

Water use account spreadsheets with examples of some major river basins

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Abstract

The Challenge Program on Water and Food undertakes research to maximise water productivity in several of the world's major river basins. The research must be underpinned by information on how much water there is in a basin, where it goes and how it is used. There should, furthermore, be an understanding of future constraints (such as the impact of climate change), opportunities (such as increased diversions for irrigation) and trade-offs (such as changed land use improving dryland productivity but leaving less water for downstream use). We describe water use account spreadsheets to provide monthly estimates of major water movement, uses and losses within a river basin. The water use accounts are based on top-down modelling, at a basin overview level of detail. They help develop understanding of the water uses in a river basin, and the limits to understanding that might result from sparse data.

Starting with rainfall, the accounts track the partitioning of water into runoff, and evapotranspiration by dryland vegetation. The runoff is tracked as it becomes flow down the rivers, with losses (such as evaporation and seepage) and gains (such as tributary inflows), storages in lakes and reservoirs, diversion for irrigation or other purposes, floods in lowland floodplains and finally, in some rivers, discharges to the sea. The accounts estimate the water use by the major irrigation industries and other uses.

We show the development of the water use account spreadsheets for the Karkheh, Mekong, Murray-Darling and Limpopo river basins. These basins vary in size and climate. The Limpopo example is developed using data drawn entirely from the Internet, with limited and discontinuous flow gauge records for only a few locations.

Preliminary use of these accounts shows that they provide a systematic method of describing flow behaviour and water uses in a river basin. They have great value in helping rapidly identify data gaps and limitations, and can be used to investigate the consequences of large changes (such as climate or land use change). We emphasise however that they are not detailed catchment hydrology models and are not suited to river planning and management, nor to investigating small-scale, detailed effects. Although we concentrate here mainly on the water accounts themselves, we show briefly that they can be used to examine water productivity maximisation with economic modelling or decision making modelling.

Introduction

The international Challenge Program on Water and Food aims to explore threats, opportunities and trade-offs in water access and impact on agricultural productivity and hence poverty / livelihoods and the environment for several major river basins around the world. In Australia, the CSIRO's Water for a Healthy Country program aims to develop practical options for using water more efficiently, equitably and sustainably in the River Murray region.

Both programs must be founded on sound information about how much water there is, when and where it is available, and how it is used. Both require the means to explore trade-offs amongst uses, opportunities such as increased irrigation, and threats to the water resource such as land use change and climate change. Furthermore, the Challenge Program requires the means to assess the interactions between water and food, poverty and the environment; Water for a Healthy Country requires the means to assess the interactions between water and agricultural production, income and the environment. Water use accounting provides these means.

Water use accounting is used at national (ABS, 2004; Lenzen, 2004) and basin (Molden, 1997; Molden et al., 2001) scales to allow assessment of the consequences of economic growth, the contribution of economic sectors to environmental problems, the implications of environmental policy measures (such as regulation, charges and incentives), to identify the status of water resources and the consequences of management actions, and identifying the scope for savings and improvements in productivity. However, those accounts are static, providing a snapshot for a single year or an average year. Furthermore, they do not link water movement to use.

In this paper, we describe water use accounts and their application to three of the Challenge Program basins (the Mekong, the Karkheh and the Limpopo) and to the Murray-Darling Basin. In contrast to the static national and basin water use accounts referred to above, our accounts are dynamic, with a monthly timestep, and thus account for seasonal and annual variability. They can also examine dynamic effects such as climate change, land use change, changes to dam operation, etc. The accounts are in Excel, and are quick and easy to develop, modify and run. They can be developed using limited data from the Internet, as we will show with the Limpopo example.

We emphasise that these are high level, whole basin accounts: necessarily, they average or gloss over much detail. They are not hydrology models for river planning management, nor are they detailed accounts such as might be used, for example, to determine small zones of high seepage loss from a river channel (eg Gippel, 2006).

Method

The water use account is a top-down model (Sivapalan et al., 2003), based on simple lumped partitioning of rainfall into evapotranspiration and runoff for catchments in a basin, a catchment being the drainage area between upstream and downstream flow estimation points. The method is described in detail in Kirby et al. (2006). Where possible, flow estimation points are identified with measurement gauges, and also chosen such that drainage areas represent a large unit such as a tributary. The evapotranspiration in a catchment is further partitioned into the proportion accounted for by each vegetation type or land use, including evapotranspiration from wetlands and evaporation from open water. Runoff flows into the rivers, with downstream flow calculated by a simple water balance, with outflows made equal to the sum of the inflows minus losses, diversions and changes in storage. Flow is stored in dams and other storages and, during high flows, in the channels and floodplains. Water is lost from rivers (especially downstream sections in rivers in arid or semi-arid zones) by evaporation and seepage, or by the consumption as evapotranspiration of a proportion of floods on the floodplain. Water is diverted from the rivers for use, mainly irrigation, and unused water flows to the sea.

The account is based on a monthly timestep, which we consider adequate for our purpose.

The account links known quantities in the water balance, such as rain and streamflow measured in gauges, with simple, physically plausible models. We do not use complex process models. The rainfall – runoff partition is based on the concept, due to Budyko (1974), of evapotranspiration limited by supply (rainfall) and capacity (potential evapotranspiration). We use a development of this concept in which a generalised surface storage term is introduced, and the partition is calculated monthly. The irrigation crop water demand is based on the FAO crop modelling principles using crop coefficients (Allen et al., 1998).

The physically plausible models are guided by the data. Releases from many of the storage dams in the Murray-Darling Basin correlate with water demand in the downstream irrigation districts, and in such cases we model the releases as a simple function of the aggregate crop water demand multiplied by the area of crops. In other cases, storage releases follow other patterns and we choose other, simple functions to model them. Hydro-power dams, for example, may have fairly constant releases (though some supply peak power demand). Similar considerations guide temporary storage in the channel and floodplain, which can store significant quantities of water during high flow periods, and some water may be lost to the floodplain to be consumed there as evapotranspiration. Again, we choose simple, physically plausible functions that model the observed behaviour. River losses are simply taken as a lumped amount (we do not separately account for different loss mechanisms, except losses during flooding), based on observed differences in flows between upstream and downstream flow gauges.

