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Hydrological impacts of irrigated agriculture in the Manuherikia catchment, Otago, New Zealand

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Abstract

Water for irrigation is becoming an increasingly critical component of New Zealand's rural economy. Projections of expanding agricultural sectors indicate increased demands for water and a reliable water supply. Hence, it is pertinent to assess the impacts of water demand for current and future irrigated agriculture on catchment hydrology. This case study focuses on estimating the hydrological impacts of irrigated agriculture in the Manuherikia catchment upstream of Alexandra, Central Otago, New Zealand. In order to assess the impacts of irrigation on streamflow, five land-use scenarios, including three irrigation scenarios with varying efficiencies, are investigated with the ACRU agro-hydrological modeling system (Agricultural Catchments Research Unit (ACRU), Department of Agricultural Engineering, University of KwaZulu-Natal, Republic of South Africa, http://www.beeh.unp.ac.za/acru/). The results show a 37% loss of mean annual water yield under current conditions due to inefficient irrigation practices. Even with the most water-efficient irrigation infrastructure, this loss could be reduced by only 20% – meaning a 30% loss of mean annual water yield. These results emphasize the significant and inevitable water demands and catchment water yield losses associated with irrigated agriculture, which are due to losses in the conveyance system, on-farm application losses, increased actual evapotranspiration, and the development of a deeper rooting system compared to natural vegetation.

Introduction

Water for irrigation is becoming an increasingly critical component of New Zealand's rural economy. More intensive farming systems are usually accompanied by a demand for increased water quantity and a reliable water supply. Projections indicate that New Zealand's dairy, horticulture and viticulture sectors will all expand in the future, and it follows that there will be growing demands for water for irrigated agriculture (Ministry of Agriculture and Forestry, 2004; Parliamentary Commissioner for the Environment, 2004; Doak, 2005).

The economic implications of these predicted future trends have been assessed (Ministry of Agriculture and Forestry, 2004; Doak, 2005), but little is known about the impacts of irrigated agriculture on catchment hydrology and water resources due to increased water demands relative to a static, and under future climate conditions potentially declining, supply. As water resources become scarcer and water supply becomes less certain due to forecasted climate change (IPCC, 2007), it is pertinent to assess the impacts of intensified irrigation practices on catchment hydrology. The report 'Growing for good' of the Parliamentary Commissioner for the Environment (2004) contains some qualitative estimates about current trends in water quality and water quantity for New Zealand's regions. These qualitative estimates need to be translated into quantitative evaluations to manage water use in New Zealand's catchments and to balance the economic value of irrigation with environmental costs and sustainable agricultural practices (Poff *et al.*, 2003). Potential impacts of irrigation on water resources include changes to river flow rates, in particular low flows, and lowering of groundwater levels as a result of abstraction and changes in recharge rates. Surface water and groundwater systems sustain complex ecosystems. The change of water flow rates and storage quantities may have adverse effects on those ecosystems, potentially altering them significantly (Larned *et al.*, 2007; Parliamentary Commissioner for the Environment, 2004; Poff *et al.*, 2003).

In an ideal setting, the evaluation of the impacts of land-use change, including the introduction of irrigated agriculture, large reservoirs, irrigation canal systems (races), farm dams and inter-basin transfer, would be based on long-term streamflow observations both upstream and downstream of such a development. However, in New Zealand, available streamflow records are often not long enough nor dense enough to allow the quantitative assessment of the impact of irrigated agriculture. Therefore, as an alternative approach, the streamflow can be simulated for pre- and post development scenarios. Such a simulation requires that the selected model be not only able to simulate the major elements and processes of the hydrological cycle, but it also needs to be sensitive to land cover changes and incorporate elements of the infrastructure for irrigated agriculture likely to effect catchment hydrology.

This case study focuses on estimating the hydrological impacts of irrigated agriculture in the Manuherikia catchment upstream of Alexandra, Central Otago, New Zealand. The aim is to highlight differences in the catchment's hydrological responses under natural conditions and under modified conditions associated with irrigated agriculture. This is achieved by simulating both the natural hydrology of the catchment and a number of irrigation scenarios using a physically-based model of catchment hydrology. A suitably structured hydrological simulation model, operating at appropriately sensitive time steps and spatial scales, is required. The daily time step, physical-conceptual and multipurpose ACRU agro-hydrological model (the acronym ACRU is derived from the Agricultural Catchments Research Unit, Department of Agricultural Engineering, University of KwaZulu-Natal, Republic of South Africa; Schulze, 1995), was selected. In addition to calculating all elements of streamflow, it can simulate reservoir yield, irrigation supply/demand and return flows and has been structured explicitly to represent processes of land-use change impacts. In this paper we describe the characteristics of the Manuherikia catchment, and the configuration for use with the ACRU model; we apply the model with a baseline land cover to simulate pre-settlement conditions and show the effects of several scenarios of irrigated and non-irrigated agriculture on the Manuherikia's water resources.

Study area

The Manuherikia catchment is located north-east of Alexandra, Central Otago, New Zealand (Fig. 1). The Manuherikia River is a tributary to the Clutha River – one of the largest rivers in New Zealand (the largest in terms of flow volume). The Manuherikia catchment has an area of 3035 km^2 at

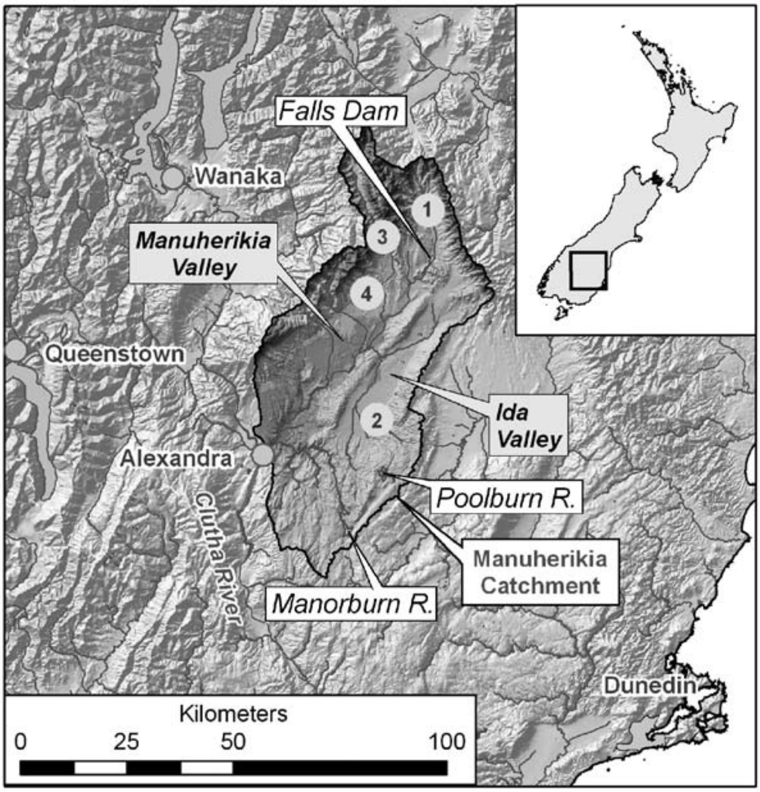

Figure 1 – Map of study area: Numbers 1 to 4 are the locations of the four gauging stations (see Table 2 for details).

