XX

Water-use accounts in CPWF basins:

5. Simple water-use accounting of the Limpopo Basin.

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CPWF WORKING PAPER

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1. Model concepts and description (CPWFWP xx).
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11. Simple water-use accounting of the Yellow River Basin (CPWFWP xx).
12. Spreadsheet description and use (CPWFWP xx)

1   Abstract

This paper applies the principles of water-use accounts, developed in the first of the series, to the Limpopo River basin in Southern Africa. The Limpopo Basin rises in South Africa and flows northwest along the border with Botswana and Zimbabwe before crossing Mozambique to enter the Indian Ocean. Rainfall in the basin varies between 200 and 1500 mm, with much of the northern and western parts receiving less than 500 mm. Rainfall is strongly seasonal, with a short rainy season leading to negligible river flows in the dry season

Net runoff from the basin is about 4% of the water received as precipitation. Grassland covers 57% of the Basin and uses about 52% of the available water. Rainfed agriculture covers 40% of the Basin and uses 38% of the available water. The area of irrigated agriculture is small and uses less than 1% of the available water. Although industrial water use in the upper Oliphants River is important locally, it accounts for only 0.3% of the total available water.

Climate change, using an assumed decrease of 7.5% in precipitation overall would reduce discharge of the Basin by 25%. A proposed dam in Mozambique to irrigate 1000 km^2 would likely reduce downstream flows in normal years, but would probably not prevent floods like those of 2000.

Keywords: Water use accounts, Limpopo basin, top-down modelling, basin water use.

2   Introduction

Go to the banks of the great grey-green, greasy Limpopo River … and find out. (Kipling 1902).

In this note, we describe a simple water-use account for the Limpopo Basin.

The Challenge Program on Water and Food (CPWF) aims to catalyse increases in agricultural water productivity at local, system, catchment, sub-basin, and basin scales as a means to poverty reduction and improving food security, health, and environmental security. The Basin Focal Projects of the CPWF works in several priority basins: the Indo-Gangetic Basin, the basins of the Karkheh, Limpopo, Mekong, Niger, Nile, São Francisco, Volta, and Yellow Rivers, and a collection of small basins in the Andes.

A useful output for each basin, and a key element of the understanding of basin function, is an overview water-use account. Water-use accounts produced in the same way for each basin would have the further benefit of making easier the development of syntheses of understandings from all the basins.

Water-use accounting is used at national (ABS 2004; Lenzen 2004) and basin (Molden 1997; Molden et al. 2001) scales to:

- Assess the consequences of economic growth;
- Assess the contribution of economic sectors to environmental problems;
- Assess the implications of environmental policy measures (such as regulation, charges, and incentives);
- Identify the status of water resources and the consequences of management actions; and

- Identify the scope for savings and improvements in productivity.

However, these accounts are static, providing a snapshot for a single year or for an average year. Furthermore, they do not link water movement to its use. In contrast to the static national and basin water-use accounts referred to above, our accounts are dynamic, with a monthly time step, 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 assembled in Excel spreadsheets, and are quick and easy to develop, modify, and run. We have applied this accounting method to several major river basins including the basins of the Murray-Darling, Mekong, and Karkheh Rivers (Kirby et al. 2006a; Kirby et al. 2006b). Here we describe the application to the Limpopo Basin.

As we shall describe below, the account has been developed using existing data, and gives an overview of water uses within the Basin. There are some problems with the data, which we shall describe, and the account can be improved with better data and calibration. We recommend that, should it be intended to use the account for any purpose beyond developing an understanding of the broad pattern of water uses in the Basin, that effort be directed to obtaining better data.

2.1 Other models

A Geospatial Stream Flow Model (GeoSFM) of the Limpopo Basin was used by USGS. Lévite et al. (2002) used a WEAP model for the Olifant River tributary in the Limpopo Basin.

3 Basic hydrology and an outline of the simple water account

3.1 Basic hydrology, irrigation, and land use

The Limpopo Basin covers 412,938 km^2, and is drained by the Limpopo River and its tributaries, of which the Olifants and the Changdne Rivers drain the largest areas (Figure 1 and Table 1). Rising as the Crocodile River in the Witwatersrand region of South Africa, the Limpopo flows northeast along the border of South Africa with Botswana and Zimbabwe, then southeast across Mozambique, before emptying into the Indian Ocean. Descriptions of the hydrology and water resources, with references to more general literature, may be found in FAO (2004).