We calibrate the water use accounts using two main calibration steps.

1. The runoff into any reach must equal the sum of the outflow, losses, diversions and changes to storage minus the sum of the inflows. This is true for any period, from a single month to the full length of the record being considered. We set the sum of the runoff over the full period to be modelled to equal the sum over the full period of the outflows and changes to storage less the sum of the inflows. We did not calibrate monthly or seasonal behaviour.
2. We made the calculated annual average diversions equal to independently measured values where we had them. Again, we did not calibrate monthly or seasonal behaviour. We were able to do this in only the Mekong and the Murray-Darling.

The spreadsheet has two checks of the overall water balance for each catchment.

1. For each catchment, the sum of the monthly rain over the full period equals the sum of the monthly evapotranspiration plus the sum of the monthly runoff plus the difference in the surface storage between the beginning and end of the period.
2. For each catchment, the sum of the monthly stream inflows equals the sum of the monthly losses to discharge, evaporation from storages and diversions plus the difference in storages between the beginning and end of the period.

Example water use accounts

We applied the method outlined above to develop water use accounts for four river basins with contrasting characteristics. The Karkheh is a small, semi-arid basin with a pronounced wet season in the winter; river flow is seasonal. The Mekong is a large river basin mostly in the wet tropics, with a pronounced wet and dry season; the river flow is seasonal and complicated by a large, seasonal flow reversal into the Tonle Sap, a large lake in the lower part of the basin. The Murray-Darling is a large, semi-arid to arid basin with very variable rainfall; river flow is complex and variable. The Limpopo is a medium-sized semi-arid to arid basin with variable and seasonal rainfall; river flow is

seasonal. Data were limited for the Limpopo, and we include it as an example of developing a water use account using data gained entirely from the Internet.

Karkheh basin

The Karkheh Basin is in western Iran. It covers about 60,000 km², and is drained by the River Karkheh and its tributaries. Near the downstream end of the Karkheh is a major dam, built recently for irrigation supply. Downstream of the dam, the river discharges into a terminal swamp, where most of the remaining water is consumed as evapotranspiration. There appears to be some discharge from the terminal swamp into the Tigris-Euphrates during high flows.

We used rainfall and other climate data (to estimate potential evapotranspiration), streamflow records, and land use data gathered and translated from Iranian sources as part of a project within the Challenge Program on Water and Food.

The precipitation is around 400 mm per year in much of the catchment, falling mainly in the winter (November to March) as snow, with almost no rain in the late summer. Snowmelt is an important component of the flow, and defines its annual pattern. Snowmelt accounts for the lag in flows of some months, relative to the precipitation, and the smoother hydrograph.

Applying the runoff, flow, storage and water use expressions to 16 catchments within the Karkheh basin leads to results summarised in Figures 1 and 2. Figure 1 shows the flows prior to the commissioning of the Karkheh Dam, and that the flow characteristics are similar throughout the basin. The values of water use shown in Figure 2 are annual averages, though they are calculated monthly in the spreadsheet.

