Modelling the Hydrological Impacts of Artificial Drainage in the Western Australian Wheatbelt

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Keywords: *Hydrological modelling, salinity, engineered drainage*

EXTENDED ABSTRACT

Catchments in the wheatbelt region of southwestern Australia have experienced ongoing, slow rises in water tables since native vegetation was cleared for agriculture during the past 150 years. Water tables are very saline in much of the wheatbelt and are often overlain by large quantities of salt in the unsaturated zone. Rising water tables dissolve this salt and carry it closer to the surface. As a result, much of the wheatbelt landscape has become salinised and experiences waterlogging. Many ephemeral freshwater lakes have salinised and many of the valley flats are degraded.

Increasing concern by landholders about the impacts of salinity and water logging have led in recent years to a proliferation of local and regional scale drainage projects in wheatbelt catchments.

This paper describes the development of a regional-scale model for predicting flows and salt loads under a variety of engineering scenarios against a background of how these rivers might behave in the future without such schemes. The model is a modified version of the LASCAM-VIC model. The model is applied to a 108-subcatchment disaggregation of the Avon River catchment to predict the impacts of artificial drains, both locally and downstream.

The aridity, spatial heterogeneity and hydrological complexity of this catchment make it a challenging one to model. Of particular significance is that the system is not at hydrological equilibrium. Water tables are continuing to rise in most of the catchment and these rises are reflected in increasing trends of model predictions of streamflow and salt load for the period 1965–2100. At the catchment outlet, streamflow is projected to increase by 34 % between two 28-year time slices near the ends of the twentieth and twenty-first centuries, while salt loads are projected to increase by 542 % as saline groundwater plays an increasing role in runoff generation.

Two types of artificial drainage are separately assessed: open and leveed drainage. Open drains are assumed to be installed along the creek lines and as well as receiving and transporting drainage water, also admit and transport the natural flows generated through surface and subsurface runoff. The leveed drains are assumed to be installed adjacent to the natural creek and drainage lines. The levees on the upper lip of the drain prevent the admission of surface water. Subsurface runoff is admitted to the drain, but only from one side of the valley. The leveed drainage scenario is modelled as a dual-channel system, with drainage discharge and some subsurface runoff transported in the artificial channel and the remaining flow in the natural creek channel.

Model predictions indicate little difference in streamflow and salt load generated by the two drainage types. As a result, the drainage data presented in this paper are representative of both drainage types. Throughout the catchment, streamflow (Figure 1) and salt load significantly exceed those of the baseline scenario. Modelling of several disposal options indicate that for a leveed system, a local retention and disposal option involving subcatchment-scale evaporation basins is the most effective in reducing streamflows (Figure 1) and salt loads throughout the catchment.

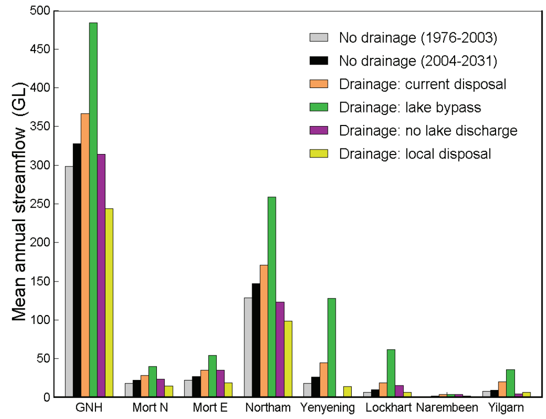

Figure 1. Predicted mean annual streamflow (2004–2031) at eight key locations in the Avon catchment for a variety of drainage scenarios.

1. INTRODUCTION

Water tables in the wheatbelt region of southwestern Australia have experienced ongoing, slow rises since native vegetation was cleared for agriculture during the past 150 years. Water tables are very saline in much of the wheatbelt and are often overlain by large quantities of salt in the unsaturated zone. Rising water tables dissolve this salt and carry it closer to the surface. As a result, much of the wheatbelt landscape has become salinised and experiences waterlogging.