Table 1.   Catchments in the Limpopo Basin with their areas.

Catchment	Location	Area, km^2
Crocodile	Crocodile	44,691
Limpopo	U/S* Oxenham	33,716
Limpopo	Oxenham Ranch	25,335
Limpopo	D/S* Oxenham	46,180
Tuli	Ntalali Causeway	7,445
Limpopo	U/S Beitbrug	26,406
Umzingwane	Glass Block	3,937
Limpopo	Beitbrug	12,002
Mwenezi	Mwenezi	14,732
Limpopo	D/S Beitbrug	34,742
Olifant	Loskop Dam	11,833
Olifant	Arabie Dam	16,424
Olifant	U/S Limpopo	58,036
Limpopo	Chokwe	9,611
Limpopo	Mouth	67,849
Total		412,938
* U/S = upstream; D/S = downstream.		

The mean annual rainfall of the basin varies considerably (200-1500 mm) with much of the northern and western parts of the Basin receiving less than 500 mm. Rainfall is highly seasonal with 95 percent falling between October and April. The rainy season is short with the annual number of rain days seldom exceeding 50. The consequence is that the Limpopo and its tributaries have a very pronounced seasonal variation in flow, with negligible flows in the dry season. The rainfall varies considerably from year to year (Figure 3).
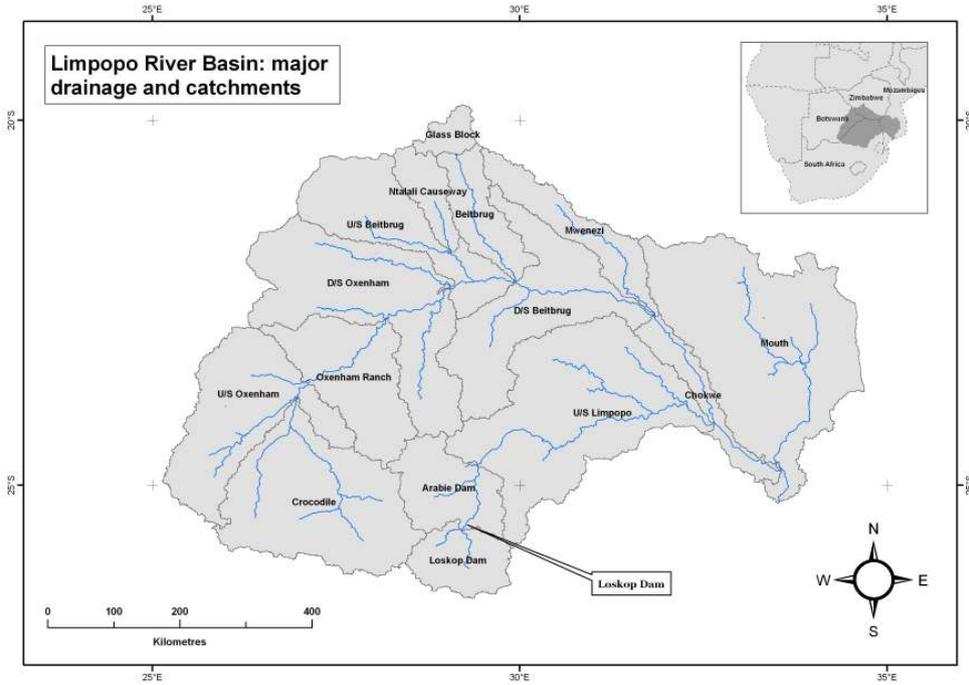
Figure 1. The Limpopo Basin, with the catchments used in the water-use account.

Figure 2.   Monthly average rain and potential evapotranspiration in the Limpopo Basin. a). Western Limpopo (U/S Oxenham Ranch); b). Tuli catchment (Zimbabwe); c). Upper Oliphants; and d). Lower Limpopo around Chokwe.