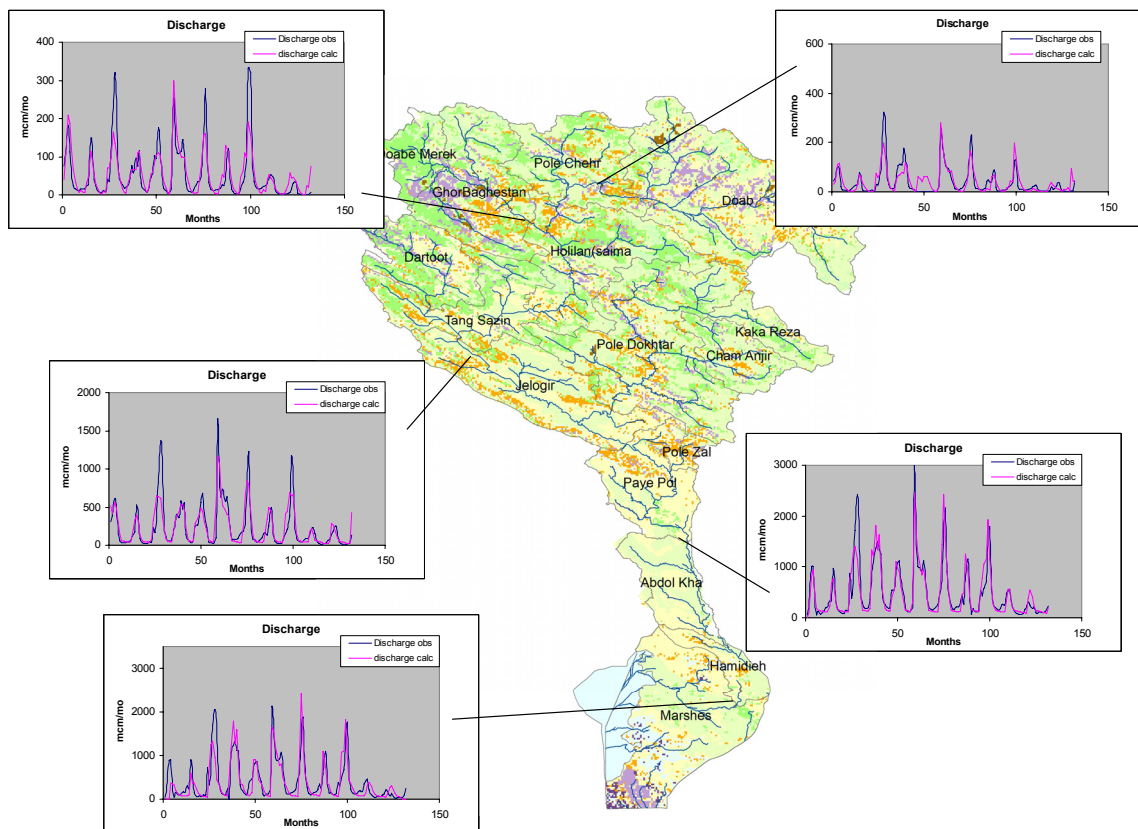


Figure 1: Measured and calculated monthly flows in the Karkheh Basin for 1990 - 2000, showing two upstream tributary catchments (Doab, top right; Ghor Baghestan, top left), mid-basin (Tang Sazin, mid left), the location of the new dam (Paye Pol, bottom right), and a downstream location just prior to discharge into the marshes (Hamidieh, bottom left).

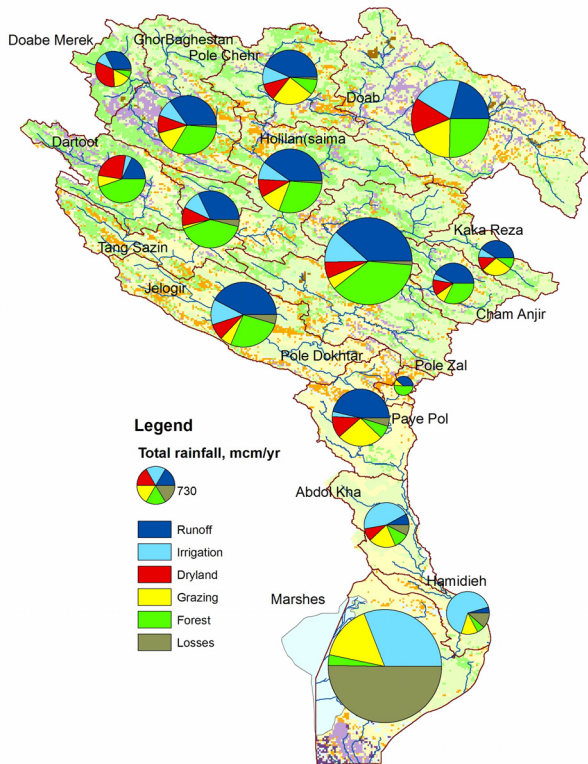


Figure 2: Major water use and runoff for main catchments within the Karkheh Basin for 1990-2000. The area of each pie chart is proportional to the volume of mean annual rainfall in each catchment.

The water use in the Karkheh Basin shows the divide between the partly forested upper basin, in which the runoff is generated, and the lower basin which has substantial irrigation and also a large consumption of water in the terminal marshes.

Mekong basin

The water use and hydrology of the Mekong Basin are described in MRC (2003, 2005). The Mekong Basin covers 795,000 km², and is drained by the 4200 km long River Mekong. The basin is mostly long and thin, particularly in the upper, Chinese part, and the Mekong is fed mostly by many short tributaries draining small catchments. The largest catchments are the Mun-Chi (about 100,000 km²), the Se San (80,000 km²) and the Tonle Sap (85,000 km²).

The source of the Mekong is fed by snowmelt. The Lower Mekong is fed by runoff, characterised by a pronounced wet and dry season. The peak flow from the Upper Mekong more or less coincides with the peak inflows from runoff into the Lower Mekong. Furthermore, the wet season affects the whole of the Lower Mekong more or less simultaneously. The consequence is that the Mekong has a very pronounced seasonal variation in flow, with the high season flow being 15 – 30 times the low season flow. Furthermore, the high season flow occurs along the whole length of the Mekong at more or less the same time, with only a short lag between upstream and downstream

The floodplain of the lower basin is extensively flooded during the high flows / wet season. The floods take water from the main channel above Phnom Penh and divert it into the Tonle Sap, across the floodplain back to the river below the Phnom Penh, or to the delta. Some of the flood water is consumed as evapotranspiration on the floodplain, and does not return to the river.

