Irrigation Mosaics. How are they different?

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EXTENDED ABSTRACT

Irrigation mosaics, involving 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 as a means of delivering improved social and economic opportunities for rural and remote communities in northern Australia. However, the longer-term environmental impacts of irrigation mosaics that may impair the sustainability of an irrigation project and the surrounding area are still largely unknown.

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

From ecological research it appears that patch size, shape and spatial arrangement are important characteristics in landscape analysis. Some simple indices exist to describe attributes such as area, perimeter and patch shape. 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.

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 increase the vulnerability of patches to external disturbance, for example wind storm or drought.

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 observed to be less than the smaller basins. The observed relationship is based on the perimeter/area ratio of disposal basins and suggests that, analogous to irrigation mosaics, the leakage (recharge to groundwater) would be more from many separate patches than from one big contiguous irrigation area.

The size of the irrigation patches has some implications in terms of operation, maintenance and environmental impacts of irrigation. In large irrigation schemes, lower unit costs result in cost-effective provision of infrastructure as well as encouraging more government support. 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 social impacts, such as displacement of settlements or disruption of wildlife habitats.

This paper provides an overview of some biophysical aspects that can be used for further study of irrigation mosaics and their potential environmental impacts. Application of simple analytical solutions for particular groundwater condition indicates some of these impacts compared to the traditional large scale systems.

It appears that irrigation mosaics could have both negative (more lateral recharge, salinisation, increased operational losses) and positive (filtering nutrient surplus, enhanced biodiversity, preventing erosion, reduced area of impact around the irrigation area, lower rate of watertable rise) effects on the environment.

1. INTRODUCTION

Most irrigation areas in Australia are characterised by large-scale contiguous irrigation systems within a region. 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 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 2007). A key question in thinking about mosaics is would they be an advantage or not? Here we examine some of the issues associated with irrigation mosaics.

Irrigation of landscapes brings many benefits to communities, but it has consequences in altering the water and salt balance of the region (Paydar et al. 2007).

Without appropriate management measures, irrigated agriculture has the potential to create serious ecological imbalances both within the irrigated area and in adjacent areas. Fertilizers and pesticides are widely applied to increase crop yields. These can percolate through the soil polluting both groundwater and surface waters. The nutrients in fertilizers may give rise to eutrophication of surface water bodies. Pesticide residues are hazardous to the health of both humans and animals. Inefficient irrigation can provide excess runoff and deep percolation. In some cases the poor quality of irrigation return flow can cause damage to other downstream uses.

Many of the above examples often interact to produce a cumulative effect over a prolonged period of time which can result in changes to the local ecology. This cumulative impact may put at risk the social resilience and impair the long-term sustainability of the irrigation project and economic activities in the surrounding area.

2. DEFINITON 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 to characterise them have been made (Gardner et al. 1987; Milne 1992). Patchiness can be continuous or discrete, and patches can vary in size, shape, intensity, spatial configuration, and interconnectedness. The hydrological connectivity of the patches 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

3. EXISTING MOSAIC SYSTEMS

Existing knowledge on irrigation mosaics and implications within the context of ecologically 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. In particular we will look at the understanding gained from ecology, saline disposal basins, and land use mosaics studies.

3.1. Ecological systems

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. Landscape ecology can track ecological processes across a range of spatial and temporal scales allowing us to understand the potential effects of human induced disturbances.

Ecological mosaics are identified by existence of ecotones which are zones of transition between adjacent ecological systems, having unique characteristics defined by space and time scales. 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 of the mosaic (linear, circular, convoluted etc) is relevant to determining the rate of transfer of 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 extent and quality of the ecotones are important for biodiversity. 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 human-disturbed landscapes ecotones play a fundamental role in ensuring biological and ecological diversity in the mosaic.

Fragmentation of the natural landscape is one of processes to depress biodiversity. The smaller the fragments the more they are influenced by the surrounding matrix. Fragmentation process has some implications for nature conservation. There is an optimal blend of patches and ecotones for the greatest biodiversity. Fragmentation increases the vulnerability of patches to external disturbance, for instance wind storm or drought, with consequences for the survival of these patches and of the supporting biodiversity (Nillson and Grelsson 1995).

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.