Figure 3.   Annual rainfall in the Western Limpopo (upstream from Oxenham Ranch).

4   Simple water account

The simple water account has two parts:

- A hydrological account of the water flowing into the basin (primarily rain), flows, and storages within the basin, and water flowing out of basin (primarily as evapotranspiration and discharge to the sea); and
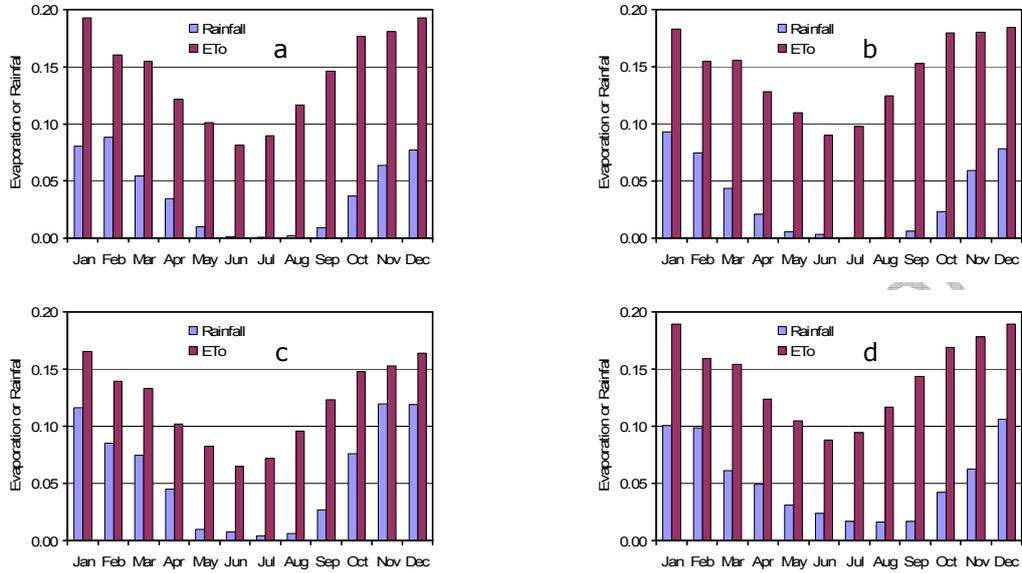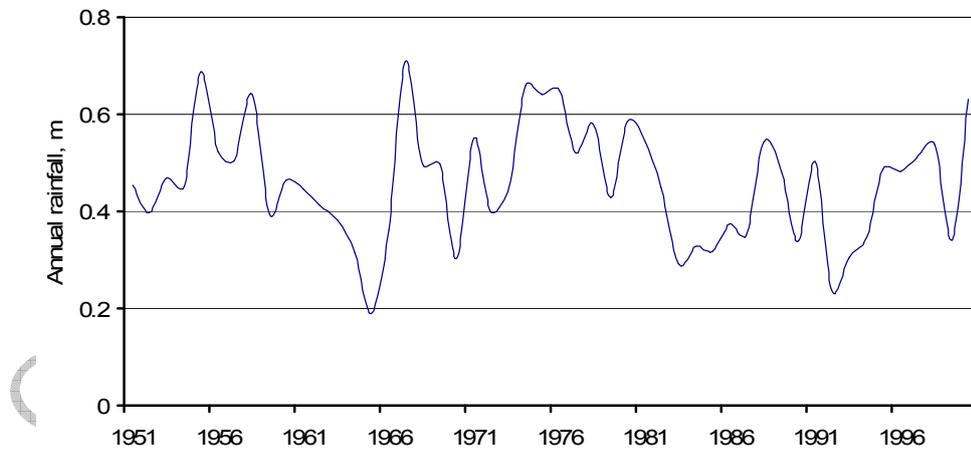
- A further partitioning of the evapotranspiration into the proportion of evapotranspiration accounted for by each vegetation type or land use, including evapotranspiration from wetlands and evaporation from open water.

The simple hydrological account is based on a monthly time step, which we consider adequate for our purpose.