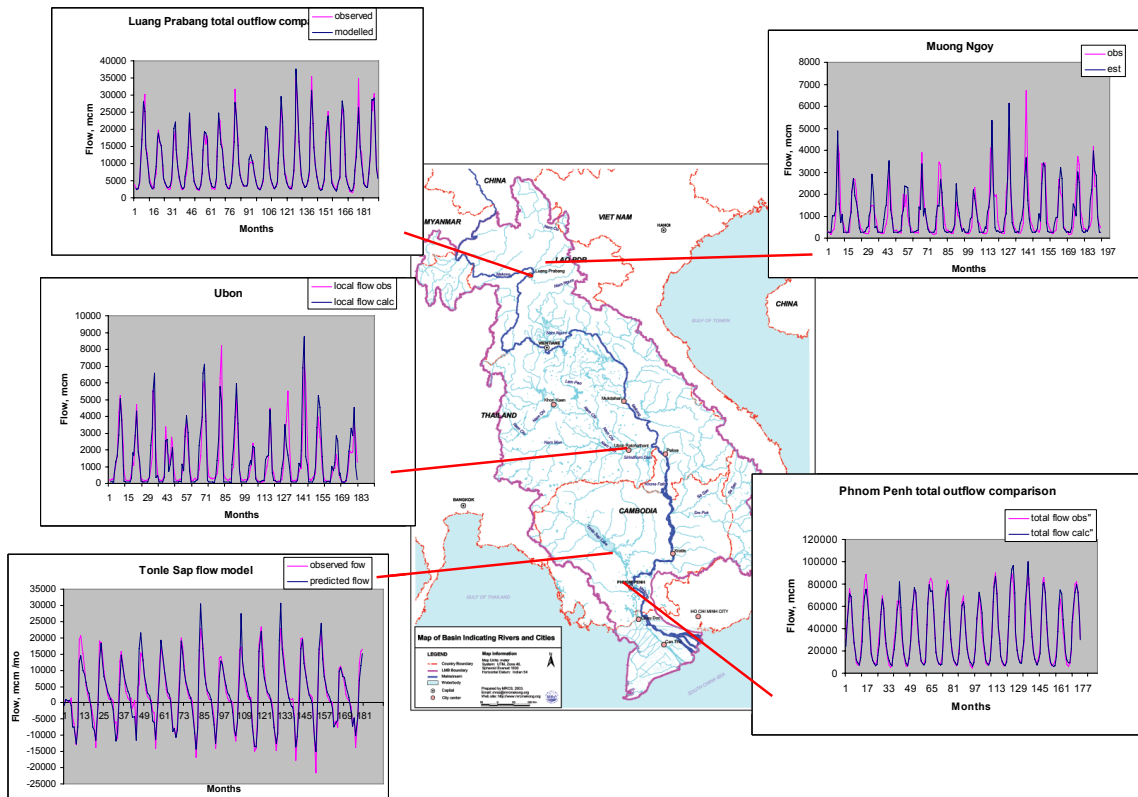


Figure 3. Measured and calculated monthly flows in the Lower Mekong for 1989 - 2000, showing an upstream location (Luang Prabang, top left), downstream (Phnom Penh, bottom right), a small tributary (Muong Ngoy, top right), a large tributary (Mun-Chi, mid left), and the reversing flow of the Tonle Sap River (bottom left).

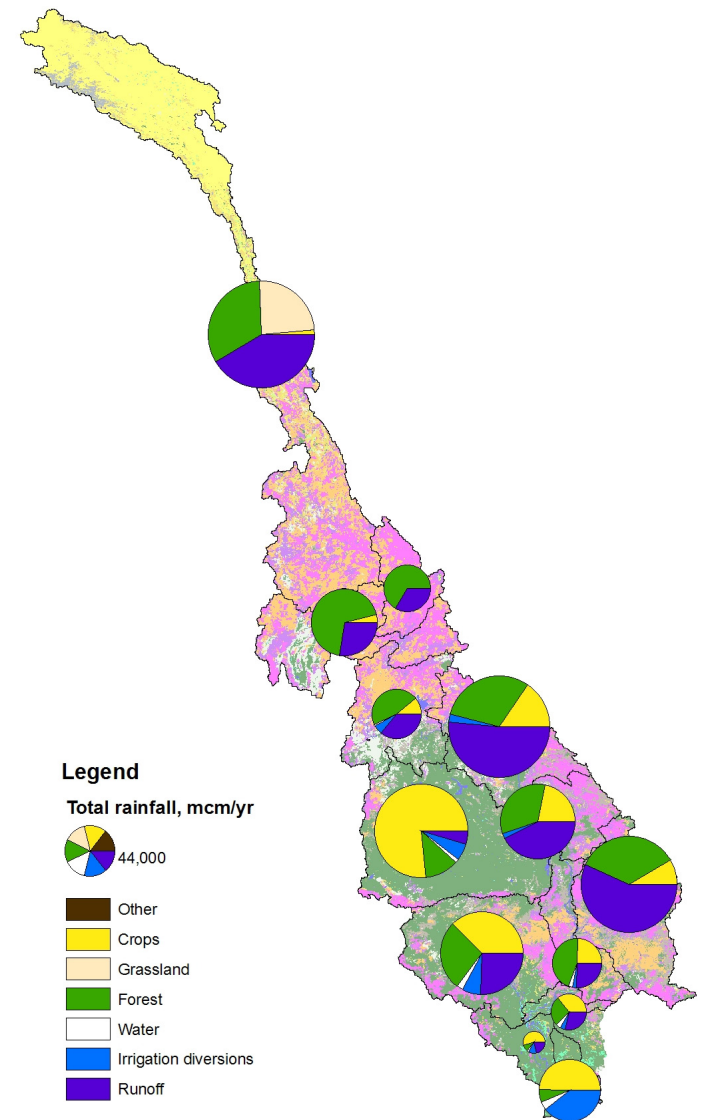


Figure 4: Major water use for main catchments within the Mekong Basin. The area of each pie chart is proportional to the volume of mean annual rainfall in each catchment.

When the Mekong is at the peak flow, its level is above that of the Tonle Sap River which drains the Tonle Sap (Great Lake). Hence, water is pushed up the Tonle Sap River and is stored in the lake. This reverse flow reverts to normal flow when the Mekong flow recedes, and the Tonle Sap River then drains the stored water plus additional water from runoff within the Tonle Sap catchment. The storage of water within the lake is of great importance to local fisheries and livelihoods. We assumed that the flow in the Tonle Sap River, and consequently storage in the Lake, depends on the difference in height between the Tonle Sap River and the Mekong and the flow capacity of the Tonle Sap River.

The climate and flow data for this model were partly supplied by the Mekong River Commission, and partly gathered from other sources as part of a project within the Challenge Program on Water and Food. Land use data were obtained from the International Water Management Institute website (IWMI, 2006).

Applying the runoff, flow, storage and water use expressions to 12 catchments within the Mekong Basin leads to results summarised in Figures 3 and 4. The values of water use shown in Figure 3 are annual averages, though they are calculated monthly in the spreadsheet. Figure 4 shows the grazing in the upper Mekong, with agriculture dominating in the middle catchments and irrigation in the lower part, especially the delta. Runoff is a major component of the water balance in more mountainous upper and eastern catchments.

Murray-Darling Basin

The water use and hydrology of Murray-Darling Basin is described in Crabb (1997) and Kirby et al. (2006). It is Australia's largest river system and has long played an important role in the Australian agricultural sector. It covers about 1.1 million square kilometres and has a population of nearly two million. Another million people outside the region depend heavily upon its resources.