In the Avon River catchment, about 5 % of the land surface is currently affected by secondary salinity. Many ephemeral freshwater lakes have salinised and many of the valley flats are degraded. By the time a new hydrological equilibrium is reached, about 25–30 % of the basin is at risk of salinisation.

Increasing concern by landholders about the impacts of salinity and water logging have led in recent years to a proliferation of local and regional scale drainage projects in wheatbelt catchments. These projects have been developed largely on an ad hoc basis, with little regulatory control and in the absence of an analytical framework for assessing the likely cumulative impacts of these systems on future flows, flooding and salt loads.

This paper describes the development of a regional-scale model for predicting flows and loads under a variety of engineering scenarios against a baseline of how these rivers might behave in the future without such schemes. The model is a modified version of the LASCAM-VIC model (Zammit et al., 2003). As well as the addition of an artificial drainage algorithm, adaptions to the model for this project include modifications to the lake routing scheme and to the flow routing algorithms to better reflect stream storage. The model is applied to the Avon River catchment to predict the impacts of artificial drains, both locally and downstream, and also of several potential disposal options.

2. THE AVON RIVER CATCHMENT

The Avon River drains 116000 km^2 of the Western Australian wheatbelt (Figure 2). The hydrology of the catchment is dominated by the significant influence of the regional groundwater system and by the presence of numerous lakes. The groundwater system plays a key role in maintaining soil moisture during the dry summer periods and in moderating the interannual variability in rainfall. The lakes are mostly located along the stream channels, have relatively large storage capacities (in comparison to their annual inflows) and discharge relatively infrequently, if at all. It is usually only during extreme rainfall events that the notional drainage network is fully linked. At other times, much of the catchment is internally draining.

Figure 2. Location of the Avon River basin.

Mean annual rainfall ranges from 850 mm in the west—most of it occurring in winter—to less than 250 mm in the east. The mean annual streamflow near the bottom of the basin over the period 1975–2003 is 2.6 mm, while the flow-weighted salinity is 4600 mg L^{-1}. Groundwater salinity ranges from 2700 mg L^{-1} in the west to over 55000 mg L^{-1} in some eastern parts of the basin.

3. ARTIFICIAL DRAINAGE

Two types of artificial drainage are separately assessed: open and leveed drainage. Open drains are assumed to be installed along the creek lines and as well as receiving and transporting drainage water, also admit and transport the natural flows generated through surface and subsurface runoff. The leveed drains are assumed to be installed adjacent to the natural creek and drainage lines. The levees on the upper lip of the drain prevent the admission of surface water. Most of this surface water eventually finds its way in to the natural creek channel, but some remains behind the levee and reinfiltrates. Subsurface runoff is admitted to the drain, but only from one side of the valley. The leveed drainage scenario is modelled as a dual-channel system, with drainage discharge and some subsurface runoff transported in the artificial channel and the remaining flow in the natural creek channel.

For each type of drain, the drain dimensions and lengths (for a given subcatchment) are the same. Bottom widths are assumed to be 1.5 m and depths

2.5 m everywhere. For each subcatchment, drain lengths are derived from the estimated salinised areas in 2000 and 2100 based on an assumed proportion of Land Monitor valley hazard mapping (Allen and Beetson, 1999). Drain lengths in a subcatchment are assumed to increase linearly over time between 2000 and 2100.

Artificial drainage delivers large amounts of excess water and salt into the stream network. One of the biggest problems with artificial drainage systems is in managing this excess. In this study we assess a number of disposal options.

The default disposal option is to use the existing stream and lake network. Under this option, drainage water discharges directly into the existing lakes. Here, the water mostly evaporates, although some will discharge downstream if the lake reaches its overflow level. Evaporation will leave most of the salt in the lakes and the salinity of the lake water will gradually increase. This means that when the lake overflows, the discharge will be extremely saline.