The account is a top-down model (Sivapalan et al. 2003), based on simple lumped partitioning of rainfall into evapotranspiration and runoff. This is done at the catchment level, with no spatial separation into different vegetation types. Runoff flows into the tributaries and thence into the Limpopo River, with downstream flow calculated by simple water balance. During high flows, some of the flow is stored in the channels, and some in lakes and wetlands from which much water is lost to evaporation.

The model is described in detail in a companion report Basin Water-use Accounting Concepts and Modelling (Kirby et al. 2009). Here we describe only that part of the model that differs from the general set of equations.

4.1   Units:

Rain, evapotranspiration and potential evapotranspiration are given in mm.

River flows and storages, and lake storage, are given in mcm (million cubic metres). 1 mcm is equivalent to one metre over one square kilometre. 1000 mcm = 1 bcm (billion cubic metres) = 1000 m over 1 km^2 = 1 km^3.

5   Data sources

The datasets used in this water-use account were all readily available on the internet.

5.1   Rainfall

The rainfall and other climate data were taken from the Climate Research Unit at the University of East Anglia (specifically, a dataset called CRU_TS_2.10). They cover the globe at 0.5° (about 50 km) resolution, at daily intervals for 1901 to 2002. The dataset was constructed by interpolating from observations. For recent decades, many observations were available and the data show fine structure. For earlier decades, few observations were available and the data were mostly modelled and lack fine structure. We sampled the rainfall and other climate surfaces for each catchment within the basin, to calculate catchment area-means of rainfall and potential evapotranspiration for each month. The method is described in more detail in Kirby et al. (2009).

5.2   Flows

Reach flows were taken from a dataset called ds552.1, available on the internet (URL: http://dss.ucar.edu/catalogs/free.html) (Dai and Trenberth 2003). The dataset also gives contributing drainage areas for each flow gauge. Flow records were not available for all the catchments: some flow records were available for following rivers: Oxenham Ranch on the upper part of the Limpopo, Ntalali Causeway of the Tuli (a tributary of the Shashe), Glass

Block on the Umzingwane, Loskop Dam on the Olifants, and Beitbrug and Chokwe on the Limpopo.

5.3   Land use

Land use was taken from the 1992-3 AVHRR dataset (IWMI 2006).

5.4   Dams

Dam storage volumes were taken from the FAO AQUASTAT database list of African dams (http://www.fao.org/nr/water/aquastat/damsafrica/index.stm). We considered only dams of greater than 10 mcm capacity.

5.5   Data limitations

The major limitation of the data is the sparse and possibly wrong flow records. As we will describe later, there appear to be significant problems with the flow gauge data, with some gauges recording excessive flows (Kevin Scott, personal communication, 2008). The measured flows do not match the well-studied runoff in some parts of the basin, and also lead in some places to unlikely runoff ratios. A particular case is the gauge at Ntalali Causeway which records flow from the Tuli catchment. Taking the flow records of this gauge at face value implies a runoff ratio of 9 %, whereas all the other gauged catchments in that part of the Limpopo have implied runoff ratios of 1 to 2 %.

Furthermore, the measured flow at Chokwe (the last gauge records before the mouth) implies a discharge from the basin greater than that estimated by other means (Boroto 2001; Kevin Scott, personal communication, 2008), and again implies that some gauges are wrong.

To overcome this problem, we have used runoff model coefficients that lead to runoff that matches the best estimates of runoff, rather than matching the flow records. The matches are based on estimates of Kevin Scott (personal communication, 2008), and better match other estimates such as those in Boroto (2001).

6   Components and results in detail

6.1   Flow

As indicated above, flow records exist only for some of the catchments of the Limpopo, but these do cover the main regions of the basin. We describe the flow in four main regions:

- The upper, western part of the Basin;
- The northern region of the Basin in Zimbabwe;
- The southern region of the Oliphants; and
- The Lower Limpopo in Mozambique.