Rainfall in the Murray-Darling Basin varies greatly, both spatially and temporally. As a consequence, runoff and river flow is amongst the most variable in the world (McMahon et al., 1992). At an average annual rainfall of about 480 mm, approximately 500,000 mcm/year of water falls on the basin. Rainfall varies significantly from the wetter and less variable east to the drier and more variable west, and exceeds potential evapotranspiration only in the southeast. Consequently nearly all of the average annual flow comes from this part of the basin. Overall average runoff is about 24,000 mcm/yr, or about 5% of the total rainfall falling in the basin. Nearly half the runoff is diverted for irrigation or other consumption, with much of the rest being consumed as evapotranspiration in floodplains and wetlands: discharge to the sea has varied in recent years from 0 to about 9,000 mcm/yr, with an annual average of about 3,000 mcm/yr.

Many rivers in the Murray-Darling Basin are disconnected, or are distributaries that end in wetlands. For these rivers, the outflow does not become the inflow to another river reach, but ends as evapotranspiration. One distributary system in the middle reaches of the Murray River, the Edwards-Wakool creek system, takes flow in excess of the capacity of a restricted channel section called the Barmah Choke. The Edwards-Wakool system discharges back into the Murray River about 200 km downstream of the Choke. To model this, we assume that for flow up to the Choke capacity, the water flows through Choke. Flow in excess of this enters the Edwards-Wakool system and reappears in a downstream reach. The rest of the flow is consumed as evapotranspiration by the Barmah-Millewa Forest, a major flood-dependent red gum forest.

Storage dam releases in the Murray-Darling (especially the Murray River) are made in response to orders from downstream irrigation areas to satisfy irrigation demand. The rules are complex, but we assumed for simplicity that the releases equalled the aggregate downstream demand multiplied by a constant to allow for losses

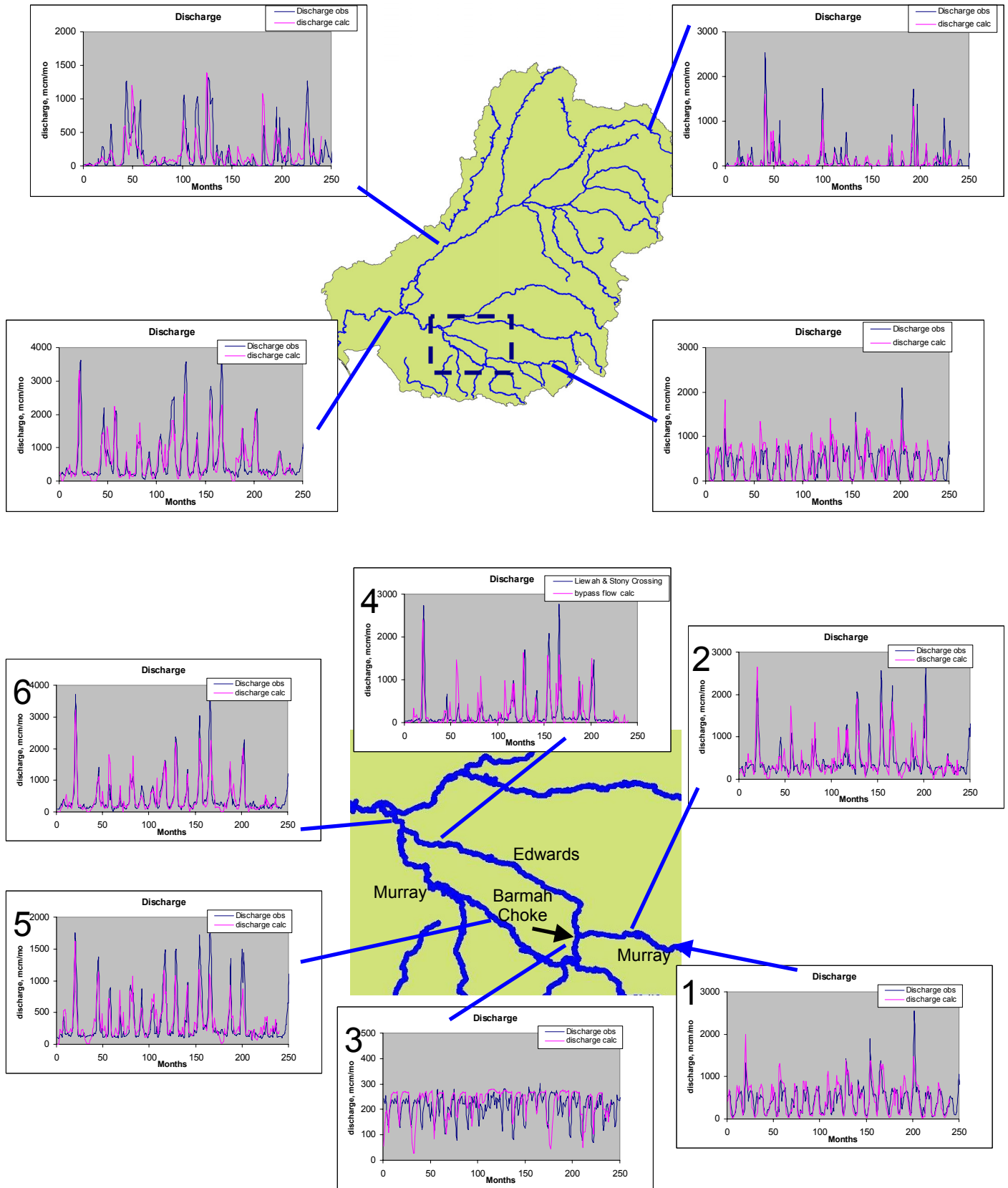


Figure 5: flow in four parts of the Murray-Darling Basin for 1981-1999. (Top) The upper Condamine (top right), lower Darling (top left), Murray just below Hume Dam (bottom right) and lower Murray (bottom left). (Bottom) Detail around the Barmah Choke, the area of the box in the top figure. The numbers on the hydrographs are explained in the text.