3.2. Salt 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.

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. This in effect represents a mosaic of disposal basins where a choice can be made between many small on-farm or a few large community disposal basins.

Salt disposal basins are a potential risk to environment, with the leakage being the most serious risk as this may contaminate groundwater below the basin; cause local salinisation of land; and impact on surrounding infrastructure (Leany et al. 2000). Similar effects occur within and around irrigated areas due to the inefficiencies in irrigation and the leaching of water to depth.

In a study of disposal basins in the Murray Darling Basin (Dowling et al. 2000) 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. This indicates that larger basins are more likely to leak less than smaller basins.

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). Management and monitoring of a single large basin was found to be significantly easier than the management and monitoring of an equivalent area of multiple smaller basins (Leaney et al. 2000).

3.3. Land use mosaics

Landuse patterns in the landscape are often characterised by mosaics. Farming systems usually form a patchwork of paddocks with different crops in landscapes.

Agro-forestry (Lefroy and Stirzaker 1999) is a 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 that land. All of these effects will need to be considered when irrigation mosaics are contemplated.

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.

Table 1. Large versus small irrigation schemes (FAO 1996)

Large Scale	Small Scale
For: Engineering economies of scale usually results in lower unit costs Governments more disposed to take actions for project success More cost-effective provision of extension services; Easier physical planning of contiguous than scattered areas; **Against:** Demand for high level professional skills for planning etc.; Relatively complex organization and management requirements; Scope for farmer management limited to tertiary system, hence greater recurrent cost burden to government or authorities; Longer period required to bring complete project into production Greater potential for adverse environmental and social impacts.	**For**: Usually less technical demands for high level professional skills for planning, implementing and operating; Greater opportunity for farmers to participate in planning, implementing, operating and maintaining; Better adapted to supplying local markets; Relatively simple organization and management; Often quick yielding; Smaller risk of adverse environmental and social impacts; **Against:** Sometimes longer period required to plan and implement; Fragmented distribution results in more difficult logistics.

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. The concept of systematic regional planning was developed to identify geographic priorities for NRM actions that most cost effectively meet multiple-objective regional targets (Bryan et al. 2005) and can carry through to irrigation mosaics analysis once the biophysical and economic principles of mosaics are established.Size of irrigation area

In designing an irrigation mosaic, one of the considerations is the size of the irrigation patches which might be important in the operation, maintenance and environmental impacts of the irrigation scheme. 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 (Bos and Nugteren 1990). 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. 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.

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 (Bos and Nugteren 1990). There are other arguments for and against large or small irrigation schemes. The obvious engineering economies of scale result in cost-effective provision of infrastructure in large irrigation schemes as well as encouraging more government support (Table 1) and being easier to organize (FAO 1996). 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 social impacts, such as displacement of settlements or disruption of wildlife habitats.

In an analysis of irrigation mosaics Cook et al. (2007b) showed that the size of the irrigation patch (unit) has a significant effect on the rise of the watertable below the irrigation area. The larger the area, the larger the rise of the watertable due to deep percolation in a lateral flow condition. They also provided some analytical approaches to help with deciding the size and spacing of patches.

4. MODELLING TOOLS

There is a lot of knowledge available about modelling of groundwater mounds associated with increased recharge. These modelling efforts can be either numerical or analytical with most of the analytical methods based on the Boussinesq equation (Bear 1972). In addition analytical solutions are available for assessing the effects of multiple wells (sources and sinks) on groundwater drawdown.

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

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.

5. PRELIMINARY ANALYSIS

Here we examine the effect of the size of the patch on groundwater rise and flux from an irrigation area. Marginal effects which occur outside the irrigation area are analysed in a separate paper (Cook et al. 2007). Let the irrigation area be represented by a circle of radius r (analogous to a centre pivot). Then the area (A) and perimeter (P) of each irrigation patch will be:

$$A = \pi r^2 \text{ And } P = 2\pi r \qquad (1)$$

Furthermore there is no interaction between the patches (i.e. they are far apart). If the area impacted by the irrigation around the patch is of some length Δr and the area is recharged (Fig 1) at a steady rate of i (deep percolation from irrigation), then the area of influence for the mosaics (I_m), using (1) is given by:

$$I_m = \pi(\Delta r^2 + 2\mathrm{r}\,\Delta r) \qquad (2)$$

True equilibrium may never occur, but assuming a quasi-equilibrium condition after a long period of steady recharge, with H and h being the watertable height above an impermeable layer inside and outside the irrigation area, k as hydraulic conductivity of the saturated layer and using Dupuit-Forchheimer assumptions for lateral flow:

