adjacent habitat for wildlife. Channels can obstruct normal wildlife migration patterns. Canals with high seepage rates help to develop and maintain groundwater and wet areas. In some areas, canal seepage and deep percolation in fields can dissolve naturally occurring toxic soil elements, such as salts and selenium. The toxic elements in the soil-water solution can then move into ground and surface water. The intensification of agriculture can lead to groundwater pollution related to the increased use of pesticides and fertilizers. Agricultural intensification generally produces a decrease in landscape mosaic complexity, a simplification of many geochemical cycles, a reduction of many ecological processes, a simplification of the chain and a decrease in system resilience.

Without appropriate management measures, irrigated agriculture has the potential to create serious ecological imbalances both within the irrigated area and in adjacent areas. Excessive clearance of natural vegetation cover in the irrigated area, for example, can affect the microclimate and expose the soil to erosion, leading to a loss of top soil and nutrient leaching. The removal of roots and vegetation disrupts the water cycle, increasing the rate at which water enters rivers and streams, thereby changing flow regimes and increasing siltation in the downstream zone. This is often to the detriment of fisheries and aquaculture activities. The destruction of natural habitats in this manner and the creation of agricultural monocultures also impacts on the local flora and fauna reducing biodiversity. The introduction of exotic species of plant or animal may oust indigenous species or introduce disease agents which may affect plants, animals and/or man. Fertilizers and pesticides are widely applied to increase crop yields. These can percolate through the soil and/or be carried away in the drainage water polluting both groundwater and surface waters especially in the downstream zone. The nutrients in fertilizers may give rise to eutrophication of surface water bodies and promote the growth of algae and aquatic weeds. Pesticide residues are hazardous to the health of both man and animals.

Surface water can transport chemicals through the soil and off the field. Inefficient and non-uniform on-farm irrigation can provide excess surface water runoff and deep percolation. Runoff water can carry sediment, animal waste, and other soil surface pollutants into surface water which might be used downstream for irrigation, fish, wildlife or other uses, such as for wetlands. However, in some cases the poor quality of water from irrigation runoff can cause damage to other downstream uses.

Many of the above examples may be of relatively minor significance in their own right but they often interact to produce a cumulative effect over a prolonged period of time which can result in significant long term changes to the local ecology. This cumulative effect may impair the long-term viability of both the irrigation project and economic activities in the surrounding area.

1.3. Existing knowledge and systems

Bos and Nugteren (1990) have investigated the effect of size of irrigation schemes on system losses.

They regarded the movement of water through an irrigation system, from its source to the crop as three separate operations: conveyance, distribution, and field application.

- Conveyance is the movement of water from its source through the main and (sub) laterals or conduits to the tertiary off-takes;
- Distribution is the movement of water through the tertiary (distributaries) or farm canals or conduits to the field inlet;
- Field application is the movement of water from the field inlet to the crop.

The efficiencies of water use in each of these operations, and in three combinations of operations, are defined as follows:

- *Conveyance efficiency,* e_c, is the efficiency of canal and conduit networks from the reservoir, river diversion, or pumping station to the off-takes of the distributary system.
- *Distribution efficiency*, e_d, is the efficiency of the water distribution canals and conduits supplying water from the conveyance network to individual fields.
- *Field application efficiency,* e_a, is the relation between the quantity of water furnished at the field inlet and the quantity of water needed, and made available, for evapotranspiration by the crop to avoid undesirable water stress in the plants throughout the growing cycle.

The total system efficiency, e_s is then:

$$e_s = e_c * e_d * e_a \qquad [2]$$

Their data showed (Figure 3) that there is a sharp increase in operational losses in irrigation schemes of less than 100 ha and larger than 10 000 ha. Distribution losses (in transporting the water) can be as high as 50 percent. [The irrigation unit served by a canal system with intermittent flow is called a rotational unit. Within a rotational unit, the water distribution is organized independently of the overall conveyance and of the water distribution in neighboring rotational units. It is based only on the farm water requirements in that unit.]

The size of the tertiary or rotational units also has a significant influence on the operational losses. Bos and Nugteren (1990) estimated that optimum efficiency can be attained if the size of the rotational unit lies between 70 and 300 ha. Where the rotational units are smaller, safety margins above the actual amounts of water required are introduced, as the system cannot cope with temporary deficits. Larger rotational units require a long filling time in relation to the periods that the canals are empty, as the canals are relatively long and of large dimensions. This requires organizational measures to correct timing, which is often difficult.

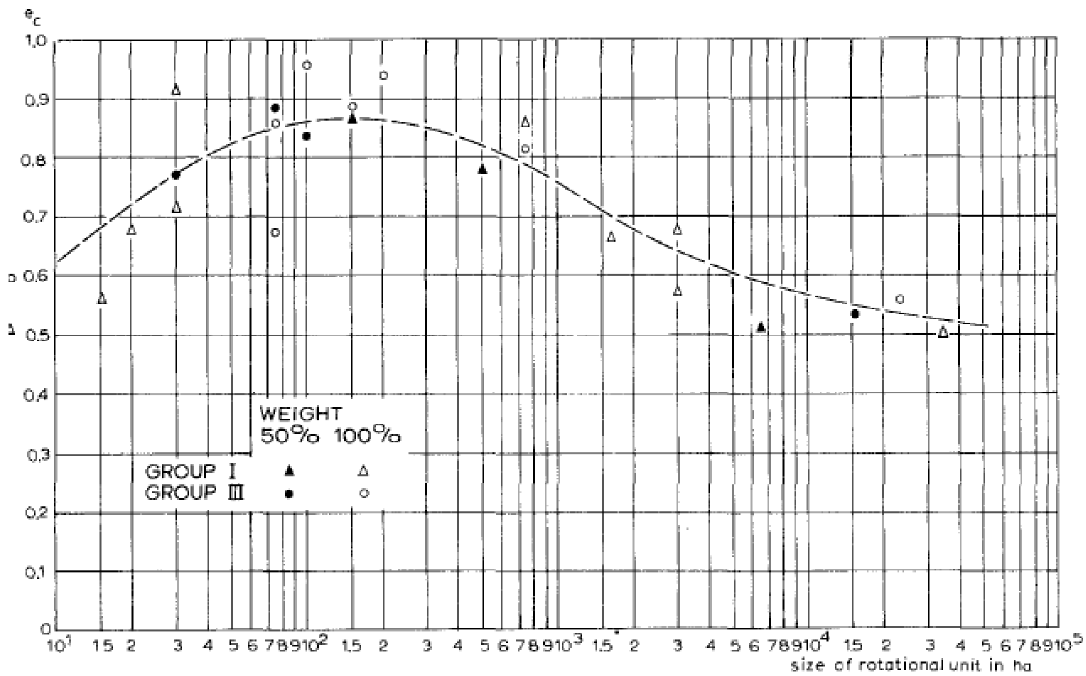

Figure 3. Influence of size of a rotational unit on the conveyance efficiency (surface irrigation) (After Bos and Nugteren, 1990)

In addition to the seepage losses from the tertiary and quaternary canals, the method of water distribution, farm size, soil type and duration of the delivery period affect the distribution efficiency (e_d). Figure 4 shows that the distribution efficiency is a function of farm size and soil type. Farm units of less than 10 ha served by rotational water delivery system have a lower efficiency than larger units. This is a result of the losses that occur at the beginning and end of each irrigation rotation. Moreover, where farms are served by pipelines or are situated on less permeable soils, the e_d will be higher than average. Most of these losses do not occur if farms receive a continuous water supply at a constant rate (e.g. rice in basin) and, these operational difficulties do not occur and consequently, in this case, the e_d is much higher.