The rainfall and other climate data were taken from the SILO (BoM, 2006) datasets, land use data from Bryan and Marvanek (2004) which also contained water use calculations for major agricultural crops. Flow data were taken from DIPNR (2004), QNRM (2005) and DSE (2005). Annual irrigation diversion and storage data were taken from MDBC (2006).

Applying the runoff, flow, storage and water use expressions to 39 catchments within the Murray-Darling Basin leads to results summarised in Figures 5 and 6. We had more detailed figures of areas for individual irrigation crops so, in contrast to the other basins, we were able to determine approximate water use of the major crops within the Murray-Darling Basin (Figure 6). The values of irrigation water use shown in Figure 6 are annual averages, calculated from the monthly values in the spreadsheet. Irrigation water use is dominated by pasture in the southern part of the basin, rice in the south-central part, and cotton in the north. The areas of irrigation are smaller in the lower, south western part of the basin, and fruit and horticulture dominate.

In Figure 5 (lower part), the flow down the Murray (plot 1) reflects the periodicity of seasonal irrigation demand and dam release. The next gauge (2) downstream looks quite different, reflecting the tributary inflows, smoothing in Lake Mulwala, and large irrigation diversions (of about 2000 mcm/yr on average). Then, at the Barmah Choke (3), only the low flows get through, with all the peaks overflowing down the Edwards-Wakool creek system (4). In the Murray channel (5), meanwhile, the Goulburn (a major tributary) puts peaks back onto the flow through the Choke, and more diversion is taken off. Finally, the Edwards-Wakool creek system peaks (4) are added back onto the Murray (5) to produce even larger peaks after the confluence (6) (compare Y axis scales of (5) and (6)).

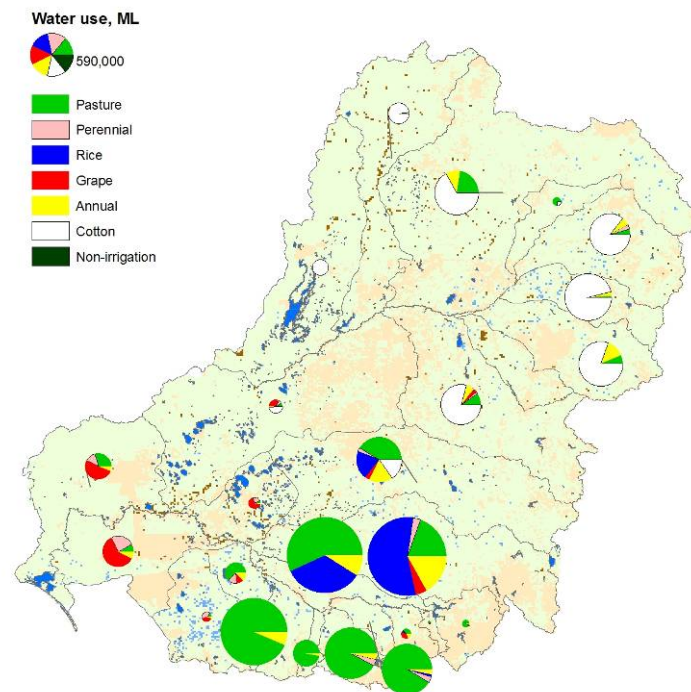


Figure 6: water use of major irrigation industries in the Murray-Darling Basin.

Limpopo Basin

The Limpopo Basin covers about 410,000 km² and is drained by the 1,750 km long Limpopo river and its tributaries. The basin is dominated by savanna and grassland, with considerable areas of wetland in the lower part. Rainfall varies from about 250 mm in the hotter, western parts to about

1050 mm per year in the eastern escarpment. Most of the basin receives less than 400 mm per year and nearly all of it falls between October and April, usually as intense storms on a few days. Rainfall varies between years and droughts are common. The Limpopo consequently has seasonal flow, with considerable variability from year to year.

We used data taken entirely from the Internet for this basin, either as datasets or from reports and papers available on the World Wide Web. Climate data were taken from the CRU_TS_2.10 dataset (Mitchell and Jones, 2005); flow was taken from the DSS522.1 dataset (Bodo, 2001); land use was taken from the 1992-3 AVHRR dataset (IWMI, 2006). Flow data were available for few locations, often as discontinuous records, and not always overlapping, and were insufficient to match runoff with discharge (as described in Methods). Therefore, we equated the mean annual runoff for each catchment to the mean annual runoff figures in FAO (2004).