6.1.1   The upper Limpopo Basin

Oxenham Ranch is the most upstream station with records in the Limpopo Basin. The upper reaches of the Crocodile, which is the source of the Limpopo, is dammed in several places with dams having a combined capacity of about 750 mcm. Figure 4 shows the measured and modelled flows at Oxenham Ranch. The figure shows the great difference between the wet season flows and the lack of flow in the dry season, as well as the great year-to-year variability of peak flows.
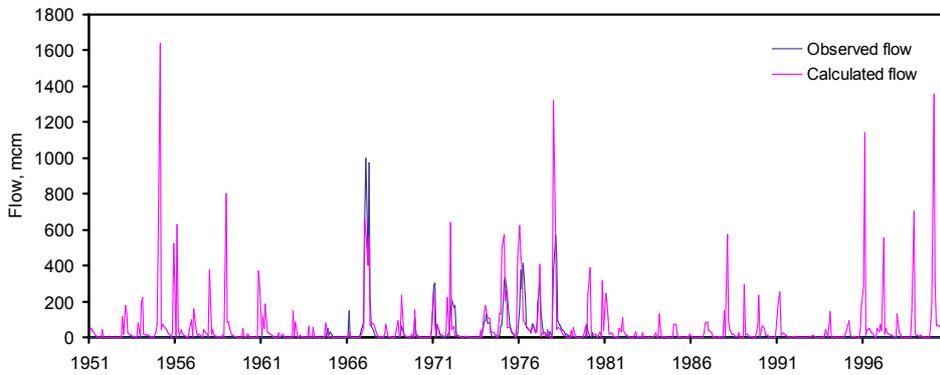
Figure 4.   Monthly measured and modelled flow for 1951 to 2000 at Oxenham Ranch.

6.1.2   The northern catchments and the mid Limpopo Basin

The northern tributaries of the Limpopo in Zimbabwe show wet season to dry season variation and year-to-year variation similar to that in the western part of the Basin. Figure 5 shows the flow at Glass Block, in the upper reaches of the Umzingwane River in Zimbabwe, and Figure 6 shows the flow at Beitbrug on the Limpopo River. This gauge shows the problem of recording a flow greater than that implied by the best estimates of runoff in the catchments upstream (Kevin Scott, personal communication, 2008), and thus the calculated flows are generally less than the observed flows.
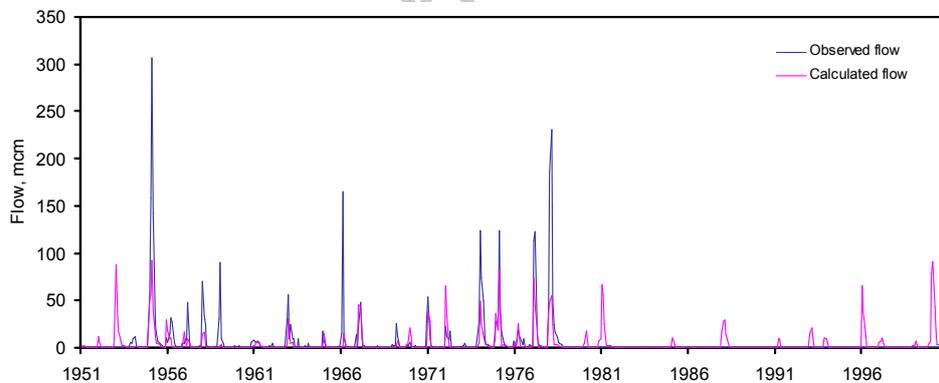

Figure 5.   Monthly measured and modelled flow for 1951 to 2000 at Glass Block.

6.1.3   The Oliphants catchment

The Oliphants catchment has the most reliable rainfall except for the lower reaches of the Limpopo in Mozambique, and has more storage in dams than most other parts of the Limpopo Basin. The storage in the Oliphants catchment is about 3500 mcm, of which about 2200 mcm is in the Massingir dam on the lower Oliphants River, just before it joins the Limpopo in Mozambique. The flow in the upper Oliphants River is shown in Figure 7, and that in the lower Oliphants River just above the confluence with the Limpopo is shown in Figure 8. There was a very large outflow in 2000.