When the delivery periods are increased, the e_d rises markedly. This is probably due to reductions in the losses that occur at the initial wetting of the canals.

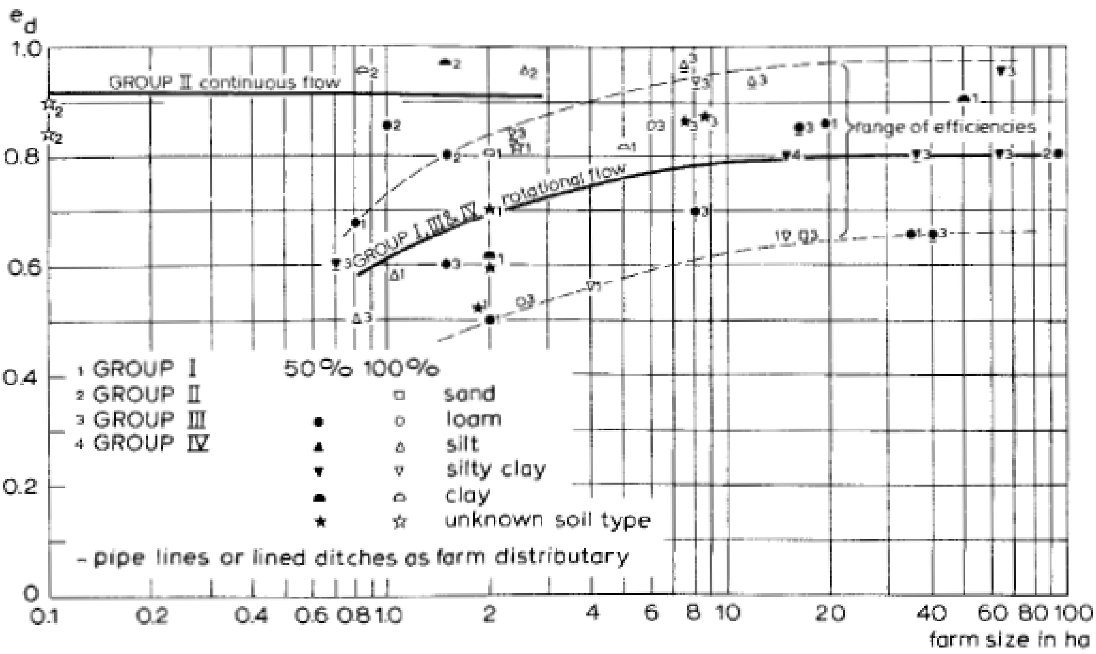

Figure 4. Distribution losses in relation to farm size and soil type (from Bos and Nugteren, 1990)

There are numerous other arguments for and against large or small irrigation schemes: for example, the obvious economies of scale and multiplier effects of large schemes (see Table 1). Smaller schemes are more conducive to farmer management and control. On the other hand, there are many examples of the development of small public irrigation systems, scattered over a wide area, that have overstretched the logistical and staffing capabilities of irrigation agencies and have eventually failed (FAO 1996). In theory, larger developments should encourage more government support, attract better management, be easier to organize, and therefore enjoy better prospects for sustainability.

In northern Australia, there are a few factors like low population density and isolation, lack of local markets, increasing cost of transport and lack of social and community services that might work against the smaller size of irrigation development. On the other hand, simple organisation and management of smaller schemes, greater opportunity for community involvement in planning, operation and maintenance might provide some advantages for smaller, mosaic style irrigation developments.

One aspect of irrigation mosaics that has gained little attention is the effect of advection on increasing the evapotranspiration rate (McNaughton, 1983) and hence the overall water use by irrigation mosaics. Given that irrigation schemes are generally located in areas where the landscape is dry this is somewhat surprising. Lang *et al.*, (1983) studied advection and estimated the effect to increase evaporation by approximately 6%. However, since they were unable to decouple some parameters these results only provide a rough guide. (Priestley, 1955) and more recently (Kadar and Yaglom, 1990) suggested that the convective boundary layer is likely to remain disturbed and not reach equilibrium for a considerable distance into an area where there is an abrupt change in water vapour and or heat flux. This may mean that evaporation is enhanced by 10-20% in small irrigation patches compared with larger irrigation areas (McNaughton K. G., *pers. comm.*, 2006). Further research is required in this area but we may speculate that irrigation mosaics will evaporate and hence require 10% more water than large scale irrigation schemes. Globally there is benefit from the water vapour entering the atmosphere as recently (Gordon, 2005) showed that this water vapour makes up for that lost by deforestation.

Table 1: Large versus Small Irrigation Schemes (FAO 1996)	
Large Scale	**Small Scale**
For: Engineering economies of scale usually possible, hence, potentially lower unit costs. Governments more disposed to take the actions necessary to ensure that project succeeds. Economies of scale result in cost-effective provision of extension services and social/economic infrastructure. Greater regional impact of secondary benefits. Easier physical planning of contiguous blocks than scattered areas. **Against:** Demand for high level professional skills and institutional capacity in planning, implementing, operating and maintaining. Relatively complex organization and management requirements; scope for farmer management limited to tertiary system, hence greater recurrent cost burden to government or other central authority (which may offset potential economies of scale). Longer period required to bring complete project into production. Greater potential for irreversible adverse environmental and social impacts, such as displacement of settlements or disruption of wildlife habitats.	**For:** Usually less exacting technical demands for high level professional skills for planning, implementing, operating and maintaining. Greater opportunity for farmers to participate in planning, financing, implementing, operating and maintaining. Better adapted to supplying local markets with (high value) horticultural products without depressing prices. Relatively simple organization and management. Often quick yielding. Smaller risk of irreversible adverse environmental and social impacts **Against:** Diseconomies of scale sometimes result in relatively longer period required to plan and implement (per ha developed). Fragmented distribution results in more difficult logistics for implementation, extension coverage and provision of social and economic infrastructure.

2. Existing mosaic systems

Mosaic systems occur in many landscape environments and here we will review these with regard to their relevance to irrigation mosaics and the information that can be gained from these that will be useful in analysis of irrigation mosaics. In particular we will look at the understanding gained from ecology, saline disposal basins, and land use mosaics studies. They each have features and analytical approaches that will be useful in studying irrigation mosaics.

2.1. Ecological

There is a considerable amount of literature covering landscape ecology. One of the main goals of landscape ecology is to study the structure of the spatial mosaic and its effects on the ecological processes. Organisms, energy and resources are distributed patchily in the environment, and this distribution is important for most ecological patterns and processes. Complex mosaics are crossed by organisms, energy, nutrients, water and disturbance processes, and all these elements are influenced by landscape heterogeneity. The heterogeneous landscape is presented as the spatial and functional integration of nature, humans and land for studies in landscape appraisal, planning, management, conservation and restoration. Landscape ecology can track ecological processes across a range of spatial, temporal and cultural scales allowing us to understand the real or potential effects of human land use and planning. The overlap of infrastructures (roads, bridges, railways) with natural structures such as rivers, lakes, valley bottoms and ridges creates hindrances to many ecological processes, such as erosion and deposition, water flux, animal movements and plant dispersion. Size, shape and the spatial arrangement of the patches are relevant for ecological processes (Gardner et al, 1987; Milne, 1992; Wiens et al., 1997; Nikora et al., 1999; Hoffman and Greef, 2003). Fractals and other scaling approaches have been used to define scaling rules for these spatial patterns but they generally only apply within certain length range.