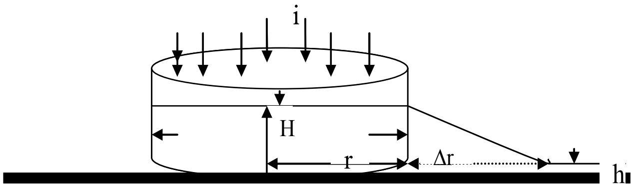

Figure 1. A schematic representation of an irrigation patch

Lateral flow (Q) = $\mathrm{i}\pi\mathrm{r}^2/2 = -\frac{kdh}{dr}(\pi r h)$ (3)

Upon integration:

$$\frac{2k(H^2 - h^2)}{i} = \Delta r^2 + 2\mathrm{r}_0\Delta r \qquad (4)$$

Comparison of equations 4 and 2 (RHS is I_m/π) shows that the area of influence (watertable rise around irrigation patch, I_m) depends on the head differences under irrigation area and the surrounding land, the rate of recharge to the watertable and the hydraulic conductivity of the soil. What it is also showing is that as the size of the irrigation patch (r) increases (RHS in 4), the watertable rise underneath the patch (H) should increase (LHS) as well as the area of influence (I_m). This is consistent with the result of the analytical solution of Cook et al. (2007b) in transient condition.

Now imagine that in a landscape we can have either one large area of size R or a number (n) of smaller patches of size r so that:

$$\sum_{i=1}^{n} \pi r_i^2 = \pi \sum_{i=1}^{n} r_i^2 = \pi R^2 \qquad (5)$$

If r is constant then, the relative impact of mosaics (I_m) compared to conventional irrigation (I_c) is given by:

$$I_m / I_c = \frac{n(2r_i \Delta r + \Delta r^2)}{(2R\Delta R + \Delta R^2)} = \frac{n(H^2 - h^2)}{(H_c^2 - h^2)} \qquad (6)$$

Where H_c is the watertable height inside a large, conventional irrigation area.

In terms of flux out of the irrigation area, assuming the same configuration as in Fig 1, the volume of the water on the area is:

$$V = i\pi r^2 \qquad (7)$$

which has to pass through the x-sectional area of:

$$P = 2\pi r H \qquad (8)$$

Where H is the depth of the saturated flow. Thus the rate of flow out of the area (flux) is:

$$Flux = i\pi r^2 / 2\pi r H = ir / 2H \qquad (9)$$

If lateral flux from the mosaics should behave like what has been observed in leakage from disposal basins (i.e. less flux from larger basins) then as r increases, H should also increase (at a high rate). This would produce higher flux from smaller patches with higher perimeter/area ratios (P/A =2/r) consistent with observed leakages from smaller basins (Dawling et al. 2000).

We can simply see that if we use a metric for impact based on the watertable rise or the flux, we will conclude from the above that irrigation mosaics have some advantages over large contiguous irrigation area. The above preliminary analysis is based on simplifying assumptions (i.e. steady state, no interaction between irrigation patches and only lateral flow) and does not take into account the water quality and solute transport issues. These are dealt with elsewhere (Cook et al. 2007a, Knight and Cook 2007).

6. CONCLUSION

Ecological and hydrological research has provided tools for studying landscape spatial patterns but careful study and adaptation of these to irrigation mosaics is 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, can be used to identify geographic priorities for NRM actions that most cost effectively meet multiple-objective regional targets.

Ecotones, which are zones of transition between adjacent ecological systems, are important characteristics of mosaics and play an important role in 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 irrigated fields. On the other hand, fragmentation, due to discontinuous, isolated patches, can be detrimental for biodiversity. Fragmentation increases the vulnerability of patches to external disturbance, for example wind storm or drought.

In summary, it appears that irrigation mosaics could have both negative (more recharge, salinisation, increased operational losses, probably more costly) and positive (filtering nutrient surplus, enhanced biodiversity, preventing erosion, decreasing the areal impact of waterlogging) 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.

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