Alexandra. The central valley bottoms of the catchment, divided into two major valleys, constitute one of the largest intra-montane depressions of the tilted fault mountain and basin systems of Central Otago, and are filled with Tertiary and Pleistocene deposits. The northernmost headwaters of the catchment reach an elevation of 2100 m and drop 1200 m over a distance of 20 km to the headwater valley bottoms. The central valley bottoms of the catchment have an altitude of 100–500 m (Fig. 2a).

Due to the distance to the sea and the high altitude in Central Otago, the climate is the most continental in New Zealand. Temperatures range from a maximum of 35°C in summer to a winter minimum of –20°C. The annual mean temperature is approximately 10°C. Temperature ranges and associated potential evapotranspiration ranges within the catchment are largely due to the wide variations in altitude. The valleys in the Manuherikia catchment are sheltered from south-westerly and north-westerly rains and have the lowest recorded rainfall in New Zealand. Rainfall increases from an average of 330 mm/y around Alexandra to 1500 mm/y in the northern Hawkdun Range (Fig. 2b). Rainfall occurs throughout the year, with approximately 60% falling in spring and summer. In the valleys only 3% of annual precipitation falls as snow, while on the highest ridges snowfall can constitute up to approximately a third of the annual precipitation.

The Manuherikia catchment can be divided into two major subcatchments (Fig. 1). The eastern Ida Valley drains the eastern and south-eastern Otago uplands ('Rough Ridge'), which has a lower rainfall than the northern part of the catchment (Fig. 2b). The western Manuherikia Valley is separated from the Ida Valley by the central Raggedy Range, where the Idaburn River drains through a single gorge into the Manuherikia River. A five year flow record from gauging station 75252 Poolburn at Cobb Cottage indicates very low streamflow contributions from the Idaburn River, with a mean annual flow of 1.32 m^3s^{-1}, constituting a runoff coefficient of approx. 9% under current conditions. This is an indication of high evapotranspiration (Fig. 2c) and water use in the low rainfall Ida Valley. The Manuherikia River drains the northern part of the catchment (Hawkdun Range, Bathans Range), where most of the runoff in the Manuherikia catchment is generated as a result of the 900 to 1500 mm of mean annual rainfall in the western Dunstan Mountains.

Native vegetation and soils vary mainly with altitude in the study area (Fig. 2 d,e). Above 1500 m alpine steepland soils and sparse vegetation (alpine and subalpine herbs) occur. Within the elevation range 900 to 1500 m, soils are dominantly high country yellow-brown earths, with silver tussock, hard tussock and snow tussock making up the main vegetation. Below 900 m, fescue and blue tussock grassland dominates. Soils between 700 and 900 m are mainly recent alluvial soils, while the soils in the central valley bottoms below 700 m are yellow-grey earths (Ahlers and Hunter, 1989). Knowledge of the associated soil textures (Fig. 2e) and soil depths are essential for hydrological simulations as they govern the hydrological behaviour.

Land use in the Manuherikia catchment is dominantly sheep, cattle and, to a small extent, deer farming. On terrace sediments in the lower part of the catchment extensive vineyards have been established over the last decade.

A water balance deficit occurs in nine months of the year near Alexandra, with an annual average deficit of around 300 mm. Low rainfall in the valley bottoms led to the early development of extensive water storage and irrigation schemes. Consequently, three reservoirs were established in the Manuherikia catchment to provide water for irrigation.

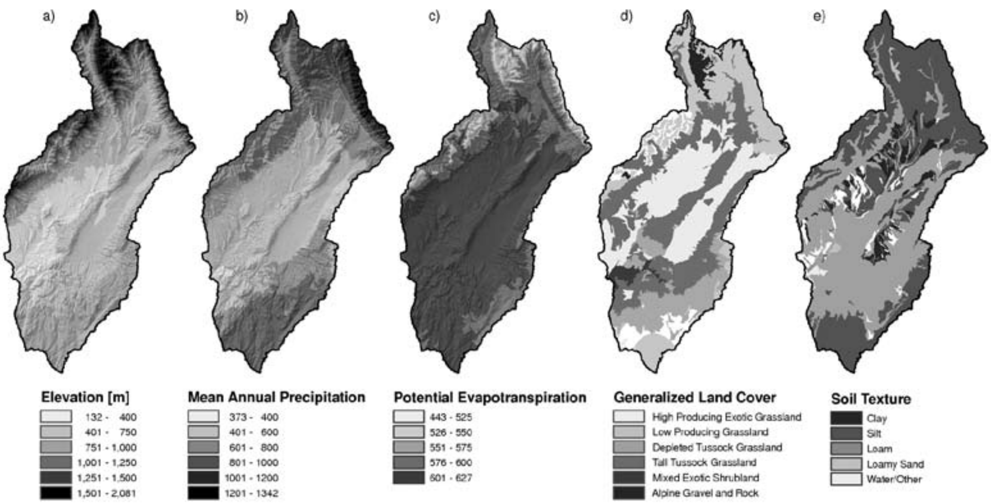

Figure 2 – Physical characteristics of the Manuherikia catchment.

Falls Dam was built in 1935 to capture the high rainfall water supply in the northern high-altitude part of the catchment and has a capacity of 11 Mm^3. Poolburn Reservoir was constructed in 1931, with a capacity of 26 Mm^3, while Manorburn Reservoir was built in 1935 and has a capacity of 51 Mm^3.

There are several major irrigation schemes. The Blackstone Hill, Omakau, Manuherikia, and Galloway irrigation schemes take water out of the Manuherikia River, which is partly controlled by the releases of Falls Dam, and distribute the water through a network of open water channels to irrigate the Manuherikia Valley bottom. The Poolburn Reservoir is used to store water to irrigate Ida Valley. Water from the Manorburn Reservoir is partly diverted into the Manuherikia Valley over an open water race to irrigate the upper Galloway Irrigation Scheme. The rest of the Manorburn water is used for irrigation in the Ida Valley.

The irrigation distribution system consists of a network of manually controlled, unlined, open water races. Water is applied in the Manuherikia catchment by sprinkler irrigation (predominantly 'K-line') or flood irrigation. It has been shown that irrigation practices in the catchment have had significant negative impacts on the river water quality (Otago Regional Council, 2006). The purpose of this study is to complement these findings with an impact assessment on catchment hydrology.