The mean annual runoff in the Olpihants is, according to these estimates, nearly 1000 mcm, which compares with the figure given by IWMI (undated). IWMI also show that under natural conditions, the mean annual runoff would be about 2000 mcm.
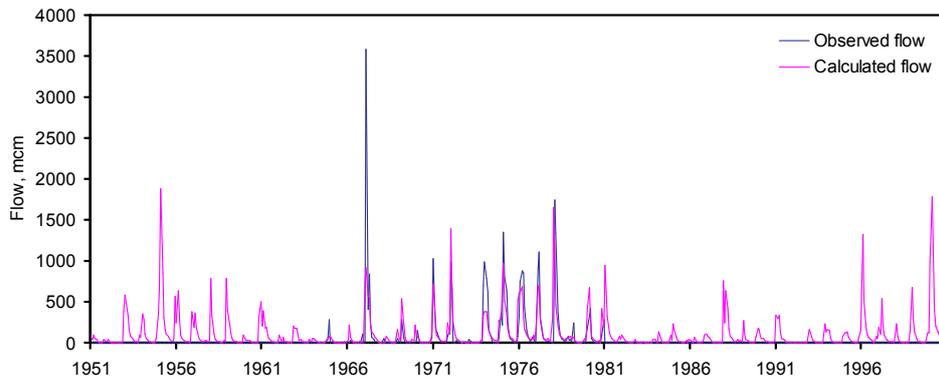

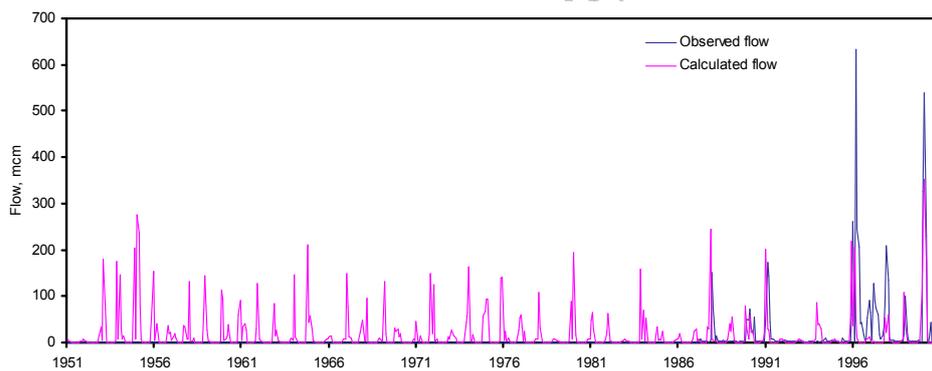Figure 6.   Monthly measured and modelled flow for 1951 to 2000 at Beitbrug

Figure 7.   Monthly measured and modelled flow for 1951 to 2000 at Loskop Dam.
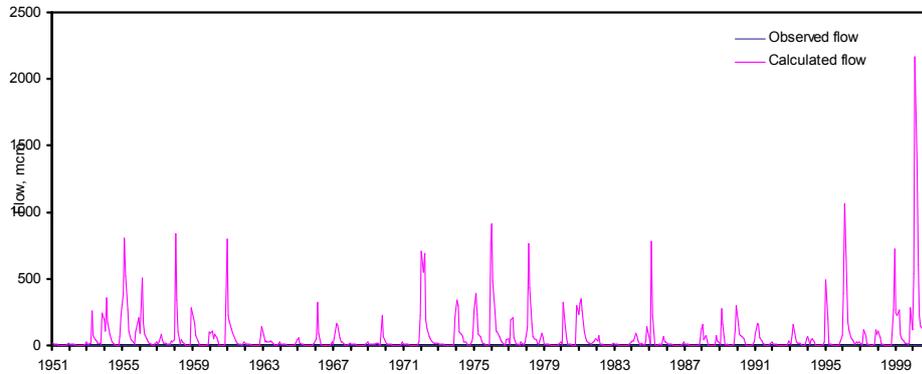
Figure 8.   Monthly measured and modelled flow for 1951 to 2000 in the Oliphants River upstream of its junction with the Limpopo.