Ecological mosaics are identified by existence of ecotones which are zones of transition between adjacent ecological systems, having a set of characteristics uniquely defined by space and time scales. Ecotones represent semipermeable membranes across the landscape, modifying the direction, the type and dimension of material and information exchanged with neighbouring systems (Forman and Moore 1992). Ecotones have been described at several scales, and play an active and a passive role in energy and nutrient fluxes. For example, Peterjohn and Correll (1984) found that in a small catchment a riverine ecotone can incorporate the surplus of nutrients flowing from the surrounding fields. The shape (linear, circular, convoluted etc) is relevant to determining the rate of transfer of information, energy and material across ecotones (Farina 1998). Ecotones created in an agricultural mosaic play a fundamental role in preventing erosion, improving the microclimate, and in absorption of nutrients. The importance of the ecotone is particularly emphasized in restoration ecology. Ecotones are more easily manipulated than other systems such as forests or grasslands.

Along the edges the abundance and diversity of animals are higher than in the adjacent habitats; this phenomenon is known as the edge effect. The extent and quality of the ecotones are important for biodiversity. The greatest biodiversity is obtained when there is an optimal blend of patches and ecotones. When a landscape is characterized by large patches the number and extension of ecotones are expected to be low. In this landscape biodiversity will also be low. In contrast, when the landscape is highly fragmented it will be the inner species that suffer (Farina 1998). In human-disturbed landscapes ecotones play a fundamental role in ensuring biological and ecological diversity in the mosaic. Ecotones are transition zones in which many organisms live at the limit of tolerance of local conditions, and react very quickly to climatic change. For this reason ecotones are preferred sites for the study of global change and its consequences.

Risser (1987) introduced a number of principles related to the functioning of an ecological system with ecotones:

1. The relationship between structures and processes is not limited to a unique spatiotemporal scale.
2. The importance of a process is scale dependent; a biogeographic process might have a negligible effect on local patterns but important at a larger scale.
3. Every species of plants and animals has its own perception of the environment (species-specific scale).
4. The scale of the ecological system is determined by the goal of the research. Some structures and processes are not perceived if the resolution of the investigation is coarser.

Over a long term, ecotones are important areas for maintaining a balanced mosaic and are sanctuaries for many species of plants and animals. Irrigation mosaics could be used to create or enhance ecotones in the landscape and the total perimeter length may be an important feature to consider in describing irrigation mosaics. Ecotones in irrigation mosaics may prevent erosion and absorb surplus material (nutrients, sediments, solutes) flowing from the surrounding fields, thus decreasing the discharge of the irrigation waste out of the irrigation area -a possible environmental off-site effect.

2.1.1. Landscape principles for natural reserves

Landscape ecology represents a scientific basis for studying, planning and managing semi-natural, rural and agricultural landscapes. The unequal distribution of energy, resources and organisms require *ad hoc* tools for non-destructive management. The landscape scale is comprehensive of socioeconomic and natural processes. Some basic principles for creating and maintaining natural reserves which recognize the importance of area, patch shape, connectedness and edge development attributes of the land mosaic as used in landscape ecology are:

- Species richness increases with forest area, especially in tropical areas subjected to forest clearing for agricultural production.
- A continuous area has more native interior species than two or more small ones.
- In a forested area separate patches close to each other support more species that are further apart
- Disjunct patches connected by strips of protected area are preferable to fully isolated patches.
- Other things being equal, a circular reserve is better than an elongated one because the portion of interior habitat is larger.

2.1.2. Fragmentation

Although patchiness can enhance biodiversity if it leads to fragmentation then this can be detrimental. Fragmentation is one of the most severe processes to depress biodiversity. It moves at an alarming rate around the world, reducing large forest cover as well as natural prairies and accelerating the local and global extinction of plants and animals. To describe the dispersion of fragments in an area it is necessary to consider their different attributes, such as density, isolation, size, shape, aggregation and boundary characteristics. The isolation of patches increases geometrically as the density of fragments decreases. The smaller the fragments the more they are influenced by the surrounding matrix. Fragmentation process has received a lot of attention from conservation ecologists because of its implications for nature conservation. Fragmentation increases the vulnerability of patches to external disturbance, for instance wind storm or drought, with consequences for the survival of theses patches and of the supporting biodiversity (Nillson and Grelsson 1995).

The patterns of fragmentation are affected by many factors. Agricultural proximity is a good indicator of fragment probability in the bottom of a hardwood forest, but access, urban development, ownership, fencing and regional differences are other, secondary, parameters useful for predicting the type and modality of fragmentation (Rudis 1995).

Fragmentation reduces the size of woodlot but also the habitat quality. Large fragments have more species, are less disturbed and have lower road access than smaller fragments. Large fragments are uncommon and their importance is great for nature conservation (Farina 1998).

In summary, fragmentation increases habitat edges and also the risk of predation, as many predators prefer edges as a hunting area. Tropical species are more vulnerable to fragmentation than temperate ones. Animal dispersion and movements increase with fragmentation rate (Farina 1998).

Conservation plans should take into account the maintenance of ecological fluxes rather than focusing on the conservation of ephemeral patterns. The maintenance of the natural disturbance regime seems a promising approach to perpetuate biological and ecological diversity. Corridors and hedgerows are important structures to be conserved in the landscape, ensuring movement and dispersal to many organisms. Their maintenance is often in conflict with socioeconomic development policies. In modified landscapes such as intensive-rural landscapes a small fragment of natural forest can conserve a valuable biodiversity. Landscape ecology resurrects the value and the importance of such fragments, producing guidelines for profitable management. With irrigation mosaics the aim must be to be wary of creating too much fragmentation if biodiversity in the landscape is to be preserved or enhanced.

2.2. Saline disposal basins

Disposal basins are used to store drainage disposal water in the irrigation areas. Their effect on the local groundwater can be analogous to what irrigation mosaics may create, but the water flux from the saline basin is likely to be greater. In the Murray- Darling Basin they are used as part of the strategy to limit salinity increases in the River Murray, by minimising salt leaving irrigated catchments of the Basin. Saline disposal basins (also referred to as evaporation basins) have been an important option for disposing of high salinity drainage water. In a study by Hostetler and Radke (1995) on all available data on more than 150 existing basins in the Murray-Darling Basin, 107 basins were reported as being active, with a total area of >15 900 ha, a total storage capacity of >113 000 ML, and an annual disposal volume of >210 000 ML/yr. Local-scale basins can be in the form of on-farm basins that occupy parts of individual properties and are privately owned. They can also be in the form of community basins that are shared by a small group of properties and are either privately or authority owned (such as the Girgarre Basin near Shepparton). This in effect represents a mosaics of disposal basins where a choice can be made between many small on-farm or a few large community disposal basins. These local-scale on-farm and community basins which were the subject of a study by CRC for Catchment Hydrology and CSIRO Land and Water for recommending a set of guidelines for siting, design and management of such disposal basins (Leaney *et al*. 2000). The guidelines describe the technical and financial issues that need to be considered for the effective and environmentally safe use of local-scale saline disposal basins on the Riverine Plain of the Murray-Darling Basin. The guidelines apply to disposal basins associated with farm subsurface drainage in irrigated areas. These guidelines and results have possible applications to irrigation mosaics.

How does a disposal basin function?

The primary purpose of a saline disposal basin is to evaporate sub-surface drainage water and store the remaining concentrated salt in a defined location within the basin and in the soils and groundwater beneath it (Figure 5). Evaporation and leakage are the key processes that govern the behaviour and effectiveness of a basin.

