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AN OVERVIEW OF IRRIGATION MOSAICS†

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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 some rural and remote communities as well as better matching land use opportunities with landscape properties. 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. However, there are findings from ecological and hydrological studies of other mosaics that can help with analysis of irrigation mosaics. This paper provides an overview of some biophysical aspects of irrigation mosaics, lessons learnt from other mosaics (e.g. landscape and farming system mosaics) and the potential environmental impacts of irrigation mosaics. Application of some tools for particular groundwater conditions indicates some of these impacts compared to traditional large-scale systems. Irrigation mosaics could have both negative (more evaporation and water use, increased operational losses and costs) and positive (filtering surplus nutrients, enhanced biodiversity, preventing erosion, reduced area of impact around the irrigation area, lower water-table rise) effects on the environment. Copyright © 2010 Commonwealth of Australia.

KEY WORDS: irrigation mosaics; mosaics; irrigation impact; irrigation patches

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RÉSUMÉ

L'irrigation en mosaïque constitue une alternative aux grands systèmes irrigués issus du génie rural traditionnel. Elle consiste en un semis de petites parcelles irriguées réparties dans le paysage, avec pour principaux avantages de fournir des opportunités sociales et économiques aux populations rurales éloignées, et une meilleure adéquation entre l'utilisation du sol et les propriétés du paysage. Les impacts à long terme de l'irrigation en mosaïque qui peuvent affecter la durabilité du projet et les zones avoisinantes sont assez peu connus.

Néanmoins, la recherche issue de travaux sur l'écologie et l'hydrologie d'autres mosaïques aide à analyser l'irrigation en mosaïque. Ce papier donne un aperçu des aspects biophysiques de l'irrigation en mosaïque, tire des leçons d'autres systèmes en mosaïque (paysages ruraux en mosaïque par exemple), et examine les impacts potentiels de l'irrigation en mosaïque. A cet effet certains outils de modélisation d'hydraulique souterraine utilisés sous certaines hypothèses de condition de nappe souterraine permettent une comparaison avec les grands systèmes irrigués classiques. Les impacts de l'irrigation en mosaïque sur l'environnement pourraient être négatifs (augmentation de l'évaporation et de la consommation d'eau, augmentation des pertes et des coûts opérationnels) et d'autres positifs (contrôle des nutriments en excès, augmentation de la biodiversité, contrôle de l'érosion, périmètre impacté réduit autour de la zone d'irrigation, élévation moindre de la nappe). Copyright © 2010 Commonwealth of Australia.

MOTS CLÉS: irrigation en mosaïques; mosaïques; impact de l'irrigation; parcelles irriguees

INTRODUCTION

In making changes to existing irrigation systems, or designing new irrigation areas, it is necessary to determine what unwanted impacts and compensatory benefits are likely

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to occur. Most irrigation areas 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 large contiguous irrigated systems would be to have a number of small, localised irrigated areas dispersed as a mosaic across the landscape. A key question in thinking about mosaics is would they be an advantage or not? Here we review and examine some of the issues associated with irrigation mosaics, mainly in a biophysical context.

DEFINITION OF MOSAICS

Mosaics or patchiness refer to the spatial variation of some factor in the landscape. Spatial heterogeneity due to patchiness in the landscape characteristics can be due to climatic, geomorphological or land-use 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 land use, climate or irrigation.

Irrigation mosaics refer to irrigation systems where smaller discrete patches of land dispersed across the landscape are irrigated as compared to one large-scale contiguous irrigated area.

WHY CONSIDER 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.*, 2007a). Without appropriate management measures, irrigated agriculture has the potential to create serious ecological imbalances both within the irrigated area and in adjacent areas. The intensification of agriculture can lead to groundwater pollution related to the increased use of pesticides and fertilizers, 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. This may cause water-table rise, waterlogging and soil and/or groundwater salinity problems. Irrigation 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 *et al.,* 2006; Rengasamy, 2006) or due to groundwater depletion through extraction (Nativ, 2004; Yang, 2006). In some cases the poor quality of irrigation return flow can cause damage to other downstream uses. Agricultural intensification generally produces a decrease in landscape mosaic complexity, a simplification of many geochemical cycles, a reduction of many ecological processes and a decrease in system resilience (Farina, 1998).

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.