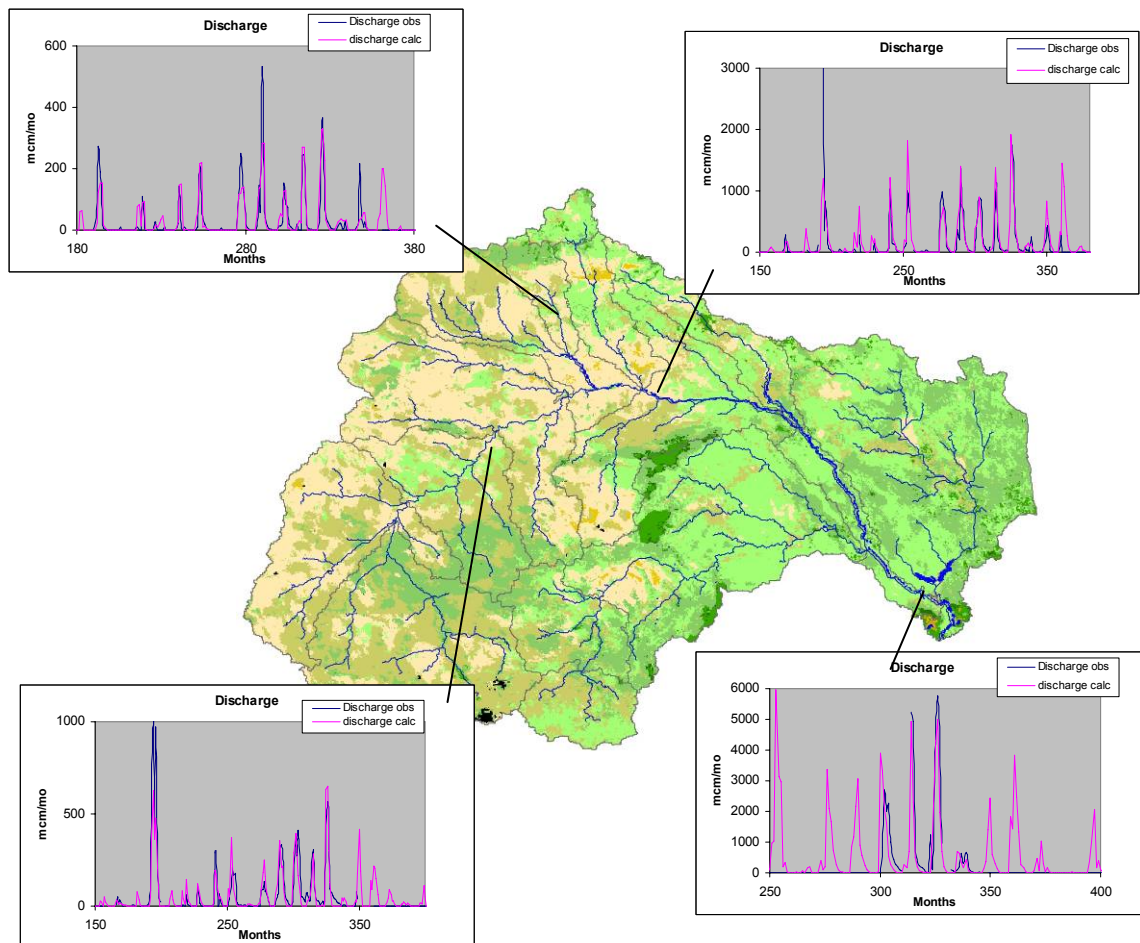


Figure 7: measured and calculated flow at four locations in the Limpopo basin for 1950-2000, superimposed on a land use map. Note that the measured flow records are discontinuous, for different periods, and may also contain some spurious values.

Applying the runoff, flow, storage and water use expressions to 15 catchments within the Limpopo basin leads to results summarised in Figures 7 and 8. The values of water use shown in Figure 8 are annual averages, though they are calculated monthly in the spreadsheet. Runoff and irrigation are a small proportion of the overall volume of rainfall: it can be seen that irrigation takes a significant share of runoff only in the southern part of the basin.

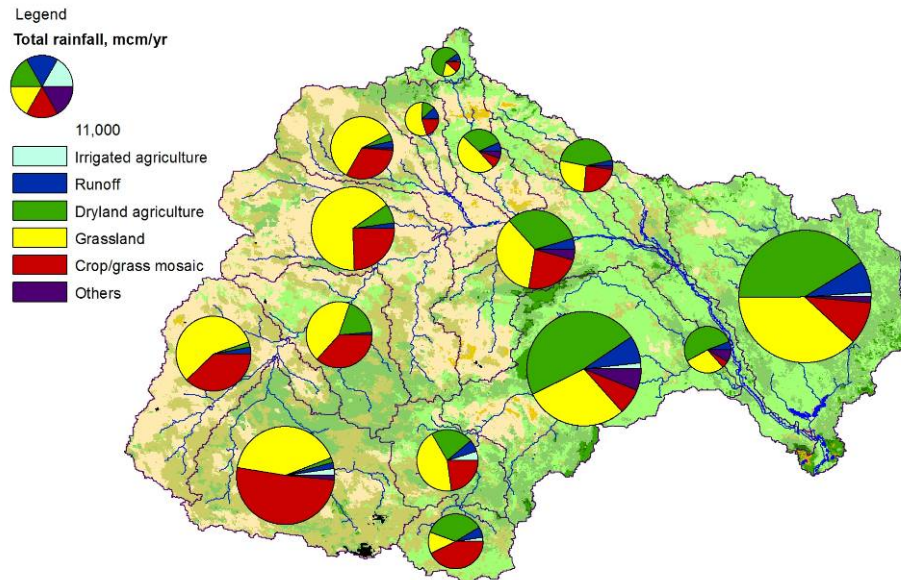


Figure 8. Water use in Limpopo catchments. The pie charts show total water use, dryland and irrigated, together with runoff not diverted for irrigation. The area of each pie chart is proportional to the volume of mean annual rainfall in each catchment.

Discussion

The water use account spreadsheets are an example of top-down modelling in that they attempt to describe the overall behaviour of a basin based on observed responses, which Sivapalan et al. (2003) regard as the defining feature of a top-down approach. They are at a level of detail appropriate to basin overviews. Individual model components are inferred from the data, rather than pre-determined.

The elements of the water account (flow, storage, water use) are, as required, linked to time-series graphs (such as the hydrographs in figures 1, 3, 5 and 7, comparing observed and calculated flows). Systematic learning about catchment and basin behaviour is facilitated, gaps and deficiencies in data are readily apparent, and hypothesis testing is quick and easy. Fitting calculated flows to observed flows can be done with the Solver function in Excel, though care is required in its use: the user must be satisfied that the underlying sub-model is reasonable and that the optimum is sensible. We use this method in some of our calibrations.