6.1.4   The Lower Limpopo

The flows in the Limpopo River downstream of Beitbrug are shown in Figure 9. The volumes are similar to the flows in the Oliphants River, despite the much greater drainage area of the main Limpopo River (Figure 8).
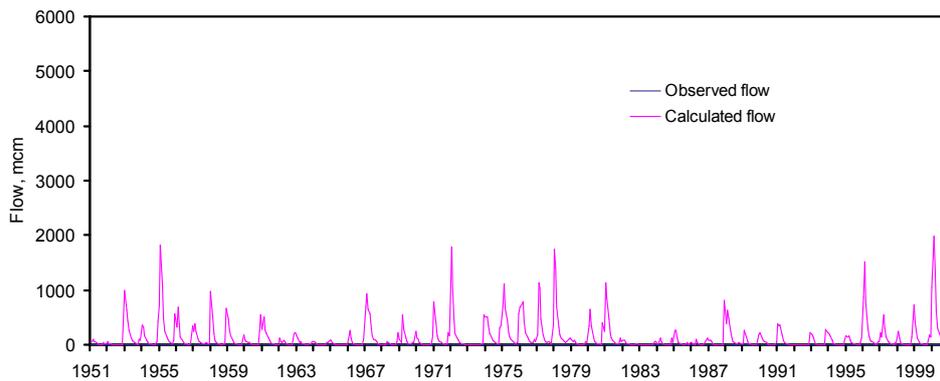

Figure 9.   Monthly measured and modelled flow for 1951 to 2000 downstream from Beitbrug.

The Limpopo and the Oliphants Rivers combine just above Chokwe, which has the last flow records before the Limpopo drains to the Indian Ocean (Figure 10). Figure 10 shows the calculated flows for the match with the best estimate of runoff (upper figure) (using information given by Kevin Scott, personal communication, 2008), and for the match with the flow records at Chokwe and in all upstream gauges (lower figure). The latter plot implies runoff volumes larger than those according to the best estimates throughout the basin. The Oliphants river would have to discharge on the order of 3,500 mcm (annual average) if the flow at Chokwe is to match the four years of gauge records, whereas IWMI (undated) show that the mean annual runoff is of order 1000 mcm. The analysis implies that some of the flow gauges (including the Chokwe gauge) are in error.

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The large flow in the Limpopo, and more especially the Oliphants in 2000, combined to make an exceptional flow in the lower reaches that year (shown in both the upper and lower plots in Figure 10), resulting from two cyclones delivering very heavy rains to the eastern parts of the Basin in February and March of that year (World Bank 2000).
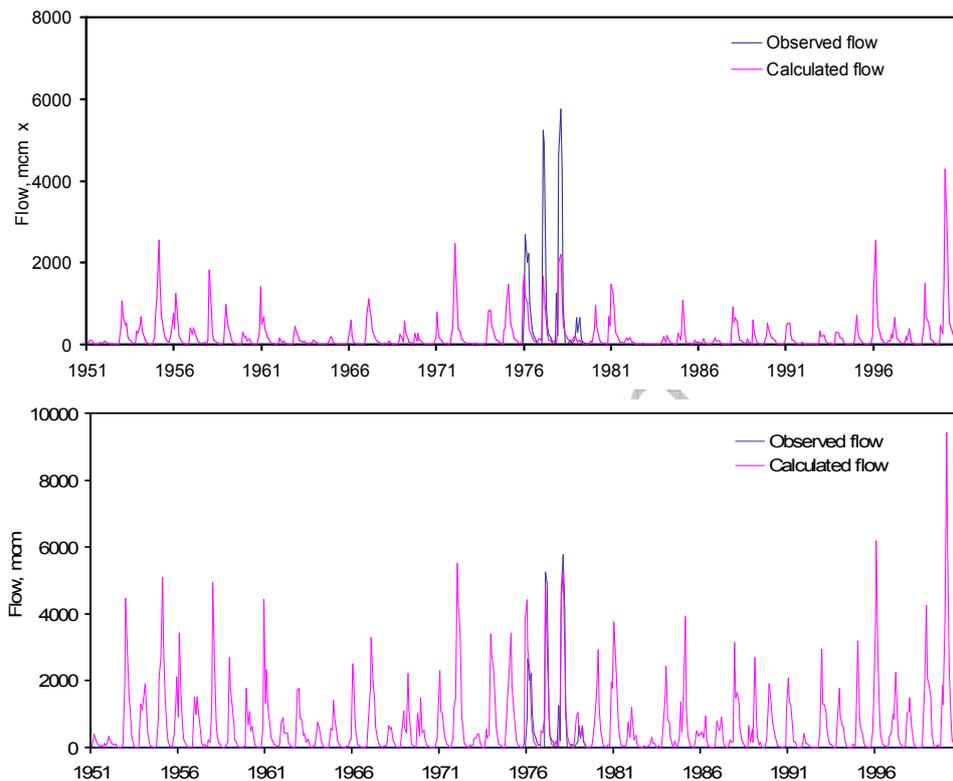