Irrigation mosaics as an alternative to the traditional large-scale irrigation scheme can offer some advantages as irrigation is often not suitable for all areas within a region and smaller discrete patches of irrigation allow more options and opportunities for adaptive management. 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 landownership is different from 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, 2008). They could also deliver improved social and economic opportunities for rural and remote indigenous communities.

LESSONS FROM OTHER MOSAICS

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.

Ecological systems

One of the main goals of landscape ecology is to study the structure of the spatial mosaic and its effects on 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 the 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 surplus nutrients.

The extent and quality of the ecotones are important for biodiversity. When a landscape is characterised 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.

Although patchiness can enhance biodiversity if it leads to fragmentation then this can be detrimental.The smaller the fragments the more they are influenced by the surrounding matrix. The fragmentation process has some implications for nature conservation. There is an optimal blend of patches and ecotones for the greatest biodiversity, and properly managed nature reserves with connectivity can provide the buffer that wildlife need in the face of changes in temperature, fires and/or precipitation. Fragmentation increases the vulnerability of patches to external disturbance, such as wind storm or drought, with consequences for the survival of these patches and of the supporting biodiversity (Nilsson and Grelsson, 1995).

Over the 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 excess water and solutes out of the irrigation area – which could lead to unwanted off-site impacts.

Salt disposal basins

Disposal basins are used to store drainage disposal water within 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 (Leany *et al.*, 2000).

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 the environment, with leakage being the most serious risk as this may contaminate groundwater below and/or downstream of 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 and solutes.

In a study of disposal basins in the Murray-Darling Basin 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 (Dowling *et al.*, 2000). In these areas, much of the leakage is shallow lateral flow away from the basin. This supports the results of Wooding (1968) who found the same ratio for infiltration from shallow circular ponds. Dowling *et al.* (2000) concluded that basins which have a larger perimeter compared to their area can have higher leakage rates.

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. For example, large community basins were thought to make regional planning simpler, but higher levels of construction, management and monitoring expertise are required due to their greater technical complexity compared with the smaller on-farm basins (Leaney *et al.*, 2000). 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 I).

Land-use mosaics

Land-use patterns in the landscape are often characterised by mosaics. Farming systems usually form a patchwork of paddocks with different crops within the landscape. Land-use planning relies on various criteria and tools to help decide ‘‘what needs to be planted where’’. The Heartlands

Table I. Large versus small irrigation schemes (FAO, 1996)

Large scale	Small scale
For: • Engineering economies of scale usually result in lower unit costs • Governments more disposed to take actions to ensure 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. • Requires more complex organisation and management; 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 such as displacement of settlements or disruption of wildlife habitats	*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 organisation and management • Often quick yielding • Smaller risk of 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

Initiative (Cresswell, 2004) designed a land-use planning process to support the prioritisation of investment in land-use change for achieving multiple environmental benefits. The process sought to explore and balance land-use options, as informed by underlying analysis of land resources, salinity and groundwater processes, biodiversity and commodity production. Spatial multiple criteria analysis was used as part of a method in helping to decide where to target revegetation in the landscape. Targeted land-use change (i.e. establishing trees or increasing the area of perennial pastures) was then studied using models (Paydar and Gallant, 2008) and monitoring to improve understanding of catchment function (Cresswell *et al.*, 2002). Mosaics for agricultural systems were investigated by Brennan *et al.* (2004). They gave a good overview of the existing knowledge for using farming mosaics in the Murray-Darling Basin. Brennan *et al.* (2004) concluded that knowledge gaps and cost in obtaining information to develop mosaic farming limit the adoption of mosaic farming. Agro-forestry (Lefroy and Stirzaker, 1999) is a land use 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 within 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). Alternatively, 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, 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 and wind erosion. In effect, land-use change in the Corridor has broken the connectivity of the landscape and the river. This SRP 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 timescale. Regional targets need to be set to address these multiple NRM 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 be adapted through to irrigation mosaics analysis once the biophysical and economic principles of mosaics are established.

DOES SIZE MATTER?