The ACRU agro-hydrological modelling system

The ACRU agro-hydrological modelling system (from here on referred to simply as the ACRU model) has been developed in the Agricultural Catchments Research Unit (ACRU), Department of Agricultural Engineering (now the School of Bioresources Engineering and Environmental Hydrology) at the University of KwaZulu-Natal, Republic of South Africa, since the late 1970s (ACRU, 2007). The developers (Schulze, 1995; Smithers and Schulze, 1995) refer to the ACRU model as a multi-purpose, multi-level integrated physical-conceptual model that can simulate total evaporation, soil water and reservoir storages, land cover and abstraction impacts on water resources and streamflow at a daily time step. The ACRU model revolves around multi-layer soil water budgeting with specific variables governing the atmosphere-plant-soil water interfaces (Fig. 3). Runoff is generated as quick flow, which responds to the magnitude of daily rainfall in relation to dynamic soil water budgeting, i.e., the antecedent moisture conditions.

The ACRU model has detailed routines to simulate irrigation and can account for a multitude of hydrological processes and practices, including farm storages, conveyance losses, spray irrigation losses, irrigation scheduling, and water stress behaviour of crops (Schulze, 1995; Smithers and Schulze, 1995). The ACRU model is not a parameter-fitting or optimizing model, as variables, rather than optimized parameters, are estimated from the physical characteristics of the catchment. However, not all required variables are always available, and these are then estimated within physically meaningful ranges based on either the literature or field observations.

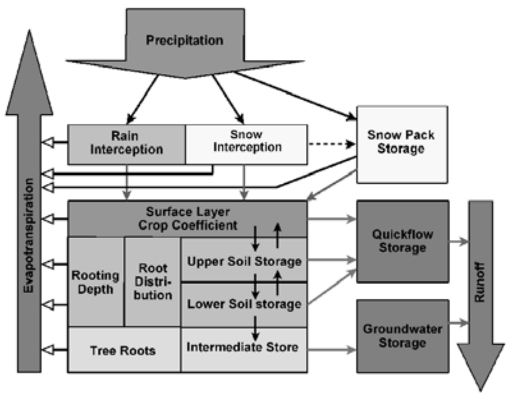

Figure 3 – Major elements of the ACRU agro-hydrological modelling system (Schulze, 1995).

In a typical simulation, only one variable has to be fitted to streamflow observations, which is the depth of the soil column where quickflow is generated. Spatial variation of rainfall, soils and land cover is facilitated by operating the model in distributed mode, in which case the catchment is subdivided either into subcatchments or hydrological response units, each of which represents a relatively homogenous area of hydrological response.

The ACRU model has been used extensively in South Africa for water resource assessments (Everson, 2001; Kienzle *et al.*, 1997; Schulze *et al.*, 2004), flood estimation (Smithers *et al.*, 1997; 2001), land-use impacts (Kienzle and Schulze, 1991; Tarboton and Schulze, 1993), nutrient loading (Mtetwa *et al.*, 2003), climate-change impacts (New, 2002; Schulze *et al.*, 2004) and irrigation supply (Dent, 1988) and often requires extensive GIS pre-processing (Kienzle, 1993, 1996; Schulze *et al.*, 1990). Model manuals are available through the internet at the ACRU web page (ACRU, 2007; Schulze, 1989, 1995; Smithers and Schulze, 1995).

Setup of the ACRU model for the Manuherikia catchment

Hydrological response units

Hydrological response units were delineated, based on elevation, catchment boundaries, land cover and climate, and, where necessary, they had to correspond to locations of streamflow gauging stations. A total of 198 hydrological response units were derived, which represent land areas similar in mean annual precipitation, mean elevation, soil texture and land cover (Fig. 4). For the simulation of streamflows and modifications by reservoirs, abstractions, return flows and irrigation practices, the model input for each response unit included:

- Location information such as its area, links to up- and downstream subcatchments and mean elevations,

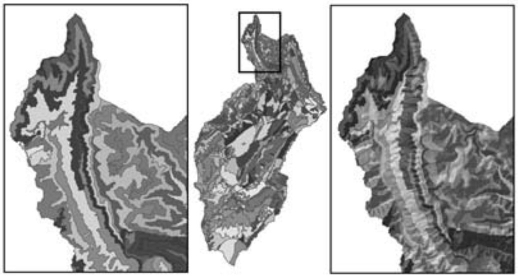

Figure 4 – Hydrological response units derived for the Manuherikia catchment based on elevation, rainfall, soils, and land cover (see Fig. 2). The units (left map) follow elevation bands (right map) for the mountainous headwaters.

- climate data on rainfall and potential evapotranspiration (see below),
- soils information, i.e., area-weighted texture values for critical soil water retention constants, plus thicknesses of top- and subsoils, as well as values of saturated drainage rates,
- land-use information consisting of monthly above- and below-ground hydrological attributes of land cover/use (e.g., interception loss per rain day, leaf area index, water use coefficient, root mass distribution),
- streamflow control variables such as baseflow recession constants, monthly abstractions, fractions of impervious areas and effective soil depths from which stormflows are generated,
- dams, which include both major water supply reservoirs as well as farm dams located in the catchment (Fig. 5), giving for each estimates of the full supply capacity, surface area at full supply capacity, dam area to volume relationships, and, if available, monthly abstractions and return flows, legal and environmental flow releases, seepage rates and inter-catchment transfers, and
- irrigated areas, with associated monthly crop water demands, monthly interception values and monthly rooting depths, as

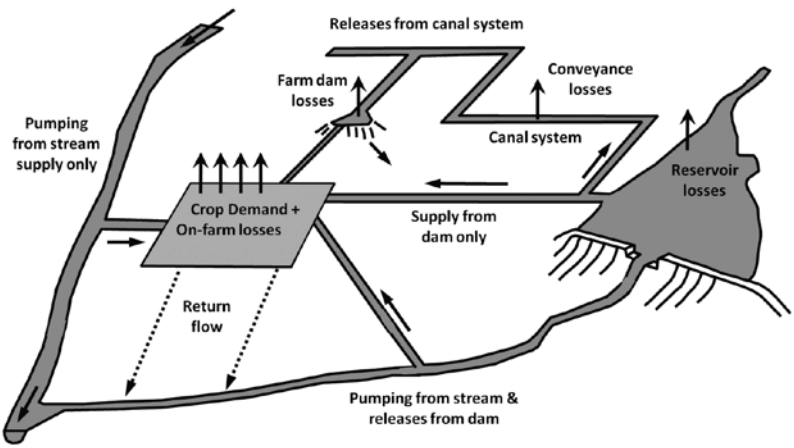

Figure 5 – Flow chart of options to simulate irrigation water supply in the ACRU agro-hydrological modelling system (from Schulze, 1995, modified)

well as soil properties of the irrigated areas, source of irrigation water, mode of irrigation scheduling and cycle times, and conveyance, farm dam and application losses (Fig. 5).