The discharge of highly saline water from the lakes can be reduced by engineering the lake discharge levels. Increasing the discharge height will increase the amount of dead storage that a lake can hold before it overflows, thus reducing the frequency and volume of lake discharges. The lake outlet engineering option assessed here involves increasing discharge heights to such an extent as to prevent the lakes from discharging altogether.

A further option is to bypass the lakes completely, so that water and salt from artificial drainage can flow without impediment to the catchment outlet.

A final option (one that is appropriate only for a leveed system) is to build evaporation basins within each subcatchment, so that drainage water and salt are retained locally. Only flows in the natural creek channels are allowed to pass from one subcatchment to the next.

4. MODEL DESCRIPTION

4.1. The LASCAM model

The hydrological model used to predict flows and loads in the Avon catchment is based on LASCAM (Sivapalan et al. 2002, Zammit et al. 2003). LASCAM was developed to predict the impact of climate and land use changes on fluxes of water, salt, sediment and nutrients in forested and agricultural catchments. It operates on a daily time step and relies on calibration of model parameters against one or more observed records of streamflow and load. Topographic information is used to divide a catchment into a number of subcatchments and to delineate a stream network. LASCAM is applied separately to each of these subcatchments and the resulting flows are routed along the stream network. For application of LASCAM to the Avon catchment, the catchment was subdivided into 108 subcatchments ranging in size from 5 km^2 to 9000 km^2.

At the subcatchment scale, the model is built around four inter-connected stores of soil water representing the near-stream perched aquifer, the upper soil layers, the deeper, regional groundwater and the unsaturated zone. Streamflow is generated from infiltration-excess and saturation-excess overland runoff and from a baseflow discharge from the near-stream perched aquifer store. The hydrological processes and subcatchment properties influencing them are assumed to be lumped at the subcatchment scale, but are allowed to vary between subcatchments.

Each of the four water stores has a mass of salt associated with it. Any discharge of water from a store carries with it an amount of salt that is commensurate with the salinity of the store. There is an additional fifth salt store which includes the large quantity of salt that is stored out of solution in the unsaturated zone. This salt has accumulated over millions of years. It is mobilised into the groundwater store by matrix recharge and by dissolution by the rising groundwater tables.

A key aspect of LASCAM—and one that distinguishes it from most other lumped rainfall-runoff models—is that a global set of model parameters is used (i.e., all subcatchments use the same parameter set). Modelling of the spatial variability in streamflow is achieved through taking account of the spatial (and temporal) variability in vegetation density, climate and soil characteristics. This framework allows a high degree of confidence in predictions on ungauged parts of the catchment.

4.2. Model modifications

Channel routing

Stream velocities in the pre-existing LASCAM are based on a two-parameter empirical equation and vary nonlinearly with flow volume. In this project, this routing scheme was replaced by one based on Manning's equation. This yields stream velocities that depend on channel cross-section morphology and substrate, as well as on flow volume. The main advantage of this approach is the ability to represent different types of channel (engineered or natural) by changing the relevant coefficients describing channel shape and dimensions.

Lake storage and routing

The existing LASCAM model has a rudimentary lake routing algorithm, but it is considered too simple to adequately describe lake processes in a region such as the upper parts of the Avon Basin where playas exert a dominant control on stream routing. In this project, which includes a comprehensive lake survey campaign, coupled with some detailed GIS-based lake modelling, the opportunity arose to revise the lake algorithm in LASCAM, while still retaining the original lake modelling framework.

The hydrological and river routing modules of LASCAM generate volumes of inflows into the lakes. The basic requirements of a lake model are to enable predictions of the discharge of water and salt from the lakes and the evaporation of water from the surface. In the modified model, discharge is a nonlinear function of lake volume, provided the volume exceeds the dead storage level of the lake. Evaporation from a lake surface is modelled as a function of its area, which, in turn, depends on the volume.

The new lake modelling equations require the specification of up to four characteristic dimensions and rates for each modelled lake. These can be obtained from lake survey data. The equations also introduce two new (global) model parameters that must be optimised during the calibration process.