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 implications in terms of system losses in transporting water. It has been estimated that conveyance efficiency can be at its maximum for irrigable areas of between 40 000 and 60 000 ha. For smaller (<1000 ha) irrigable areas, conveyance efficiency reduces, probably due to reduction of management to fewer people who would be engaged in extension work, maintenance and transport as well as handling the distribution system. Large systems (>10 000 ha) tend to be less flexible in controlling and adjusting the water supply due to longer travel time in open channels (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 risks of adverse social impacts, such as displacement of settlements or disruption of wildlife habitats.

In theory, larger developments should encourage more government support, attract better management, be easier to organise, and therefore enjoy better prospects for sustainability. On the other hand, according to a World Bank review (World Bank, 1994) there is no evidence to suggest that small-scale irrigation is more or less likely than large-scale to achieve success. It is argued (FAO, 1996) that where irrigation institutions are still relatively weak, where there is a lack of capacity to plan, implement, operate and manage large schemes, attention should focus on smaller developments. There are also 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). Thus, the issue of scale seems best to be approached by considering the individual circumstances of the project and institutional capacities in the region and country concerned. More important issues than scale might play a role in predisposing irrigation to success such as the commitment of stakeholders to good engineering design, quality construction, efficient operation and maintenance (FAO, 1996).

MODELLING AND ANALYSIS TOOLS FOR STUDYING MOSAICS

Mathematical modelling is one of the most useful tools for exploring potential impacts of various mosaic designs. It is the tool to assess both flow quantities and qualities (e.g. salt/water balances, pollutant transport, changing flood patterns).

There is a lot of knowledge available about modelling groundwater mounds associated with increased recharge, occurring under irrigation. These modelling tools have involved both numerical and analytical methods, with most of the analytical methods based on the Boussinesq equation (Bear, 1972).

Knowledge gained from the analysis of injection and extraction wells offers 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 allows extension to multiple wells (irrigation mosaic).

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. Mantoglou *et al.* (2004) provide solutions for multiple well pumping to manage saltwater intrusion and these solutions also have application to groundwater management in irrigation mosaics. The periodic solutions of Bakker (2004) and additive solutions of Manglik *et al.* (2004) would also be useful when designing irrigation mosaics to minimise the impact on groundwater systems.

There has been much published recently on solutions of the Boussinesq equation for water flow in groundwater (Chapman, 2005; Chapman and Ong, 2006; Knight, 2005) and these have applications to irrigation mosaics. 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 are 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.

Cook *et al.* (2007a) presented a scaling framework that is useful for determining the marginal effect of size on some biophysical properties associated with irrigation mosaics. The analysis of circular irrigation patches has provided a means to explore the likely effect of irrigation mosaics compared to traditional large-scale irrigation by the use of one scaling parameter. They also simulated square and hexagonal grids of irrigation patches using the principle of superposition, using new solutions based on Hantush (1967) and Lin (1967) for groundwater heights and velocities for uniform areal recharge. The mathematical approach is useful in irrigation planning to help assess the likely number and spacing of irrigation patches in a particular 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. For a model to be suitable for mosaic analysis, it should be able to simulate hydrological components, including the movement of surface and subsurface water, groundwater, and exchanges between surface water and groundwater. In addition the model 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 groundwater flow, overland flow, channel flow and evapotranspiration. Each component solves a corresponding equation of a 3-D Boussinesq equation for saturated groundwater flow; 1-D Richards' equation for unsaturated groundwater flow; 2-D diffusion wave approximation of the Saint Venant equations for overland flow and 1-D diffusion wave approximation of the Saint Venant equations for river flow. Parameterisation of the MIKE-SHE model requires considerable effort but would be worth it to learn more about irrigation mosaics.

The MODFLOW model is also suitable for analysis of mosaics (Cook *et al.*, 2008). The main objective of groundwater modelling is to predict changes in water levels in response to changes in groundwater withdrawal and recharge. Application of groundwater response models to mosaics is especially challenging when patch boundary geometry and exogenous variables are complex. The capability to overlay map layers of soil, land use and weather and other spatial information makes it suitable for analysing patchy recharge and interaction between the patches in mosaics.