Evapotranspiration

Daily evapotranspiration values were calculated using both Penman (Penman, 1948) and Priestley-Taylor (Priestley and Taylor, 1972) equations as class A-pan type evaporation pan equivalents. Class A-pan equivalents are corrected by a factor 0.7 to derive both lake evaporation and crop reference evaporation (van Zyl *et al.*, 1989). While Penman results are preferable because they include the effects of humidity and wind, results were questionable due to a high uncertainty in the wind data, resulting in unrealistic spatial distributions of daily class A-pan equivalent evaporation. The Priestley-Taylor results show a more realistic spatial distribution of daily class A-pan equivalent evaporation. However, potential evapotranspiration was much lower, as Priestley-Taylor's method estimates the potential evapotranspiration of wet grass rather than an evaporation pan. An important component of the Priestley-Taylor method is the empirical coefficient alpha, which relates actual evaporation to equilibrium evaporation. In order to adjust the Priestley-Taylor method to calculate class A-pan evaporation, the parameter alpha was calibrated using observed class A-pan data available in the Manuherikia catchment, and an additive correction factor beta was introduced to give results coinciding with class A-pan measurements. The resulting alpha value of 2.53 is significantly higher than the default value of 1.26, but is consistent with recommendations that alpha increases with aridity, and with the observation by Woodward *et al.* (2001) that the relative contribution of the ventilation effect in New Zealand is large enough to require alpha values considerably larger than the default value. Woodward *et al.* (2001) applied alpha values ranging from 0.63 to 6.3. Correlation analysis of 24 measured monthly class A-pan data versus Priestley-Taylor values revealed an r^2 value of 0.986, with a slope of 0.982. We could, therefore, consider that daily potential evaporation values, expressed as class A-pan equivalents, were realistic. Mean annual potential evapotranspiration values, expressed as lake evaporation, are presented in Figure 2c.

Soils

Soils information was derived from the New Zealand Land Resource Inventory (LRI) Fundamental Soils Layer (FSL) extension (Wilde *et al.*, 2000). Soil polygons were overlaid with the derived hydrological response units, and soil parameters were area-weighted in a GIS. In the ACRU model, the soil depth is considered to be equal to the average rooting depth of the plants in order to account for soil moisture losses through transpiration. Soil porosity, field capacity and wilting point were estimated based on the soil texture and reduced proportionally by the amount of gravel reported in the soil database. The proportion of rock outcrops is translated in the ACRU model into an impervious proportion, where water, after initial abstractions, runs off into the neighbouring soil and is added to the precipitation.

Land Cover

As the purpose of this study is to analyse the impact of irrigated agriculture on natural water resources, the comparison baseline is tussock grass, often referred to simply as 'The Tussock'. In hydrological modelling, the significance of different land covers is expressed in terms of the interception, rooting depth and distribution, and crop coefficients. As many of these change significantly during the course of the seasons, monthly estimates are required. In the ACRU model, all monthly values are transformed into daily values by harmonic transformation (Fourier analysis).

Actual evapotranspiration is calculated daily following the crop factor approach (Doorenbos and Pruitt, 1977). The crop coefficients listed in Table 1 represent the maximum evapotranspiration of the vegetated surface relative to the reference evapotranspiration, which in the ACRU model is the class A-pan equivalent evapotranspiration. Tussock grass is dormant during the winter months, reflected by the very low crop coefficients. The native tussock grasses have apparently adapted to the arid conditions by closing their stomata as the atmospheric demand for water vapour increases, thus lowering actual evapotranspiration (Davie *et al.*, 2006). This behaviour of stress reduction by the plant is simulated in the ACRU model by setting a soil matric potential value when actual evaporation is reduced by stomatal closure.

Table 1 – Hydrological variables used for land under natural cover and cultivated pastures

Natural Conditions (based on Acocks, 1988; Fahey and Watson, 1991)												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crop Coefficient	.43	.43	.43	.33	.17	.13	.13	.13	.20	.30	.33	.40
Interception loss (mm)	0.9	0.9	0.9	0.9	0.8	0.7	0.7	0.7	0.7	0.8	0.9	0.9
Proportion of roots in A-Horizon (%)	90	90	90	95	95	100	100	100	95	90	90	90
Cultivated Pastures (after Green, 1985)												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crop Coefficient	.80	.80	.80	.70	.60	.50	.50	.50	.60	.70	.80	.80
Interception loss (mm)	1.4	1.4	1.4	1.4	1.2	1	1	1.2	1.3	1.4	1.4	1.4
Proportion of roots in A-Horizon (%)	80	80	80	90	100	100	100	100	90	90	80	80

The critical leaf water potential value was set to –800 kPa.

Daily interception values can have a large effect on evaporation losses, as any intercepted water reduces the effective precipitation input. The major source of interception loss information for use with the ACRU model is derived from De Villiers (1975, 1978, 1980 and 1982), which were organized by Schulze (1981) for direct use in the ACRU model. As the tussock grasses on the South Island of New Zealand are assumed to be hydrologically similar to the South African highveld, the contributions by Acocks (1988) on natural veld types in South Africa were used to estimate the hydrological parameters for tussock (Table 1). The interception values listed in Table 1 sum up to an annual interception of 298 mm, which compares well with figures reported by Fahey and Watson (1991), who reported transpiration of snow tussock (*Chionochloa rigida*) under grazing conditions to be 20% in the high rainfall (1355 mm) Lammerlaw Range in the upper Waipori catchment. This is also in agreement with findings by Campbell and Murray (1990), who reported wet canopy evaporation from tussock in a weighing lysimeter at Glendhu of approximately 300 mm per year.

Due to the lack of detailed information on irrigated pastures, it was assumed that all irrigated land is cultivated pasture with a mix of ryegrass and clover. Associated hydrological parameters are based on the work by De Villiers and Schulze (Table 1).

Verification of Simulated Hydrological Outputs

Model verification is important to establish if the behaviour of the simulation model is consistent with the behaviour of the hydrological system. In an ideal setting verifications are carried out on research catchments, with a dense hydrological network and with long-term data of high quality and where land-use influences are fully accounted for. As this study is carried out in an operational (in contrast to research) catchment, the expected performance level is relaxed because the rainfall network is sparse and the streamflow is influenced by upstream dams and river abstractions, many of which are not known in detailed quantity and timing. For this reason, and as the aim of this investigation is to provide water yield information to water resources managers and local catchment management agencies under different land-use conditions, the verifications undertaken here were focused on the total generated streamflow and its seasonal behaviour as well as the standard deviation and correlation statistics.