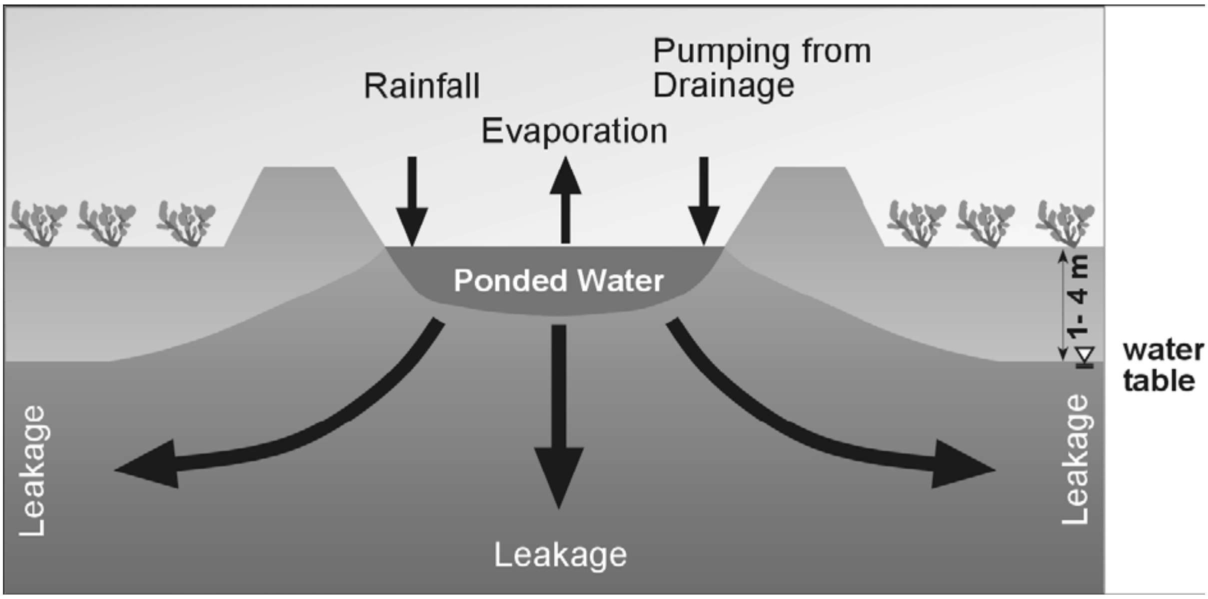

Figure 5. Conceptualization of a disposal basin water balance (Leaney et al 2000).

Basins are a potential risk to the surrounding environment, infrastructure, and human and other activities. For safe and sustainable use, their off-site impacts must be minimised. The most serious environmental risk is that of basin leakage as this may contaminate groundwater below the basin; lead to a plume under adjacent properties or surface water features (e.g. streams, lakes, channels); cause local salinisation of land around the basin; and impact on surrounding infrastructure such as roads and railways, buildings and other engineered structures. Similar effects occur within and around irrigated areas due to the leaching of water to depth. This leaching is necessary to prevent the build up of solutes in the soil but results in the solutes being transferred elsewhere (Cook *et al*., 2006).

Before developing policies for local-scale basins, it is important to have an assessment of those parts of any region where such basins are suitable. If a site is not suitable, then it will be difficult and expensive to engineer and manage the basin in a safe and sustainable manner.

A relationship has been observed between leakage and perimeter/area (P/A) ratio under existing basins on the Riverine Plain in shallow water table areas. In these areas, much of the leakage is shallow lateral flow away from the basin. The authors conclude that basins which have a larger perimeter compared to their area can have higher leakage rates – larger basins leak less than smaller basins. This indicates that larger basins are more likely to leak less than smaller basins. In northern Australia with very high rate of evaporation, the leakage might be less important than evaporation. Also with high watertable fluctuations in parts of the north, the leakage process might occur as a transient process rather than the steady state assumed in these studies in the southern regions. We will examine this assertion in later reports. Figure 6 shows the relationship between observed differences between estimated leakage rate and P/A ratio for ten existing basins in the Riverine Plain.

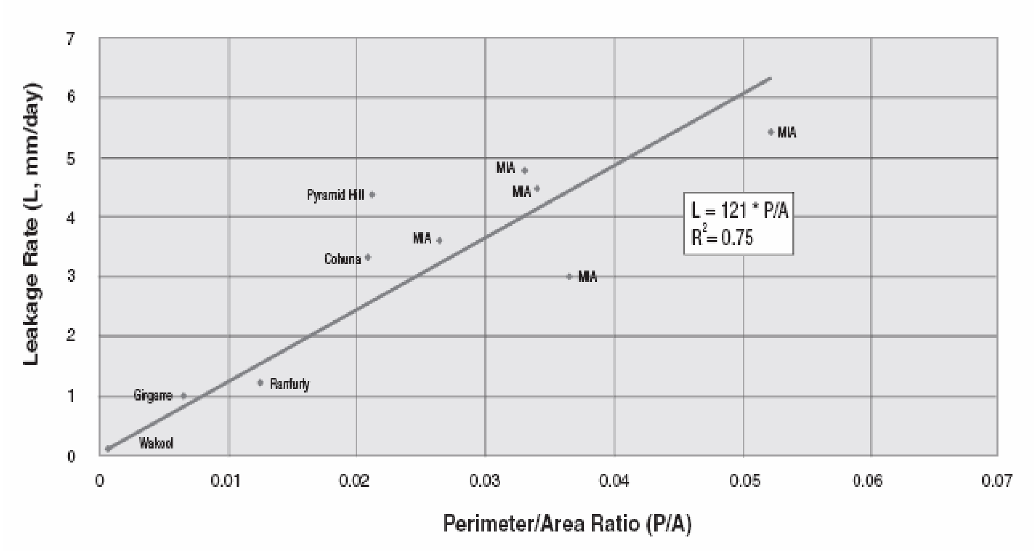

Figure 6. Effect of basin size (Perimeter/Area ratio) on the basin leakage rate.
P is the perimeter of the basin (m), and A is the area (m^2) (from Dowling *et al*. 2000).

The report on saline basins examined some social and economic issues which will be of interest when assessing implementation of irrigation mosaics. Some of the advantages and disadvantages of on-farm and community basins are listed below as examples of issues that need to address.

In general, the **advantages of on-farm basins** are:

- All costs of designing, operating, monitoring and maintaining the basin are borne by the primary beneficiaries of the drainage development.
- The ownership and responsibility for the basin remains with the primary beneficiaries.
- There is a direct cost incentive for the landholders to improve irrigation efficiency and drainage management so as to reduce drainage volumes.
- The physical presence of the basin on-farm has a strong psychological impact on farmer's irrigation management as the results of over irrigation or over drainage are immediately visible.
- The environmental and human impacts of the basins are generally restricted to primarily the landowner.
- There is no export of salt from the place of extraction.

In general, the **disadvantages of on-farm basins** are:

- It may be difficult to find suitable sites.
- These basins will generally be smaller and so leakage rates will be potentially higher.
- The basins have to be placed somewhere on the farm and so there is a higher probability of using unsuitable sites.
- There are greater construction costs per basin area and larger buffer areas per basin area (due to small basins having large perimeter to area ratios).
- They pose a potentially higher environmental and human risk due to the probability of lesser controls on their siting, management and monitoring.
- Large numbers of on-farm basins complicate long-term regional planning and may be more difficult to decommission if a better salt disposal or storage method becomes available in the future.

In general, the **advantages of community basins** are:

- They provide a better opportunity to find suitable sites.

- Leakage rates will be generally lower due to larger basin sizes and the lower probability of using unsuitable sites.
- The construction costs and buffer areas are less per basin area due to the generally larger basin sizes.
- They pose a lower environmental and human risk due to better siting and probable better quality of management and monitoring.
- Salt production or aquaculture is potentially more feasible as more water is available and inflows are more regular.
- Smaller numbers of larger community basins make long-term regional planning simpler and will be easier to decommission if a better salt disposal or storage method becomes available in the future.