SOME EFFECTS OF IRRIGATION MOSAICS

In this section we provide a simplified analysis of the effect of the size of an irrigation patch on groundwater rise and flux from the irrigated area under steady-state conditions. Later, we present results for more general conditions. If the irrigation area is represented by a circle of radius r (analogous to a centre pivot), then the area (A) and perimeter (P) of each irrigation patch is

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

The assumption here is that 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 (Figure 1) at a steady rate of i (deep percolation from irrigation), then the area of influence for the mosaics (I_m), using Equation (1) is given by

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

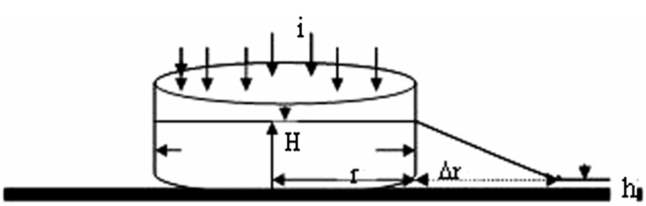

Figure 1. A schematic representation of an irrigation patch

True equilibrium may never occur, but assuming a quasi-equilibrium condition after a long period of steady recharge, with H and h being the water-table 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, then:

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

Upon integration:

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

Comparison of Equations (4) and (2) shows that the area of influence (water-table rise around the irrigation patch, I_m) depends on the head difference between the area under irrigation and the surrounding land, the rate of recharge to the water table and the hydraulic conductivity of the soil. The above gives a simple description of the main drives of water-table rise and spread, while Cook *et al.* (2008) give a more complete analysis of this problem and have shown that as the size of the irrigation patch (r) increases, the water-table rise underneath the patch will increase, which results in a larger area of influence.

If we use a metric for impact based on the water-table rise, we conclude from the above that irrigation mosaics have some advantages over a large contiguous irrigation area. The above analysis is based on a number of simplifying assumptions (i.e. steady state, no interaction between irrigation patches and only lateral flow) and does not address water quality and solute transport.

The effect of spacing of irrigation patches has been studied using the principle of superposition on grids of irrigation patches with continuous recharge (Cook *et al.*, 2007a,b, 2008). Their analysis showed that the height of the water table under the patch is directly related to time since the start of irrigation and inversely related to the spacing between patches. This means that the number, spacing and size of irrigation patches will need to be carefully planned to avoid unwanted impacts of water tables. Figure 2 shows the increase in the water-table height (compared to that for an isolated patch) with spacing between mosaics for different dimensionless times τ ($\tau = t\bar{b}K/\phi R^2$, where t is time [T], ϕ is the specific yield [$L^3\ L^{-3}$], $\bar{b}$ is the linearisation parameter, and K is the saturated hydraulic conductivity of the aquifer [$L\,T^{-1}$]).

Another important result of the analysis was that the water-table rise under isolated circular irrigation patches

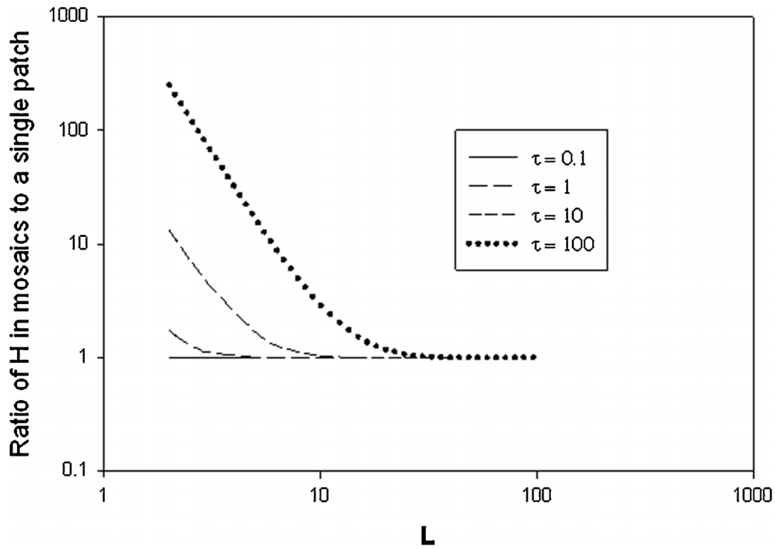

Figure 2. The ratio of the water-table height at the centre of the patch for a square grid of mosaic to that for an isolated patch versus the mosaic spacing *L*, for various values of dimensionless time (τ) (from Cook *et al.*, 2008)

increases exponentially with the radius of the patch (Cook *et al.*, 2008).