Simulated streamflows were calibrated and verified for various periods between 1975 and 2005 at gauged outflows of four subcatchments (locations and periods shown in Figure 1 and Table 2). These four sites represent upstream headwaters of the Manuherikia catchment in a range of different environments (high altitude/rainfall to low altitude/rainfall), which are uninfluenced by water abstraction and irrigation. Uncertainty in some of the input data, such as daily rainfall and soil depth, required the calibration of these variables within their expected physical limits. Table 2 lists the various objective functions used to evaluate the success of the simulations, while Figures 6 and 7 show the cumulative and seasonal streamflows for observed and simulated scenarios. Accumulated streamflows compare very well for three sites, while site 75255 (#2 in Figure 1) exhibits the largest deviations. The fact that the accumulated streamflows do not deviate by a large margin is evidence that both wet and dry years are simulated realistically. Results of monthly totals of modelled versus observed streamflows show that simulations for all four gauged subcatchments produced an accumulated streamflow yield within

Table 2 – Results of verification analysis for four simulated subcatchments

Number in Figure 1	**1**	**2**	**3**	**4**
Station Number	75251	75255	75257	75256
Station Name	Manuherikia at D/S Forks	Dovedale Creek at Willows	Dunstan Creek at Gorge	Woolshed Creek at Lauder Station
Catchment size [km^2]	172.9	39.3	157.8	10.9
Verification period	1978-1993 1999-2004	1978-1993	197 -1994	1973-1979
Sample size (# of months)	244	156	202	97
Mean observed flows (mm)	45.66	10.14	38.73	29.31
Mean simulated flows (mm)	44.98	9.87	39.29	27.69
Difference between the means [%]	**1.48**	**2.70**	**–1.45**	**5.51**
t statistic for comparing means	0.281	0.216	–0.233	0.532
Standard deviation observed	26.19	12.49	24.20	21.38
Standard deviation simulated	26.91	9.8	24.23	20.90
Difference between standard deviations [%]	**–2.74**	**21.51**	**–0.10**	**2.23**
Coefficient of determination	0.667	0.519	0.618	0.509
Coefficient of efficiency	0.642	0.211	0.573	0.858

an accuracy of 5.5%, and for three subcatchments within 3%. The variance of monthly streamflows is well represented for three subcatchments, with a difference in standard deviations of less than 3%. Only one subcatchment (associated with gauging station 75255, #2 in Figure 1) was simulated with a difference in standard deviations of 21.5%. The relatively poor simulations at subcatchment 75255 are attributed to uncertainties in precipitation, climate, and soil variables, where inconsistencies between the soils database and field observations were found.

Coefficients of determination are all above 0.5, and the coefficient of efficiency (Nash-Sutcliffe efficiency) is high for two subcatchments (#1 in Figure 1: 75251 and #4 75256) and low for one subcatchment (#2 in Figure 1: 75255). The range for the coefficient of efficiency lies between 1.0 (perfect fit) and $-\infty$. The largest disadvantage of both the coefficient of determination and the coefficient of efficiency is the fact that

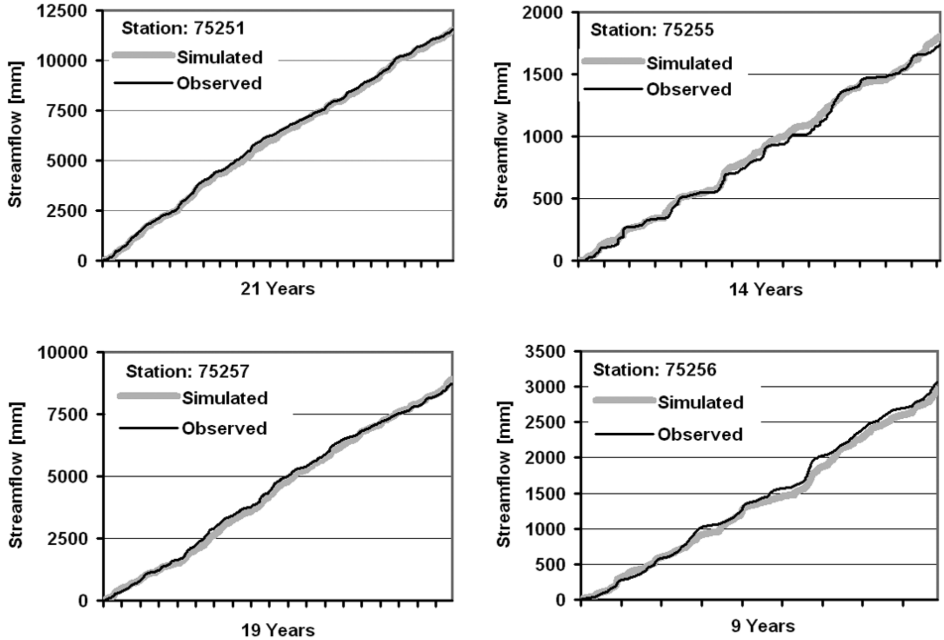

Figure 6 – Simulated and observed accumulated streamflow for four subcatchments

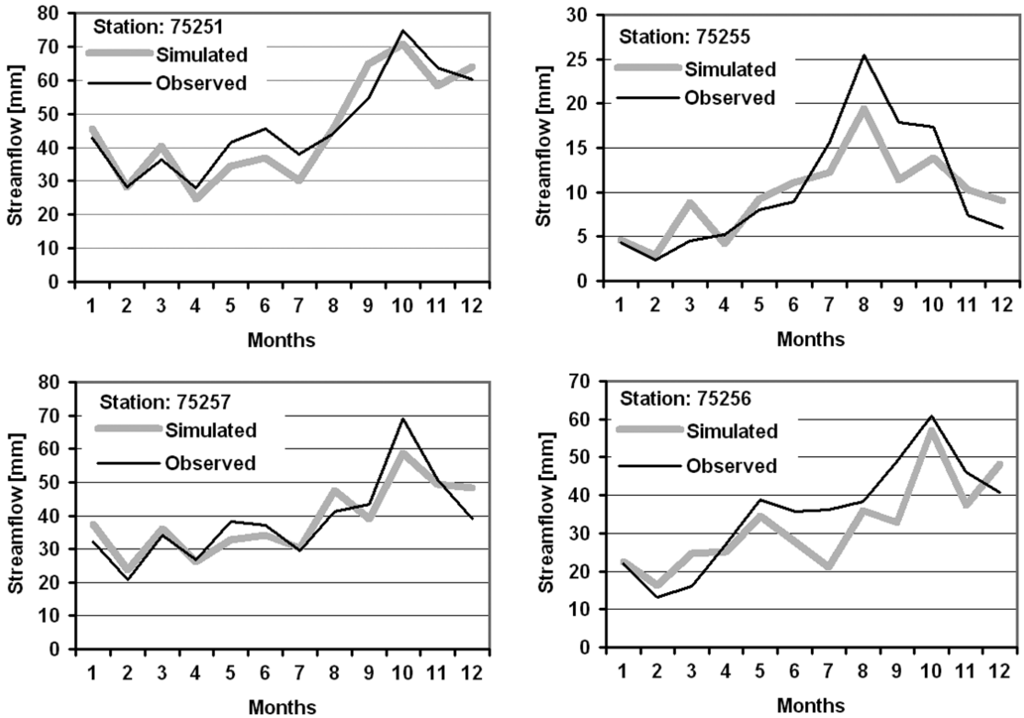

Figure 7 – Simulated and observed mean monthly streamflow for four subcatchments

the differences between the observed and simulated values are squared, so differences in higher streamflow values have a much larger effect on the coefficients than differences during low streamflows (Legates and McCabe, 1999). Based on the uncertainty of many input parameters and variables, in particular climate data, which was interpolated from sparsely distributed climate stations, the simulations can, overall, be regarded as representing the natural system reasonably well.