Artificial drainage

Calculations of the impacts of artificial drainage in LASCAM are based on the Hooghoudt Equation which relates drainage spacing to discharge rates. The effective area drained is given by the length of drains, λ, multiplied by the length of effectiveness, L, which is the length of hillslope over which water tables are directly affected. Thus, the actual drain discharge rate is given by

$$Q_d = 8\, K_s\, \lambda\, (D_b - d)\, h\, /\, L$$

where K_s is the saturated hydraulic conductivity, D_b is the depth to bedrock, d is the depth of the drain and h is the height of the water table above the bottom of the drain. For a given subcatchment, K_s, D and L are fixed. The length of artificial drainage, λ, is allowed to vary over time and in the Avon catchment, is assumed to increase linearly from its 2000 value to a notional equilibrium value, which we assume applies in 2100.

The value of h is tied to LASCAM's predictions of water table depth. For each subcatchment LASCAM predicts daily fluctuations of the depth of water in the deep groundwater (B) store. This depth, though, is a subcatchment average and can not be related directly to the water table depth at any particular point (e.g., the drain location) in the subcatchment. We expect that the actual water table depth will be shallower near the drainage lines and deeper on the hillslopes, but we have no way of knowing exactly how deep it will be near the drains. To overcome this, we assume that at the onset of drainage (2000 in the Avon), the water table depth is some fixed height above the bottom of the drain. This fixes an initial value of h. Thereafter, fluctuations in the predicted subcatchment-average B store are assumed to lead to concomitant rises or falls in h, the magnitudes of which are determined by a lateral fluxing scheme between the zone of effectiveness and the remainder of the subcatchment. If the average water table falls to such an extent that h drops to zero, then discharge ceases. Using the B store predictions of LASCAM, we may then replace h with $h_0 + (B - B_0)/\varphi$, where h_0 is the initial value of h, B is the B store level, B_0 is the level of B at the onset of drainage and φ is porosity.

Assuming values of D_b, K_s and L typical for the eastern wheatbelt, then at the onset of drainage, when $B \approx B_0$, the predicted rate of drainage per kilometre of drains ($1000\, Q_d\, /\, \lambda$) is $25\ \mathrm{kL\ km^{-1}\ d^{-1}}$, which is extremely close to observed rates. Note that this rate of discharge will change over time in response to changes in B.

LASCAM has also been modified to accommodate the way artificial drainage affects other aspects of the surface hydrology. These include changes to the discharge rates and fate of subsurface and surface runoff in the presence of artificial drains.

5. RESULTS

5.1. Calibration

LASCAM has been calibrated for the Avon catchment by comparing observations and predictions of streamflow and salt load at a number of gauging sites throughout the catchment. This yields a single set of model parameters that apply everywhere. Of fourteen key stream gauging stations, most have daily model efficiencies (Nash and Sutcliffe, 1970) in excess of 0.55 and most have absolute biases that are less than 12 %. For salt load, most sites have daily salt load efficiencies in excess of 0.55 and absolute biases less than 25 %. Most monthly efficiencies exceed 0.7 for both streamflow series and salt load series.

5.2. Benchmark scenario

To enable the model to make predictions to 2100, the observed climate for the 28-year period 1976–2003 was repeated about three and a half times, beginning in 2004. An implied assumption is that this climate will prevail for the remainder of the twenty-first century.

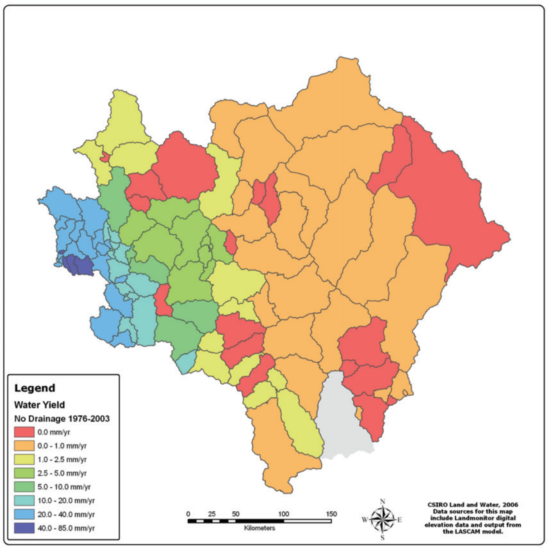

Figure 3. Predicted mean annual water yield (outflow minus inflow), 1976–2003.