In general, the **disadvantages of community basins** are:

- The requirement to get community agreement to the scheme and cost sharing arrangements.
- Compulsory acquisition to provide appropriate siting may lead to land equity and other legal disputes.
- The distribution of site purchase, construction, operating and monitoring costs to beneficiaries may be complex and difficult (although ownership of the land and basin by an authority or investment group can overcome this).
- Monitoring of drainage, in terms of quality and quantity, is required in order to ensure that the drainage water is of an acceptable quality (pesticides especially) and in order to distribute costs (which should be on a *user pays* principle).
- Since the disposal of the drainage water is remote from the farm and shared between a number of farmers, the measuring of and charging for drainage water must be sufficiently sensitive that it ensures a high standard of water management. This will ensure the basin does not have to be over designed.
- High levels of construction, management and monitoring expertise are required due to their greater technical complexity.
- Construction and operating costs may be higher in some situations due to need to transport water greater distances.
- A long-term commitment on the part of the beneficiaries is required (for reasons outlined above).
- While they pose less risk to the environment and the community, it may be difficult to obtain community acceptance due to the perception that big is bad.
- There is export of salt from the place of extraction (but not necessarily from the irrigation region).

The choice between on-farm or community basins is similar to choosing the size of irrigation mosaics and should consider physical, environmental and social-political issues as well as cost. Economic analyses suggest that there will generally be little cost difference between the two options for disposal basins, though for irrigation, engineering economies of scale usually favour the larger scale irrigation schemes (see Table 1). From environmental risk management, monitoring and regional decommissioning perspectives, it would be better to have fewer large community basins than many small on-farm basins. Management and monitoring of a single large basin is likely to be significantly easier than the management and monitoring an equivalent area of multiple smaller basins.

Community basins like irrigation schemes require careful decisions with regard to siting and cost sharing, to ensure equitable distribution of costs among those landholders that benefit. In deciding between on-farm, small community or large community basins, other environmental and/or social considerations should outweigh the negligible economic differences. This also holds true for irrigation mosaics using groundwater pumping as the source of water supply, in which case the cost of water delivery to individual farms is not a major factor of consideration (contrary to the schemes where surface water has to be delivered to each irrigation mosaic).

2.3. Land use mosaics

Landuse patterns are often characterised by mosaics. This is particularly the case with forests grassland systems which are a dynamic shifting pattern due to climate, fire, soil properties and human activities (Favier 2004). Farming systems usually form a patchwork of paddocks with different crops in landscapes.

Precision farming (Reddy and Umamaheswari 2004; Sourell and Al-Karadsheh 2005) looks to measure the mosaic of crop yield and relate this to soil properties to provide better utilisation of resources used within the farming enterprise. Spectral techniques (Jahn *et al*. 2005) and geostatistical methods (Webster and Oliver, 1990; Markus and McBratney 2001) have been used to analyse data for precision agriculture may also be useful in analysis of irrigation mosaics and/or where to site irrigation. These techniques require a lot of data in order to construct the semi-variograms and this may not always be available. The adoption of precision agriculture techniques in irrigation has been proposed by Sourell and Al-Karadsheh (2005) and a review of this has recently been done by Raine et al. (2005). Precision irrigation is a method that might be considered for adoption within an irrigation area but will not assist directly with the understanding of irrigation mosaics

Agro-forestry (Lefroy and Stirzaker 1999) is another landuse where the spatial pattern is often a mosaic. Patches of forest can act as filters in the decontamination of lateral flows (Noordwijk *et al*. 2004) and in a similar way irrigation mosaics may allow for lower overall contamination in a region. Here the inter-irrigation zones could act as filters to absorb some of the excess nutrients that may leak out of the irrigated area (mosaic). Alternately the salts that leak out may be concentrated by evaporation in the surrounding area leading to degradation of the surround area. All of these effects will need to be considered when irrigation mosaics are contemplated.

Much research has focused on quantifying various aspects of land use pattern and understanding the effect of disturbance processes, both natural and human-induced, on the vegetation mosaic (Gardner and O'Neill 1991; Turner *et al*. 1991). These studies generally model landscapes as a homogeneous space in which landscape dynamics arise as a consequence of free interaction between disturbance processes and vegetation dynamics. Dorner *et al*. (2002) incorporated the topographic mosaic into analyses of landscape pattern and dynamics. They included adjustments to 'classic' landscape indices that account for non-uniform landscape topography and application of statistical models to describe relationships between topographic characteristics and vegetation pattern. This analysis may not directly relate to irrigation mosaics since irrigation areas are usually on flat lands or small slopes.

Knowledge of changes in land use, driving forces and implications of changes within the context of sustainable development is limited. A study by Semwal *et al*. (2004) looked at the trends and implications of changes in spatial patterns of agricultural land use, crop diversity, yields, manure input, soil loss and run-off from cropland, and dependence of agroecosystems on forests in a central Himalayan watershed during the 1963–1993 period.

Data obtained from existing maps, satellite imagery, geographic information system (GIS) based land-use change analysis, participatory survey and field measurements were integrated to quantify changes at the landscape/watershed scale. The analysis used the pattern of land uses in the landscape, number of patches, areas and shape indices to study changes. The analysis showed that during that period, agricultural land use increased by 30% at the cost of 5% loss of forestland. Changes in land use and management have improved household income but at the cost of increase in intensity of biomass removal from forests and loss of forest cover. As farm productivity is dependent on forests in that region, continued depletion of forest resources will result in poor economic returns from agriculture to local people together with loss of global benefits from forest biodiversity and ecosystem services.

In Australia, the concept of systematic regional planning (SRP) for natural resource management (NRM) as developed in the context of the South Australian River Murray Corridor provides a structured and quantitative approach to the analysis of complex natural resource management decisions (Bryan *et al*. 2005) and can be used for regional land use planning (mosaics of land use). In the Corridor, the large scale clearance of deep-rooted native vegetation for agriculture and the grazing of remnant vegetation by livestock have led to the degradation of the native biodiversity, an increase in groundwater recharge and river salinity, and increased soil wind erosion. In effect, landuse change in the Corridor has broken the connectivity of the landscape and the river. This concept is useful in the planning of irrigation siting and hydrological linkage to rivers as some locations in the landscapes (e.g. corridors) can have large off-site impacts on a short time scale. Regional targets have been set to address these multiple natural resource management objectives. Carbon sequestration is also discussed as another NRM objective in the Corridor. The aim of the study was to assess the feasibility of different policy options for encouraging the large scale NRM actions (revegetation and vegetation management) required for achieving stated regional resource condition targets for NRM. To achieve this, the concept of systematic regional planning was developed to identify geographic priorities for NRM actions that most cost effectively meet multiple-objective regional targets based on established biophysical and economic principles. Systematic regional planning is a process based on decision theory and implemented within a spatial Multi-Criteria Decision Analysis framework (Bryan *et al*. 2005) and can carry through to irrigation mosaics analysis once the biophysical and economic principles of mosaics are established.

3. Modelling tools relevant to analysing mosaics

Mathematical modelling is one of the most useful tools for prediction work. It is the natural tool to assess both flow quantities and qualities (eg salt/water balances, pollution transport, changing flood patterns). However, it is essential to use methods with an accuracy which reflects the quality of the input data, which may be quite coarse. It should also be appreciated that model output is not necessarily an end in itself but may be an input for assessing the impact of changes in economic, social and ecological terms.

3.1. Salt load assessment in the Mallee

SIMPACT is a GIS regional scale simulation model that estimates the salinity impact of groundwater recharge as a result of irrigation on the Lower Murray floodplains (Miles *et al.* 2001, Overton *et al.* 2003).