Model scenario setup

Gathering accurate quantitative data for irrigation practices in New Zealand is very demanding, because metering of abstracted and applied water is not mandatory. We based our information about irrigation in the Manuherikia on different sources. First, proxy information about irrigated area and applied water quantities were obtained for consented irrigation takes (Otago Regional Council, pers. comm.). As a next step, communications with local farmers and a local irrigation manager added valuable information (John Anderson, aqua irrigation limited, pers. comm.). We used these quantitative and qualitative information sources to estimate current management practices of irrigation scheduling and application in the catchment, which are distributed over five major irrigation schemes: Blackstone, Omakau, Manuherikia/Galloway, Ida Valley and Poolburn. All farms with irrigation rights (Otago Regional Council, pers. comm.) were assumed to irrigate fully using the consented water amount. Irrigated farms for which no irrigated areas were available were assumed to irrigate 40 ha (median value of all surveyed farms). In the Manuherikia scheme, 1200 mm is provided each year, and applications every two weeks of 71 mm are assumed for the irrigation period from November to April. In the Omakau and Ida Valley schemes, the assumed 800 mm provided annually is distributed every three weeks, with 73 mm per application. Flood irrigation is border dyke and contour, and sprinkler irrigation is predominantly K-Line, but other static or movable sprinkler systems are also in use. Almost all irrigation canals (races) are unlined earth canals with associated high water losses. All irrigated pastures are presumed to be ryegrass with clover.

This estimation about current irrigation practices in the Manuherikia catchment was then used to set up model scenarios for assessing the impacts of irrigated agriculture on catchment water yield. The five scenarios include two non-irrigated scenarios (natural vegetation and dryland agriculture) and three irrigation scenarios with water transport and irrigation techniques of varying efficiency (Table 3). The hydrological simulation for 'natural conditions' of the Manuherikia catchment (*Natural Scenario*) assumed the catchment to be completely under tussock and with no reservoirs or water abstractions, and serves as the baseline against which the impacts of irrigated and non-irrigated agriculture are assessed. The *Current Scenario* likely represents the present situation most realistically (Table 3). The following assumptions are made: 50% of the irrigated area is under flood and 50% under spray irrigation, conveyance losses are 35%, farm dam losses due to evaporation are 10%, and spray irrigation losses are 15%. The *Improved Scenario* represents improved conditions in such a way that the proportion of spray irrigation would increase to 75%, spray application would be increased in its efficiency and reduce the spray losses to 10%, and earthen canals would be partly lined by concrete or polyethylene or replaced by pipelines to reduce conveyance losses to 20%. The *Optimal Scenario* represents the best possible scenario, where all flood irrigation is replaced by spray irrigation, spray efficiency is optimized to minimize farm application losses to 5%, and most conveyance canals

Table 3 – Five model scenarios and their variables

Scenario	Natural Conditions	Irrigated Agriculture Current	Irrigated Agriculture Improved	Irrigated Agriculture Optimum	Dryland Agriculture
Irrigated area [ha]	0	34,640	34,640	34,640	0
Reservoir Volume Dams [million m^3]	0	91	91	91	0
Natural Vegetation	Tussock Grass	Tussock Grass	Tussock Grass	Tussock Grass	Tussock Grass
Irrigated Vegetation	n/a	Ryegrass & clover	Ryegrass & clover	Ryegrass & clover	Ryegrass & clover
Spray Irrigation %	n/a	50%	75%	100%	n/a
Spray losses %	n/a	15%	10%	5%	n/a
Flood Irrigation %	n/a	50%	25%	0%	n/a
Flood losses %	n/a	35%	35%	35%	n/a
Conveyance losses %	n/a	30%	20%	10%	n/a
Farm dam losses %	n/a	10%	10%	10%	n/a

are lined, reducing the assumed conveyance losses to 10%. The *Dryland Scenario* represents the most conservative land use for the Manuherikia catchment: all irrigated pastures are converted to dryland pastures, and the reservoirs and irrigation races are taken out. This scenario, therefore, represents a land management approach with minimal water use, and water losses due to irrigation relative to that scenario can be compared to the economic gain of dryland irrigation (Ministry of Agriculture and Forestry, 2004). These scenarios are preliminary and we plan refinement in the future in consultation with stakeholders. However, as the goal of this study is to provide first estimates of relative irrigation impacts on regional hydrology, we consider these scenarios sufficient for this purpose.

Results

Results listed in Table 4 are for the entire catchment, which has 11.4% of the 3035 km^2 area under irrigation. The *Current Scenario* shows a decrease in mean annual water yield of 324 million m^3, a 37.1% decrease, while the *Optimum Scenario* exhibits a decrease in mean annual water yield of 259.3 million m^3 relative to the *Natural Scenario*, a 29% decrease. The differences between the *Current Scenario* and the *Optimum* and *Improved Scenarios* indicate the amount of water lost due to an inefficient irrigation system, which could be improved. The mean annual amount of water that could be returned to streamflow at the outlet of the Manuherikia catchment, instead of being lost due to evaporation, is 64.7 million m^3. These results indicate that 80% of the water demands for irrigation are due to the increased crop water demands, a deeper rooting depth of irrigated exotic plants, and hence the normal and inevitable losses associated with irrigated agriculture (Fig. 8). The remaining 20% are due to an irrigation water distribution system which is currently based on earthen irrigation races and mainly simple and low investment irrigation methods, i.e., flood irrigation and K-Line sprinkler. Figure 8 shows the seasonal impacts of three scenarios (*Natural*, *Current*, and *Optimum*) on streamflow. There are almost no impacts during the period June

Table 4 – Scenario model results for five scenarios (see Table 3)

Scenario	Natural Conditions	Irrigated Agriculture: Current	Irrigated Agriculture: Improved	Irrigated Agriculture: Optimum	Dryland Agriculture
Mean Annual Water Yield [million m^3]	873.9	549.9	586.60	614.6	838.6
Change of mean annual water yield [%]	–	– 37.1	– 32.9	– 29.7	– 4.0
Mean annual streamflow [m^3 s^{-1}]	27.6	17.4	18.5	19.4	26.5
Runoff Coefficient [%]	45.3	28.5	30.4	31.9	43.5
Mean annual actual evapotranspiration [mm]	347.6	454.3	442.2	433.0	359.2
Change in actual evapotranspiration [%]	–	+ 30.1	+ 27.2	+ 24.6	+ 3.3
Mean 7Q [m^3 s^{-1}]	8.48	1.25	1.54	1.74	7.90

to September, and impacts are highest in the irrigation season from October to April.