It must be noted that these results are based on analysis of an infinite array of patches with continuous recharge and do not consider extraction from the groundwater. This will tend to overestimate the water-table rise compared to an actual finite number of patches with periodic irrigation and with some groundwater extraction. For irrigation mosaics as the patches are placed closer together the water-table rise tends towards that of a single large patch and as the spacing between patches increases the water-table height (*H*) tends to that of a single isolated patch. However, as time increases the spacing at which *H* tends towards that of the isolated patch increases too (Figure 2).

The effects of irrigation mosaics on groundwater and solute transport was also investigated using numerical models by Cook *et al.* (2008). The MODFLOW groundwater model was used with different patch configurations (single, rectangular and hexagonal configurations) with periodic seasonal recharge from irrigation patches for periods up to 3 years. The solute transport module MT3DMS which uses the three-dimensional advective–dispersive–reactive transport equation was used to analyse the effects of the various patch configurations on solute transport. The following figures are extracted from the outputs of this modelling exercise to compare the mosaics with single large patches of irrigation. Figure 3 shows water-table heights at the centre of the irrigation patch (H_0) for a single large patch (radius $=7500$ m) and a mosaic of nine rectangular circular patches ($R = 2500$ m) (i.e. same irrigated area) with time.

Figure 4 shows the spread of the water-table rise (above the initial 5 m) in areas surrounding irrigated patches. It shows more spread and higher water-table rise for the single large patch than for the mosaic. The benefit of a lower water-

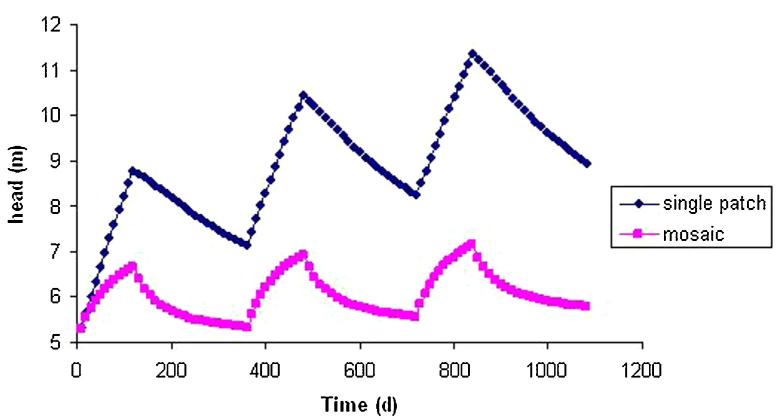

Figure 3. Comparison of water-table height at the centre of irrigation patch (*H*) vs time for single and mosaic patches. This figure is available in colour online at wileyonlinelibrary.com/journal/ird

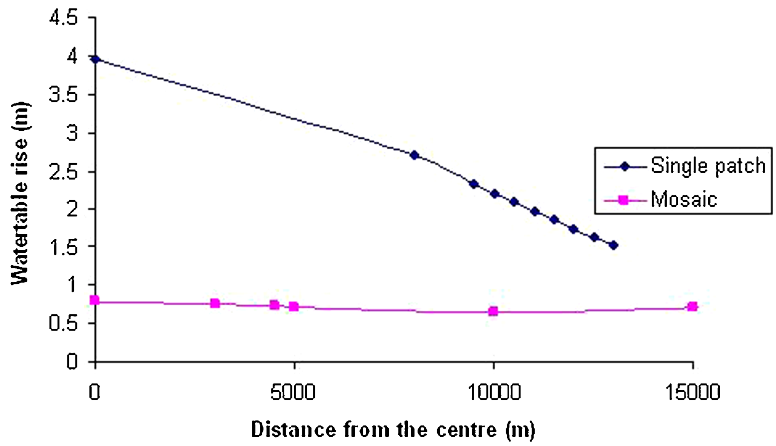

Figure 4. Extent of water-table rise (above 5 m) around irrigated patches after 3 years of irrigation. This figure is available in colour online at wileyonlinelibrary.com/journal/ird

table height by using irrigation mosaics may be at the cost of water-table rise, albeit at a lower level, over a larger area. This means that determining the benefit or cost of irrigation mosaics will require knowledge of their multiple impacts on existing ecosystems.