The SIMPACT GIS framework was developed to assess the impact of increased drainage on the Murray River salinity. The first version of SIMPACT (Miles *et al*. 2001) was developed to identify salinity impacts of potential irrigation development in highland irrigation areas of SA, The model focussed on comparing impacts at a regional scale by producing a river-wide perspective on where irrigation development would have higher and lower impacts. The methodology has the potential to be expanded to other areas of salinity assessment including existing irrigation.The model used a ‘grid cell’ (500mx500m) approach to assess points on the landscape within 10km either side of the Murray River. Vertical drainage rates through sandy and clay layers were used with layer thickness information to estimate unsaturated lag times. Saturated lag times were based on a process for predicting potential salt loads from new irrigation developments published in Watkins and Waclawik (1996). This work developed type curves (Figure 7) for discrete distances from the river valley and for each major aquifer in the region to quantify the relationships between irrigation and induced salt loads to the river. These curves were used to derive an appropriate algorithm for each cell location. The original curves were derived using MODFLOW model to simulate a new irrigation development operating over time. There are numerous factors that may vary over time that can modify actual salt impacts from modeled results. These could include rainfall recharge, changes in crop types or management regimes, and interception of drainage or groundwater. As a result, the quantities represented by the curves are given as an estimate rather than a prediction with error bars of reliability.

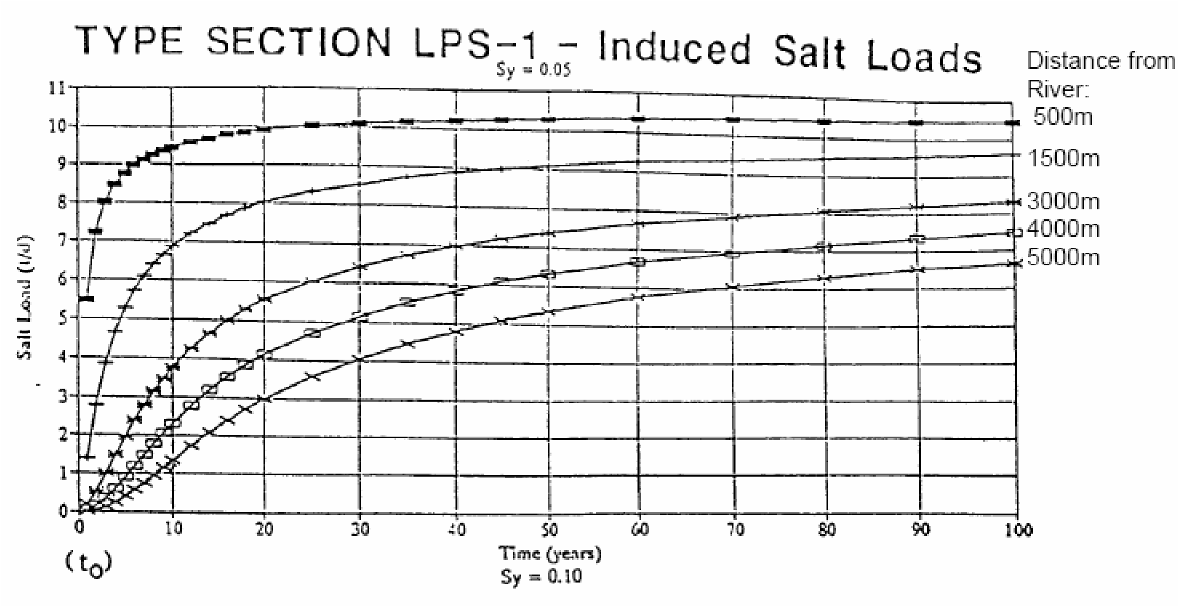

Figure 7. Example of salt curves from Watkins and Waclawik (1996), Loxton Parilla Sands aquifer.

In SIMPACT II and its offspring the rapid assessment tool SIMRAT (Fargher *et al*. 2003), the unsaturated zone method (Cook *et al*. 2004) was integrated to calculate lag times. It uses the drainage rate, together with depth to groundwater and clay thickness, as inputs and equations linking to subsoil moisture contents to estimate recharge over time (Figure 8b). In addition, the unit response equation (Knight *et al*. 2005) was used to assess the impact of increased recharge on discharge to the river. Aquifer salinity at discharge was multiplied to the discharge over time to get the salt load into the river.

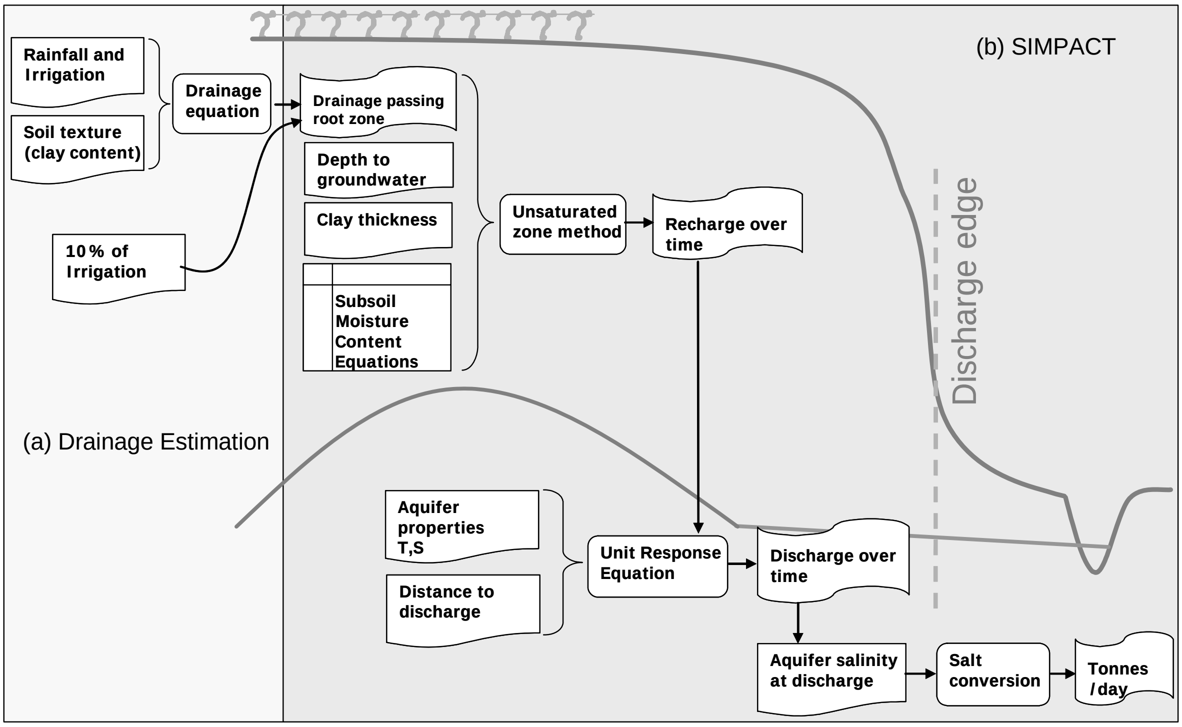

Figure 8. Schematic representation of the SIMPACT II. Section (a) represents the drainage estimation Section (b) represents SIMPACT I using drainage as input for simulating recharge process.

Since SIMPACTII algorithms allow a greater range of drainage rates to be assessed, a number of methods have been developed to estimate appropriate drainage as input for the unsaturated zone equations to estimate recharge over time (Figure 8 a). SIMRAT uses a constant 10% of traded volume as the added drainage as it requires an administratively robust and equitable way of calculating drainage from irrigation development. More recently, new algorithms have been developed to estimate annual mean drainage in the Mallee region based on mean annual rainfall and soil textures in the top 2 metres of soil. This was derived by combining Soil Landscape Unit (SLU) mapping (at 1:100000) and constituent soil type texture estimates. (Wang *et al*. 2005). The model can be used to simulate the impact of land use change at specific locations on the discharge or salt load into the river in a spatial context. Therefore, it can be used as a prioritisation tool for identifying areas where revegetation or other land use change can have the largest or most immediate impact on discharge or salt load into the Murray River. In the case of an individual development, SIMPACT would be used with more locally relevant data than with the default regional data.