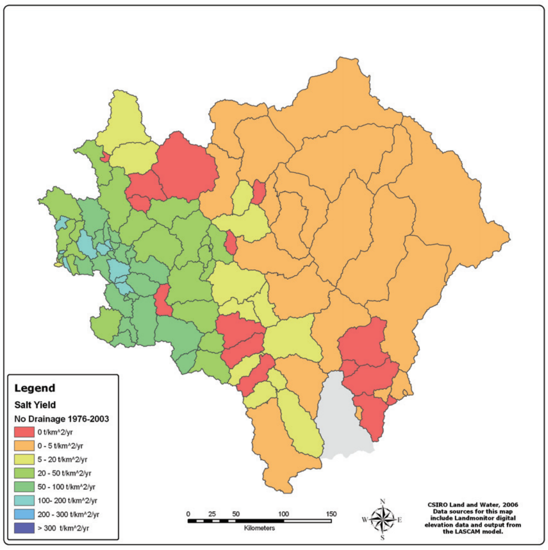

Figure 4. Predicted mean annual salt yield, 1976–2003.

The main source areas for water within the Avon catchment during the period 1976–2003 are shown in Figure 3. In the main, streamflow production is closely related to the rainfall distribution. The largest source areas of streamflow are in the far west, where annual generation exceeds 40 mm. There is very little streamflow generated in the Lockhart and Yilgarn regions, which comprise more than 70 % of the catchment. In contrast, the salt discharged from the catchment is sourced from much farther upstream (Figure 4). The largest salt sources are in the upper Avon Valley (between Toodyay and Brookton) and exceed 100 t km^{-2} y^{-1}.

By the end of the twenty-first century, streamflow yield increases across most of the catchment above Northam (Figure 5). Substantial sources of water extend well into the Yilgarn region and include almost all of the Lockhart region. Exceptions in the Lockhart are the subcatchments whose discharges are governed by lake processes. The increases in salt yield by the end of the century are even larger (Figure 6), with some subcatchments now contributing more than 300 t km^{-2} y^{-1}.

The non-stationarity in water and salt yields evident in Figures 3–6 is shown in more detail in Table 1, which compares mean annual streamflows and salt loads at eight key locations within the catchment for two different time periods. At the catchment outlet (Great Northern Highway), there is a 34 % increase in predicted streamflows between these two time slices and a 542 % increase in salt loads. At each of the other key sites, moderate to large increases in streamflow are accompanied by substantial increases in salt load.

Table 1. Predicted mean annual streamflows and salt loads for two time periods.

Location	Water (GL/y)		Salt (kt/y)	
	1976–2003	2073–2100	1976–2003	2073–2100
Gt Northern Hwy	298	399	1366	7400
Mortlock North	18	33	128	926
Mortlock East	22	37	178	804
Avon at Northam	128	193	770	5100
Yenyening	18	57	237	3336
Lockhart	6	30	49	2208
Narembeen	1	6	7	218
Yilgarn	8	17	50	520

Increased flows are also manifested as increased frequencies and volumes of lake discharge. Between the two 28-year periods, 1976–2003 and 2073–2100, discharge frequencies increase for all but one of the non-terminal lakes, although only one of the previously identified terminal lakes (Gulsen) discharges in the final 28 years of the simulation period. Several of the lakes that are near-terminal in the twentieth century fill quite frequently by the late twenty-first.

Since the lakes discharge more frequently, it is no surprise that their mean annual discharges are also greatly increased. There are also significant increases in (flow-weighted) discharge salinity, which reflect the increased salinity of lake inflows.