The solute concentration of the groundwater showed similar patterns after 3 years of irrigation. For the single large irrigation patch, at a distance of 9500 m from the centre, groundwater concentration was about 200 times that for the mosaics at a distance of only 4500 m. The solute transport results for a hexagonal arrangement of patches were similar to those for the square grid arrangement, but the concentrations were higher and breakthrough times were earlier. These all show that the impact of irrigation on water-table rise and hence waterlogging and salinity are more pronounced for single large areas of irrigation than for mosaics with smaller patches of irrigation, if all other factors such as irrigation rate, initial depth to water table, crops and soils are the same. The fact that water tables rise under irrigation no matter what the size of the irrigated area highlights the need to incorporate drainage management strategies as part of any irrigation system.

One aspect of irrigation mosaics that has gained little attention to date is the effect of advection and the potential to increase the evapotranspiration rate (McNaughton, 1983) and hence the overall water use by irrigation mosaics. Lang *et al.* (1983) studied advection and estimated the effect to increase evaporation by approximately 6% as a rough guide. Priestley (1955) and 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% for small irrigation patches compared to one large patch of irrigation (McNaughton K. G., pers. comm., 2006). For a single patch some understanding on how the size of an irrigated patch may affect evaporation can be gained from research that has been done on the effect of the size of a water body area on evaporation. This topic has recently been reviewed by McJannet *et al.* (2009) who have developed an area-adjusted wind function for water bodies of any size. Their wind function when used with the Dalton equation for evaporation can estimate the evaporation from different size water bodies. The Dalton equation, although rarely used for evaporation from land surfaces due to the requirement for surface temperature, has been shown to be applicable (Conway and van Bavel, 1967). Cook *et al.* (2008) used the Sweers (1976) wind function, which has the same exponent of -0.05 for the area adjustment as McJannet *et al.* (2009), to show that the evaporation rate from an irrigated patch is likely to be inversely related to the area of the patch. With mosaics there will be a number of patches and any increased evaporation rate is likely to be reduced in the downwind direction. Further research of these issues is needed to gain a better understanding of the likely impacts of irrigation mosaics on evapotranspiration. The work of Allen (1998) on wetland evapotranspiration showed that ET from small and isolated wetlands increased compared with the large areas of wetland. This increase was due to the vegetation being subjected to advective transfer of energy and the “clothes-line effect” which varies with height, density and shape of the canopy.

While further research is needed in this area to quantify this, current indications are that irrigation mosaics will evaporate more and hence will 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.

CONCLUSION

Irrigation mosaics as an alternative to traditional large-scale irrigation schemes offer some advantages as irrigation is often not suitable for all areas within a particular region.

Mosaics of smaller discrete patches of irrigation may allow more options for matching irrigated areas with the landscape properties and opportunities for adaptive management. Ecological and hydrological research has provided tools for studying landscape spatial patterns but careful study and adaptation of these to irrigation mosaics are required. For example, the concept of systematic regional planning can be used to identify geographic priorities for new irrigation developments that most cost effectively meet multiple-objective regional targets and match the landscape capabilities. The size of the irrigation patch (unit) has a significant effect on the rise of the water table below the irrigation area. The larger the irrigated area, the larger the rise of the water table due to deep percolation in a lateral flow condition will be. The spacing of the patches is also an important design consideration as the water-table height under the irrigation area is inversely related to the spacing between patches, while fragmented, isolated patches can be more vulnerable to external disturbances such as wind, storm or drought. With correct spacing and design irrigation mosaics can result in reduced water-table rise and less groundwater and solute spreading, and hence have the potential to deliver more environmentally friendly irrigation systems. However, if poorly designed and managed they are unlikely to deliver better outcomes than large contiguous areas of irrigation.

In summary, irrigation mosaics could have both negative (more evaporation, increased operational losses, probably more costly – though not considered in detail here) and positive (less water-table rise, filtering nutrient surplus, enhanced biodiversity, preventing erosion, decreasing the areal impact of waterlogging and solute transport) effects on the environment. These potential impacts will need careful analysis, and design criteria in terms of size, shape, density, connectivity and spatial arrangement together with economic analysis will need to be established to ensure irrigation mosaics are designed and managed in harmony with the landscape. These design criteria are needed if irrigation mosaics can be considered as plausible irrigation options.

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