3.2. Groundwater flow analysis

Irrigation of an area generally has some effect on the groundwater system. This can be due to elevated groundwater tables caused by increased flow of water to the groundwater (Khan 2006; Rengasamy 2006) or due to groundwater depletion through extraction (Nativ 2004; Yang *et al*., 2006). The use of multiple sources for irrigation water (Tsakiris and Spilotis 2006) may be a useful method for control of water tables that could have applications in groundwater mosaics. The main objective of groundwater modelling is to predict changes in water levels in response to changes in groundwater withdrawal and artificial recharge. In addition, future changes in groundwater quality can be predicted. Both objectives can be achieved if we can predict groundwater motion. Application of groundwater response models to mosaics is especially challenging when patch boundary geometry and exogenous variables are complex.

Knowledge gained from the analysis of injection and extraction wells offer useful approximations to flow in groundwater for irrigation patches (Dillon, 1995). The analysis of Dillon (1995) is for a single well but the use of the superposition principle (Bear, 1972) for linear processes will allow the extension to multiple well (irrigation mosaic) problems.

Multiple capture wells have been used to prevent contamination of surface and groundwater systems and the design criteria for these (Hudak, 1997) may be useful in assessing the spacing of irrigation mosaics. Mantogluo (2004) has used nonlinear optimisation techniques to look at the spacing of wells and his analysis may assist in guiding how to design spacing of the irrigation mosaics.

The recent analysis for reactive transport of Luo et al. (2006) offers guidance on reactive solutes where the processes may not be linear. For linear process Konikow and Hornberger (2006) and Sanford et al. (2006) have provided recent solutions. The work of Knight and Kluitenberg (2005) provides methods for looking at the uncertainty of the solutions for water flow and non-reactive solutes.

There is a lot of knowledge about modelling of groundwater mounds associated with increased recharge (Bear, 1972). These modelling efforts can be either numerical or analytical with most of the analytical methods based on the Boussinesq equation. Recent advances in analytical methods (Knight 2005; Knight *et al*. 2005; Knight and Klutinberg, 2005) will be useful in assessing the effects of size, inter- mosaic distance and distance to surface sinks when considering irrigation mosaics. In addition analytical solutions are available for assessing the effects of multiple wells (sources and sinks) on groundwater drawdown. Computer simulation models contain equations describing how groundwater levels and flows respond to groundwater pumping, changes in recharge rates and their respective locations. The models also contain estimates of aquifer characteristics (transmissivities, effective porosity etc). Recently in as yet unpublished work, Khan et al., (2006) has considered the use of extraction wells surrounding an irrigated area used for land treatment of waste water to intercept the groundwater leakage from the irrigated waste water area and use this for irrigation elsewhere. This concept has obvious applications with irrigation mosaics.

3.3. Scale issues

Traditionally, patch theory and dynamics are focused on micro- and mesoscales, whereas heterogeneity is focused largely at mesoscales and landscape ecology looks at the meso- and macroscale (Wiens 1997). Fractals and other scaling approaches have been used to define scaling rules for spatial patterns in the landscape but they generally only apply within certain length range (Nikora *et al*. 1999). The appropriate metric to scale these approaches to patchiness depend on the nature of the system under study. For example, a holistic view of a river in its fluvial valley would consider river–floodplain systems in a landscape context (Ward *et al*. 1999). The approaches described by Nikora et al. (1999) and Hoffman and Greef (2003) offer methods to describe the spatial properties of irrigation mosaics. The temporal properties in terms of the irrigation frequency and climate variables can be described using frequency decomposition methods such as Empirical Mode Decomposition (EMD) (Huang *et al*. 2003a, b).

Ecological research has provided tools to study landscape mosaics but careful study and adaptation of these to irrigation mosaics will be required. Hydrology has used both top-down and bottom up approaches to looking at surface water generation and stream flow. The distributed bottom up models may have some utility for use with irrigation mosaics but parameterising these models is problematic (Cook *et al*. 2005).

3.3.1. Point and line sources

Within the irrigated patch itself we will have point and line sources of different scales from trickle emitters, to flooded basins. Close to the source the flow regime is likely to be spatially and temporally discrete but further away or over a longer time this discrete behaviour will be lost.   Flow from point and line sources have been a fruitful method for analyzing water distribution and flow patterns (Raats 1971a,b; Philip, 1984a,b,c; Philip and Knight, 1991) these solutions have been used for problems associated with trickle irrigation in particular (Revol et al. 1997a,b; Cook et al., 2003). These approximations describe the flow of water close to the source. At further distance in time and space away from the source the flow is smoothed by the capillary processes and this problem has been studied in an unpublished manuscript by (Knight J.H. and P. Adamson pers. comm.). Much work still needs to be done on this topic which will assist in determining the recharge rate to groundwater models. If calculations of Irrigation mosaic effects are to be realistic some effort should be spend on studying far field effects of point and line sources.

3.4. Analytical models

The DIVAST model of (Dillion 1989) and an adaptation of this for the MEDLI waste water model have applications for investigating solute transport from irrigation mosaic patterns. The DIVAST model uses the stream-tube approach similar to that of Raats (1978) but with the addition of dispersion to model the solute. The DIVAST model can also be used to consider solutes where the solute (*C*) decays as a simple first order processes with time (*t*) i.e. $C(t) = C_o e^{-at}$ where C_o is the concentration at $t = 0$. This will be useful for modeling such solutes as nitrate.

MEDLI (Gardner and Davis, 1998) is a model for designing irrigated land treatment wastewater schemes. Part of the design processes is to estimate the effect on the groundwater (Dillon and Sharma, 1998). In a supplementary unpublished addition to this Dillon used solutions from Bear (1972) developed for an injection well to estimate the solute transport away from a small patch in the landscape. This solution is only applicable at distance from the patch that is, as large as the characteristic length for the patch, where the assumptions are valid. This solution may be of use when studying irrigation mosaics.

There has been much published recently on solutions of the Boussinesq equation for water flow in (Chapman 2005; Chapman and Ong 2006; Knight, 2005) groundwater and these have applications to irrigation mosaics. There are many numerical modeling platforms that are also available and these are reviewed separately below. Hantush (1967) using Dupuit Forchheimer assumptions and his solutions allow the shape and maximum height under circular and rectangular areas to be calculated. These solutions will be useful for examining the effect on groundwater heights and the penetration of elevated groundwater levels into the surrounding land. The Dupuit-Forchheimer assumptions do not give accurate predictions of the velocities and so are not useful for predicting solute transport.

Zlotnik and Ledder (1992, 1993) found solutions for groundwater heights and velocities for uniform areal recharge from circular and rectangular areas. These will be very useful if more complicated than the Hantush (1967) solutions as the solutes can be coupled by advection to the velocities. As with the DIVAST, model use of exponential decay functions allow solute concentrations, for solutes where such decay occurs, to be directly calculated. These models should allow the effects of the spacing and to some degree the shape of the irrigation mosaic patches to be investigated. For linear systems the principle of superpositioning will allow for some understanding of the overall effect of irrigation mosaics.

3.5. Numerical models

To adequately account for the near and far effects of several small irrigation patches in a mosaic pattern as compared to large monolithic schemes spatial modelling using GIS tools are required. The effect of non-point source pollution on near and far fields can be determined using the GIS framework coupled with deterministic landscape process models. Several landscape models have been developed over the years with differing capabilities and ease of use. Numerical models specifically designed to analyse mosaic are hard to find.