The largest relative impacts of irrigated agriculture on streamflow occur during the low flow period, typically in the summer. The low flow simulations have, in terms of absolute values, a high level of uncertainty, because the emphasis of the verification study was to mimic the overall water volumes rather than the low flows. A comparison of the simulated and observed 7Q low flows – the annual minimum flow over seven consecutive days, showed that the mean 7Q value was under-simulated by 27% (and the median 7Q was under-simulated by 32%). Because the same variables controlling the baseflow are the same for all five scenarios, the errors in the low flow simulations are consistent. However, due to the under-simulation, impacts resulting in lower 7Q values could be exaggerated. Initial results indicate that 7Q values are significantly lower under all irrigated scenarios relative to the natural streamflow regime (about 15% of 'natural' low flows, Table 4).

The results for the *Dryland Scenario* show a small reduction of 4% in mean annual streamflow (from 27.6 m^3s^{-1} to 26.5 m^3s^{-1},

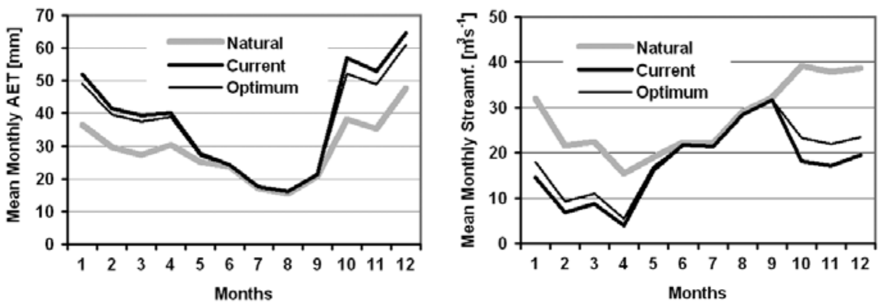

Figure 8 – Seasonal impacts of various scenarios on actual evapotranspiration and streamflow for the entire Manuherikia catchment

Table 4), which is attributed to the higher crop coefficient of pastures compared with tussock, with associated slightly higher actual evapotranspiration and subsequently drier soils. The impact of dryland agriculture on low flow conditions would also be small (about a 4% reduction, Table 4).

Conclusions

Because irrigated agriculture traditionally results in high water demands (Poff *et al.*, 2003), its impacts on streamflows in the Manuherikia catchment were investigated. The interesting outcome of practical value for water resources managers is that the impacts of irrigated agriculture remain large, even if major capital investments were to be made by irrigation farmers, irrigation boards and regional councils to improve the water delivery system and the irrigation efficiencies. The simulated reduction of water yield, relative to a natural tussock condition and assuming no water abstractions, is between a minimum of 30% for optimal conditions and 37% under present conditions.

The results presented here serve as a first estimation, as many variables used in the setup of scenarios and simulations are uncertain – in particular irrigation quantities. The objective of future work will be to refine those scenarios in more detail, once appropriate field data become available. Nevertheless, the results show the significant impact of irrigation on the water resource and on the catchment water cycle and give an indication of the magnitude of that impact. Moreover, the simulations point out the limitations of increased irrigation efficiency in reducing the impact of irrigation impact.

Future climate change (IPCC, 2007) may further aggravate conditions in the arid valleys of the Manuherikia catchment due to further drying of the headwaters of the catchment, which would result in additional reductions in water yield, especially during low flow and drought conditions. Impacts on both downstream users and the aquatic ecosystem during low flows have to be further evaluated. Instream flow needs, once established, are an important measure to potentially provide limits for expansion or intensification of irrigated agriculture. Should economic opportunities arise to initiate a shift to crops with higher water requirements than pasture, impacts on water resources could be further increased. The data presented in this paper are intended to contribute to a more extensive cost-benefit analysis of irrigation effects in managed catchments, which should include the environmental costs and the economic benefits (Ministry of Agriculture and Forestry, 2004; Parliamentary Commissioner for the Environment, 2004; Poff *et al.*, 2003).

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References:

ACRU 2007: The ACRU Model: Home Page. http://www.beeh.unp.ac.za/acru/. Last accessed 11/28/2007.

Acocks, J.P.H. 1988: Veld types of South Africa. Botanical Research Institute, Pretoria, *Botanical Survey of South Africa, Memoirs 57.*

Ahlers, W.W.; Hunter, K.A. 1989: A baseline survey of water quality and trace metals in the upper Manuherikia and Idaburn rivers, Central Otago. Report RD8820, Ministry of Energy, Wellington, New Zealand.

Beecroft, F.G.; Smith, S.M.; Griffiths, E. 1986: Suitability of land for irrigation in the Manuherikia valley, Central Otago, New Zealand. *New Zealand Soil Survey Report 90*, New Zealand Soil Bureau, Department of Scientific and Industrial Research, Lower Hutt, New Zealand.

Campbell, D.I.; Murray, D.L. 1990: Water balance of snow tussock grassland in New Zealand. *Journal of Hydrology 118*: 225-245.

Davie, T.J.A.; Fahey, B.D.; Stewart, M.K. 2006: Tussock grasslands and high water yield: a review of the evidence. *Journal of Hydrology (NZ) 45 (2)*: 83-94.

Dent, M.C. 1988: Estimating crop water requirements for irrigation planning in southern Africa. *Agricultural Engineering in South Africa 20*: 7-19.

De Villiers, G. Du T. 1975: Reënvalonderskeppingsverliese in die Republiek van Suid Afrika - 'n Streekstudie. Unpublished PhD thesis. University of the Orange Free State, Bloemfontein, Department of Geography.

De Villiers, G. Du T. 1978: Grondreënval en onderskeppingsverliese by landbougewasse. *Crop Production 7*: 153-157.

De Villiers, G. Du T. 1980: Rainfall interception by grass. *Journal of the University of Durban-Westville 3*: 237-239.

De Villiers, G. Du T. 1982: Predictive models for estimating net rainfall and interception losses in savanna vegetation. *Water SA 8*: 208-212.

Doak, M. 2005: Value of irrigation in New Zealand. *In* OECD Workshop on agriculture and water: sustainability, markets and policies, 14-18 November, 2005. Adelaide, Australia.