A significant advantage of a water use account for a whole basin is that there are many potential sources of data with which to constrain or calibrate a model. We have used variously: many flow gauges, known annual discharge, mean annual runoff, known diversion volumes, and independent estimates of water use (especially in irrigation districts). Furthermore, the requirement to balance all gains, losses and changes to storage, both across the basin and for each and every component, places severe constraints on permissible use, flows and storages. When several tributaries contribute to a main channel, the calculated flow in each is constrained so that, even if one or more is ungauged, tight limits can be placed on the flow from each. This is even more the case if there are independent estimates of vegetation water use. Of course, this balancing should be done whatever hydrology or water use modelling is envisaged. In another context, Raupach et al. (2001) noted the usefulness of mass balances in providing physical constraints to material flows, particularly when several flow calculations are linked (their context was several entities – carbon, energy, water, nutrients - in one place, whereas here we deal with one entity – water – in several places).

Sivapalan et al. (2003) note problems and caveats with the top-down approach. Finer scale processes are glossed over, and the user must be confident that key features are not ignored, and that large scale models are physically reasonable interpretations of the processes. There are dangers in generalisations and extrapolations to new situations. Thus, the water use accounts should be used to investigate scenarios that are but modest perturbations of the conditions for which they are tested and calibrated.

The water use account spreadsheets provide basin overviews of major dryland and irrigated water uses, flows, storage, major losses and discharge. They provide a basis for examining the impact of physical changes to the system and for interactions with agricultural productivity, economics and livelihoods.

As an example of use of the spreadsheets to examine physical impacts, Figure 9 shows the impact on downstream flows of a 10 % reduction in rainfall (the record in the CRU dataset reduced by 10 %), which is sometimes used in climate change scenarios for the region (de Wit and Stankiewicz, 2006). Resulting peak flows at Chokwe reduce to about 75 % of their current values in this scenario. Such a reduction in flows would affect water availability and the wetland ecosystems in the lower part of the basin. The reductions to vegetation water use across the basin are also calculated in the spreadsheet.

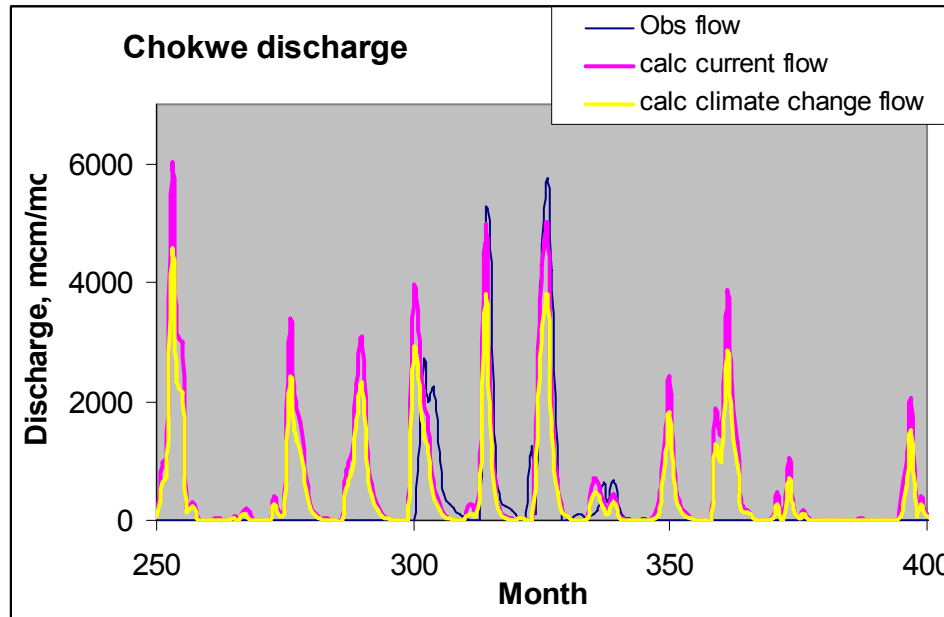


Figure 9: Flow calculated at Chokwe (just above the mouth of the Limpopo) with actual (historical) rainfall and with 10 % decrease in rainfall under a possible climate change scenario.

Other physical impacts that we have briefly examined include: the changed water availability in the lower Karkheh Basin following commissioning of the Karkheh Dam which, depending on management and the volumes diverted for irrigation, could significantly affect the marshes into which the river discharges; climate change in the Mekong; and, changed supply due to climate change, bushfire recovery and other impacts in the Murray-Darling.

However, our main motivation for developing water use accounts is to study the impacts on agricultural productivity, economics and livelihoods. Many of the purely physical changes mentioned above, particularly flow regimes, could be examined as well or better with catchment – hydrology models. We do not propose that water use account spreadsheets should be used in place of such models though, where none exist, such as in the Limpopo and Karkheh, the water

use accounts can be developed quickly and used for such studies pending the development of more sophisticated catchment – hydrology models.

We have used the models outlined above, particularly in the Murray-Darling, as the basis for assessments of water allocation under various policy scenarios. Often, we use the information in an aggregated form, such as annual average flows and water use in partial equilibrium economic analyses (eg Qureshi et al, 2006a, 2006b), or annual (time varying) flows and water use in optimal decision making about water trading and environmental water use (Kirby et al., 2006). In our future work we aim to use the models as outlined above to investigate seasonal effects in water trading and environmental water use, and to investigate impacts on poverty and livelihoods in the Mekong and Karkheh.

Conclusions

Water use accounts are a powerful way of describing the overall water use and flow behaviour of a river basin. They capture the main aspects of the behaviour, both spatially and temporally (seasonally, annually), and the balance between different types of water use (dryland, irrigated, forest, wetland and other water uses).

The spreadsheets we have developed are useful for systematic learning and hypothesis testing, and also help the user rapidly identify gaps and limitations in the data. They can be applied in cases where data are limited, and it is possible to construct a reasonable account based on data available on the Internet.

The water use accounts spreadsheets provide a basis for examining the impact of physical changes to the system and for interactions with agricultural productivity, economics and livelihoods. We emphasize, however, that they are not detailed catchment hydrology models, and are not suited to river planning and management, nor to investigations of small-scale, detailed effects.

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