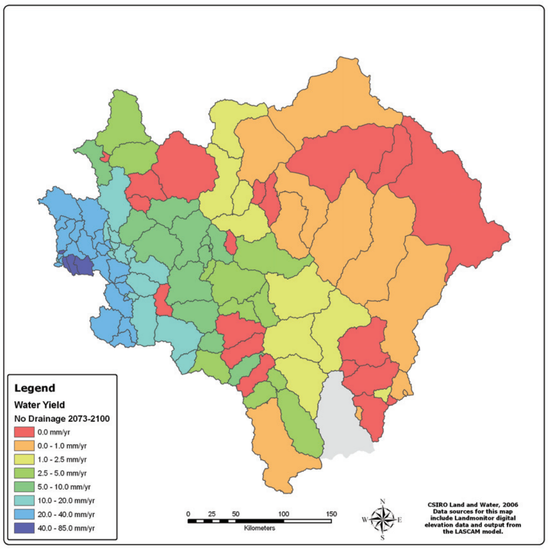

Figure 5. Predicted mean annual water yield, 2073–2100.

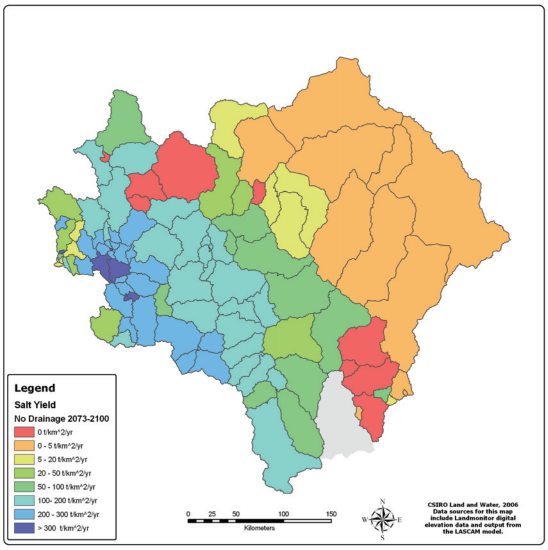

Figure 6. Predicted mean annual salt yield, 2073–2100.

Lake Dowerin, the next modelled lake upstream of the Mortlock East flow gauge, remains terminal throughout the simulation. This means that the flow and salinity increases predicted at the gauge site (Table 1) are unaffected by increases in flow and salinity from the lake system, and are entirely due to increased flow generation downstream of Lake Dowerin. In contrast, other key gauging sites are affected to a far greater extent by increases in upstream lake discharges. For example, Lockhart River flows increase from 6 GL y^{-1} to 30 GL y^{-1}, with flow-weighted salinities increasing from 8 g L^{-1} to 74 g L^{-1} under the influence of the frequent and highly saline discharges from Lake Kurrenkutten in the lower Lockhart.

5.3. Artificial drainage

The equations governing drainage into artificial channels are identical for open and leveed systems. Moreover, in a given subcatchment, the assumed lengths of drainage are identical for each type of system. Therefore, even though the drains interact differently with surface flow, is little difference in the predictions of streamflow, salt load, lake storage and salinity and groundwater depths and salinities between the two schemes. Long-term simulations indicate that both systems are effective in lowering water tables in drained subcatchments. In engineered subcatchments, the introduction of drainage in 2000 first reduces the rate of increase in groundwater level, relative to the baseline case, and later actually begins to lower the water table. This not only brings forward the attainment of new hydrological equilibrium, but also results in lower equilibrium water tables.

However, as well as achieving the intended outcome of lowering water tables, artificial drainage leads to some less desirable outcomes, including increases in streamflow and, especially, salt load. In comparison with the baseline case, artificial drainage increases streamflows by 12 % at the catchment outlet and by up to 100 % at some of the other key locations (Figure 1). However, artificial drainage has little impact on peak flow rates, which increase by less than 1 % at the catchment outlet and by less than 22 % everywhere. This indicates that peak flows are governed largely by surface runoff processes, rather than by the presence of artificial drainage.