Doorenbos, J.; Pruitt, W.O. 1977: Guidelines for predicting crop water requirements. *FAO Irrigation and Drainage Paper 24*, Rome.

Everson, C.S. 2001: The water balance of a first order catchment in the montane grasslands of South Africa. *Journal of Hydrology 241*: 110-123.

Fahey, B.D.; Watson, A.J. 1991: Hydrological impacts of converting tussock grassland to pine plantation, Otago, New Zealand. *Journal of Hydrology (New Zealand) 30*: 1-15.

Green, G.C. 1985: Estimated irrigation requirements of crops in South Africa. Department of Agriculture and Water Supply, Soil and Irrigation Research Institute, Pretoria, Memoirs on the Agricultural Natural Resources of South Africa, 2. p. 857.

IPCC, 2007: Climate Change 2007: *The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Solomon, S.; D. Qin; M. Manning; Z. Chen; M. Marquis; K.B. Averyt; M. Tignor and H.L. Miller (*eds.*). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kienzle, S.W. 1993: Application of a GIS for simulating hydrological responses in developing regions. *In*: HydroGIS 93: Application of Geographical Information Systems in Hydrology and Water Resources Management (Proc. of the Vienna Conference, Austria, April 1993). *IAHS Publications no. 211*: 309-318.

Kienzle, S.W. 1996: Using DTMs and GIS to define input variables for hydrological and geomorphological analysis. *In*: HydroGIS 96: Application of Geographical Information Systems in Hydrology and Water Resources Management (Proc. of the Vienna Conference, Austria, April 1996). *IAHS Publications no. 235*: 183-190.

Kienzle, S.W.; Lorentz, S.A.; Schulze, R.E. 1997: Hydrology and Water Quality of the Mgeni catchment. Water Research Commission, Pretoria, Report TT87/97.

Kienzle, S.W.; Schulze, R.E. 1991: The simulation of the effect of afforestation on shallow ground water in deep sandy soils. *Water SA 18(4)*: 265-272.

Larned, S.; Hicks, D.M.; Schmidt, J.; Davey, A.; Dey, K.; Scarsbrook, M.; Arscott, D.; Woods, R. 2007: The Selwyn River of New Zealand: a benchmark system for alluvial plain rivers. *River Research and Applications*, in press.

Legates, D.R.; McCabe Jr.; G.J. 1999: Evaluating the use of 'goodness-of-fit' measures in hydrologic and hydroclimatic model validation. *Water Resources Research 35(1)*: 233-241.

Ministry of Agriculture and Forestry 2004: Water Programme of Action. Waters of National Importance. MAF Policy Publication. August 2004.

Mtetwa, S.; Kusangaya, S.; Schutte, C.F. 2003: The application of geographic information systems (GIS) in the analysis of nutrient loadings from an agro-rural catchment. *Water SA 29(2)*: 189-193.

New, M. 2002: Climate change and water resources in the southwestern Cape, South Africa. *South African Journal of Science 98*: 1-8.

Otago Regional Council 2006: The Effect of Irrigation Runoff on Water Quality. Otago Regional Council Report. May 2006.

Parliamentary Commissioner for the Environment 2004: Growing for good. Intensive farming, sustainability, and New Zealand's environment. Wellington: Parliamentary Commissioner for the Environment.

Penman, H.L. 1948: Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society, London, A, 193: 120-146.

Poff, N.L.; Allan, J.D.; Palmer, M.A.; Hart, D.D.; Richter, B.D.; Arthington, A.H.; Rogers, K.H.; Meyer, J.L.; Stanford, J.A. 2003: River flows and water wars: emerging science for environmental decision making. *Frontiers in Ecology and the Environment 1(6)*: 298-306.

Priestley, C.H.B.; Taylor, R.J. 1972: On the assessment of the surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review 100*: 81-92.

Schulze, R.E. 1981: The land use component in hydrological modelling: An evaluation. *In:* Maaren, H. (Ed) Workshop on the Effect of Rural Land Use and Catchment Management on Water Resources. Department of Environment Affairs, Pretoria, South Africa, Technical Report TR 113, 34-61.

Schulze, R.E. 1989: ACRU: Background Concepts and Theory. ACRU Report No. 36, Dept. of Agricultural Engineering, Univ. of Natal, Pietermaritzburg, RSA.

Schulze, R.E. 1995: Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System. WRC Report TT 69/95, Water Research Commission, Pretoria.

Schulze, R.E.; Lorentz, S.; Kienzle, S.W.; Perks, L. 2004: Modelling the impacts of land-use and climate change on hydrological responses in the mixed underdeveloped / developed Mgeni catchment, South Africa. *In*: Kabat, P. *et al.* (*eds.*): *Vegetation, Water, Humans and the Climate A New Perspective on an Interactive System.* BAHC-IGBP Publication, Springer.

Schulze, R.E.; Schäfer, N.W.; Lynch, S.D. 1990: An assessment of regional runoff production in Qwa Qwa: a GIS application of the ACRU modelling system. *South African Journal of Photogrammetry, Remote Sensing, and Cartography 15*: 141-148.

Smithers, J.; Schulze, R.E. 1995: ACRU Agrohydrological Modelling System User Manual. WRC Report TT 70/95, Water Research Commission, Pretoria.

Smithers, J.; Schulze, R.E.; Kienzle, S.W. 1997: Design flood estimation using a modelling approach: A case study using the ACRU model. *In*: Rosbjerg, D.; Boutayeb, N.; Gustard, A.; Kundzewicz, Z.W.; Rasmussen, P.F. (*eds.*) Sustainability of Water Resources under Increasing Uncertainty. *IAHS Publication 240*: 277-286

Smithers, J.C.; Schulze, R.E.; Pike, A.; Jewitt, G.P.W. 2001: A hydrological perspective in the February 2000 floods: a case study in the Sabie river catchment. *Water SA 27 (3)*: 325-332.

Tarboton, K.C.; Schulze, R.E. 1993: Hydrological consequences of development scenarios for the Mgeni catchment. Proceedings of the Sixth South African National Hydrological Symposium, University of Natal, Pietermaritzburg, Department of Agricultural Engineering, p. 297-304.

van Zyl, W.H.;De Jager, J.M.; Maree, C.J. 1989: Correction factors for evaporimeter coefficients used for scheduling irrigation of wheat. Water Research Commission, Pretoria. Report 151/1/89.

Wilde, R.H; Willoughby, E.J.; Hewitt, A.E. 2000. Data Manual for the National Soils Database Spatial Extension. Internal Report. Landcare Research New Zealand Ltd.

Woodward, S.J.R.; Barker D.J.; Zyskowski, R.F. 2001: A practical model for predicting soil water deficit in New Zealand pastures. *New Zealand Journal of Agricultural Research 44*: 91-109.

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