Nevertheless, existing models with specific characteristics could be adapted and applied to mosaics.

The following processes of the models are desired:

1) spatially varying rainfall, interception, surface retention/detention, infiltration, percolation, surface runoff (overland and channel flow), crop growth, evapotranspiration, surface cover, sediment detachment and transport, soil nitrogen and phosphorus cycles (organic and inorganic, dissolved and adsorbed nutrient pools, nitrate leaching, nutrient losses in surface runoff
2) Modeling Scale: Spatial: field, farm, irrigation area and subcatchment
3) Temporal: Continuous simulation, short time step during runoff events, daily time step otherwise. Multiple years of simulation period

The model should be able to simulate hydrological components, including the movement of surface water, unsaturated subsurface water, saturated ground water, and exchanges between surface water and ground water. In addition the models should have interfaces with GIS and allow overlays of soil, land use, and weather themes. For example the MIKE-SHE model includes hydrologic process components for unsaturated and saturated ground water flow, overland flow, channel flow, and evapotranspiration. Each component solves a corresponding equation as follows:

- 3-D Boussinesq Equation for saturated ground water flow
- 1-D Richards' Equation for unsaturated ground water flow
- 2-D diffusion wave approximation of the Saint Venant equations for overland flow
- 1-D diffusion wave approximation of the Saint Venant equations for river flow
- Evapotranspiration/Interception

Models that could be used to analyse mosaics are summarized in Table 2 and Table 3. They all have interfaces with GIS and allow overlays of soil, land use, and weather themes.

Table 2: Model structural parameters

Model	Time scale		Spatial Scale					Computational time step				Target Audience
	Event	Cont-inous	Point	Field / Farm	Water-shed	Basin	Regional	Second	Hour	Day	Year	Researchers
SWAT		✓			✓	✓	✓			✓		✓
ANSWERS-2000	✓	✓		✓	✓			✓				✓
AnnAGNPS	✓				✓							✓
HEC-GEOHMS	✓	✓				✓				✓		✓
MIKE-SHE	✓	✓		✓	✓	✓		✓	✓	✓		✓
MODFLOW	✓	✓		✓	✓	✓				✓		

Table 3: Model processes

Model	Surface water flow/Runoff	Subsurface water flow	Chemical Transport		Erosion	Precipitation	Snowmelt	GIS
			nutrients	pesticides				
SWAT	✓		✓		✓			✓
ANSWERS-2000	✓		✓		✓	✓		✓
AnnAGNPS	✓		✓		✓			✓
HEC-GEOHMS	✓		✓	✓	✓	✓		✓
MIKE-SHE	✓	✓	✓	✓	✓	✓	✓	✓
MODFLOW		✓	✓	✓				

4. Key findings

Existing knowledge on irrigation mosaics and implications within the context of sustainable development is very limited. What can be learned from other systems dealing with spatial patterns in the landscape, relevant to irrigation mosaics, can be summarised as follows:

From ecological research we can see that patch size, shape and spatial arrangement are important characteristics in landscape analysis. They affect processes, patterns and organisms in different ways. To measure these landscape attributes several indices are available. Some simple indices exist to describe attributes such as area, perimeter and patch shape. In theory, for conservation planning, the bigger the reserves are, the closer they are to each other, the more circular they are and linked by habitat corridors, the better they serve the purpose of nature conservation. In practice to apply such guidelines is constrained by costs and patterns of land use history.

Ecotones, which are zones of transition between adjacent ecological systems, are important characteristics of mosaics and play an important role in energy and material fluxes. Irrigation mosaics could be used to create or enhance ecotones in the landscape for greater biodiversity, improving microclimate, preventing erosion, and in absorption of surplus nutrients flowing from the surrounding fields. On the other hand, fragmentation, which is discontinuity of patches, can be detrimental for biodiversity. Fragmentation increases the vulnerability of patches to external disturbance, for example wind storm or drought, with smaller fragments being more influenced by the surrounding matrix. Also, tropical species (existing in the north) are more vulnerable to fragmentation than temperate ones.

In a study of disposal basins in irrigated areas of the Riverine Plains in the Murray Darling Basin the leakage rate under the larger basins was found to be less than under the smaller basins. While we can learn about mosaic features from this work on disposal basins care is needed in drawing analogies with irrigated systems. The disposal basins involve ponded conditions, but irrigated areas usually (should), involve unsaturated conditions, so leakage from patches of irrigated land are likely to be much less than leakage from disposal basins (patches of ponded water).

Effect of advection on enhancing evapotranspiration and water use in irrigated mosaics seems to point to an approximately 10% increase (compared to larger irrigation schemes) which might not be a desired feature in northern tropical Australia, particularly in the dry season when one would want to irrigate.

The size of irrigation units has some implication in terms of system losses in transporting water. It has been estimated that optimum irrigation efficiency can be attained if the size of the rotational unit (the irrigation unit served by a canal system with intermittent flow) lies between 70 and 300 ha. Where the units are smaller, safety margins are introduced, as the system cannot cope with temporary deficits. Larger rotational units require a long filling time in relation to the periods that the canals are empty, as the canals are relatively long and of large dimensions. There are other arguments for and against large or small irrigation schemes. For example, the obvious engineering economies of scale and potentially lower unit costs result in cost-effective provision of infrastructure and services in large irrigation schemes as well as encouraging more government support and being easier to organize. On the other hand, smaller schemes give greater opportunity to farmers to participate in planning and management of the system; they are better adapted to supplying local markets, and they incur smaller risk of adverse environmental and social impacts, such as displacement of settlements or disruption of wildlife habitats.

Irrigation mosaics may have some negative (more recharge, salinisation, increased operational losses) and positive (filtering surplus nutrient surplus, enhanced biodiversity, preventing erosion) environmental impacts. These impacts need to be carefully studied and design criteria in terms of size, shape, density, connectivity and spatial arrangement in harmony with the landscape need to be established.

5. Conclusions

Ecological and hydrological research has provided tools for studying landscape spatial patterns but careful study and adaptation of these to irrigation mosaics will be required, particularly for northern tropical Australia.

For example, the concept of systematic regional planning which was developed for the South Australia River Murray Corridor can be used for regional planning of land use mosaics (also applicable to irrigation mosaics) once the biophysical and economic principles of mosaics are established. Systematic regional planning, based on decision theory, can be used to identify geographic priorities for NRM actions that most cost effectively meet multiple-objective regional targets.

Knowledge gained from the analysis of injection and extraction wells offer useful approximations to flow in groundwater for irrigation patches. Multiple capture wells have been used to prevent contamination of surface and groundwater systems and the design criteria for these may be useful in assessing the spacing of irrigation mosaics.

Geostatistical methods used in precision farming may be useful in our analysis of where to site irrigation in the landscape.

Numerical models that are designed specifically for analysing mosaics are scarce. However, existing process based numerical models could be adapted and applied to mosaics. The model should simulate surface and sub-surface flow at a daily time scale or finer and also process input and output in a GIS format. In addition, the models should simulate chemical transport. MIKE-SHE and MODFLOW satisfy these criteria and the SWAT and HEC-GeoHMS models could be considered although they have no sub-surface component. These models have the capability to overlay map layers of soil, land use and weather and other spatial information suitable for analysing mosaics.

This document provides an overview of existing knowledge and current biophysical understanding of systems with natural spatial patterns in the landscape. It provides a framework for further study on irrigation mosaics and its environmental impacts in the future. In particular, there exists the need to study the effect of patch number, size and connectivity on evapotranspiration rate from irrigated land in a mosaic set up, fate of solutes, recharge to groundwater and the surrounding land, salinisation, groundwater quality, system losses and biodiversity.

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