Salt loads are heavily affected by artificial drainage (Figure 7). At the catchment outlet, salt loads under artificial drainage are more than double those of the undrained scenario. Further upstream, the increases are much greater, with an eight fold increase in the Yilgarn region.

The predicted impacts of three alternative disposal options are shown in Figures 1 and 7. The lake bypass option leads to substantial increases in streamflow (by 32 %) and salt load (43 %) at the catchment outlet, with respect to the fluxes associated with the default disposal option. Larger increases are predicted at most locations upstream.

The disposal option to prevent the lakes from discharging reduces streamflows at the outlet by 14 % and 52 %, respectively, in comparison with the default disposal option. Even larger reductions are predicted for the Avon River at Northam and for the Yilgarn River, while there is no discharge at all through the gauging site at Yenyening, which is located immediately downstream of a lake. In contrast, this option has no impact on discharges at Narembeen, which has no upstream lakes, or Mortlock East, for which Lake Dowerin remains terminal for all drainage scenarios.

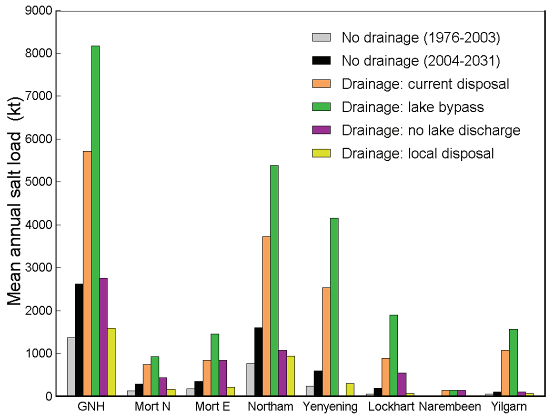

Figure 7. Predicted mean annual salt load (2004–2031) at eight key locations in the Avon catchment for a variety of drainage scenarios.

The subcatchment retention option has by far the biggest impact in reducing mean annual fluxes and unlike the other disposal options, also reduces the magnitude of peak events. At the catchment outlet, mean annual flows and loads are reduced by 33 % and 72 %, respectively, with larger reductions predicted at all seven key upstream sites.

6. DISCUSSION AND CONCLUSIONS

The Avon basin is relatively arid and spatially heterogeneous in its climate and hydrology. These factors alone make it a difficult catchment to model adequately. The modelling task is made even more challenging by the significant influences exerted by the regional groundwater system and by the lakes. The non-stationary nature of the regional water tables dictates that a conventional lumped rainfall-runoff model would not be able to adequately model this system. Furthermore, without separate explicit recalibration for each gauging site, such a model would not be able to provide credible predictions of streamflow, let alone salt load, in such a complex catchment. In contrast, given that they are derived from a single parameter set, the calibration results for LASCAM indicate that the model is capable of providing reliable predictions over a wide range of hydrological conditions and consequently that a high degree of confidence may be attached to its predictions in ungauged subcatchments.

The modelling results illustrate the significant role played by the lakes in moderating flows and salt loads. Comparison of the effects of the first three disposal options in Figures 1 and 7 show that there are substantial differences in predicted fluxes depending on whether the lakes are unmodified, bypassed or engineered to prevent discharge.

The subcatchment retention option has the greatest impact in reducing streamflows and salt loads in downstream subcatchments. In fact, for all eight key sites, the discharges of water and salt under this option are less than those for the undrained case during the same time period, and are typically similar to those experienced from 1976 to 2003. It is clear that this option has great potential to ameliorate the undesirable hydrological aspects of artificial drainage. However, such an option is likely to be costly. A detailed study of the engineering practicality and economic feasibility of all disposal options is warranted.

In this study, we have applied the various engineered drainage scenarios in all drained sub-catchments across the basin. However, although not presented here, the model is also capable of predicting the consequences of applying a mixture of scenarios in different parts of the catchment. These include scenarios involving revegetation options for salinity control. The model has also been used to predict the combined impacts of a number of projected climate changes modelled in conjunction with the various engineering options.

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