Figure 10.   Monthly measured and modelled flow for 1951 to 2000 at Chokwe. Top: using calculated runoff volumes that match the known volumes in the Limpopo (Kevin Scott, personal communication, 2008). Bottom: using runoff volumes (including in upstream catchments) that result in the best match with river gauge measurements.

6.2   Water use

The mean annual input by precipitation to the Limpopo Basin totals about 230,000 mcm. Figure 11 summarizes how this water is partitioned amongst the major water uses in the basin. Net runoff comprises the runoff remaining after all the water uses in the Basin have been satisfied, and includes all other storage changes and losses. Net runoff from the Basin is 3,595 mcm or 1.6 % of the total precipitation input.
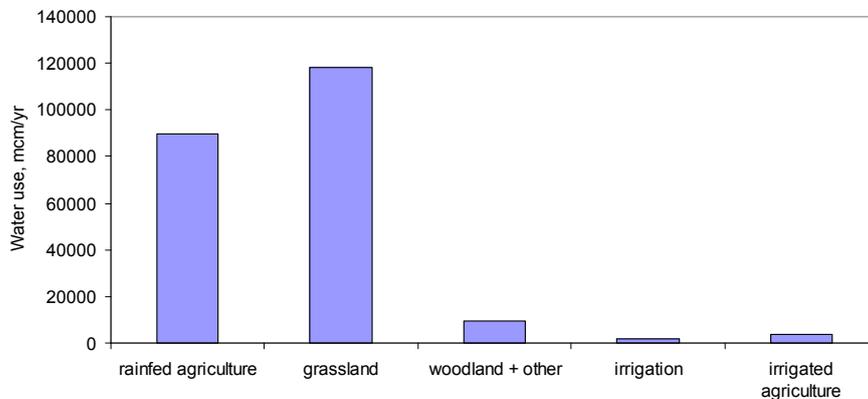
Figure 11. Summary of major water uses in the Limpopo Basin.

Grassland is the most extensive land use, covering 57% of the Basin. Its water use is correspondingly high, with a mean annual water use of about 120,000 mcm (Figure 11).

Rainfed agriculture, which covers 40% of the Basin, has the second highest use at 90,000 mcm, or 40% of the available water. Irrigated agriculture uses 0.8% of the available water (about 1,700 mcm) although it covers only 0.6% of the Basin. Human and industrial use is significant in the upper Oliphants and the lower Limpopo, though the annual use amounts to about 700 mcm or 0.3 % of the available water across the basin.

The distribution of the different water uses across the Basin is shown in Figure 12. It depicts the water uses in each catchment, and the distribution of water uses across the Basin. It does not, however, represent the water balance at the basin level. Irrigation in the lower part of the Basin, for example, uses the runoff water from the upper part, and thus this water is double counted at the basin level – the net runoff from the whole Basin is shown in Figure 11. The figure shows the different behaviour of the runoff-generating southern and eastern parts of the Basin. Irrigation is a minor water user in most parts of the Basin, with the only important use being in the southern part of the Basin.

6.3   Catchment and basin hydrological characteristics

Selected hydrological characteristics will be useful for comparing the Limpopo Basin hydrological function and its vulnerability with those of other basins under study in the Challenge Program. Some of these hydrological characteristics are outlined briefly below.

Runoff characteristics for different basins may be compared by comparing their annual percentage runoff ratios (total basin runoff/total basin precipitation). The runoff ratio for the Limpopo Basin is 2% (i.e. mean annual runoff is 2% of mean annual precipitation). Similarly, differences in runoff characteristics for the different catchments in the Basin can be seen by comparing their annual runoff ratios (Table 3). The runoff ratio is very low in the west of the basin and generally increases to the south and east.
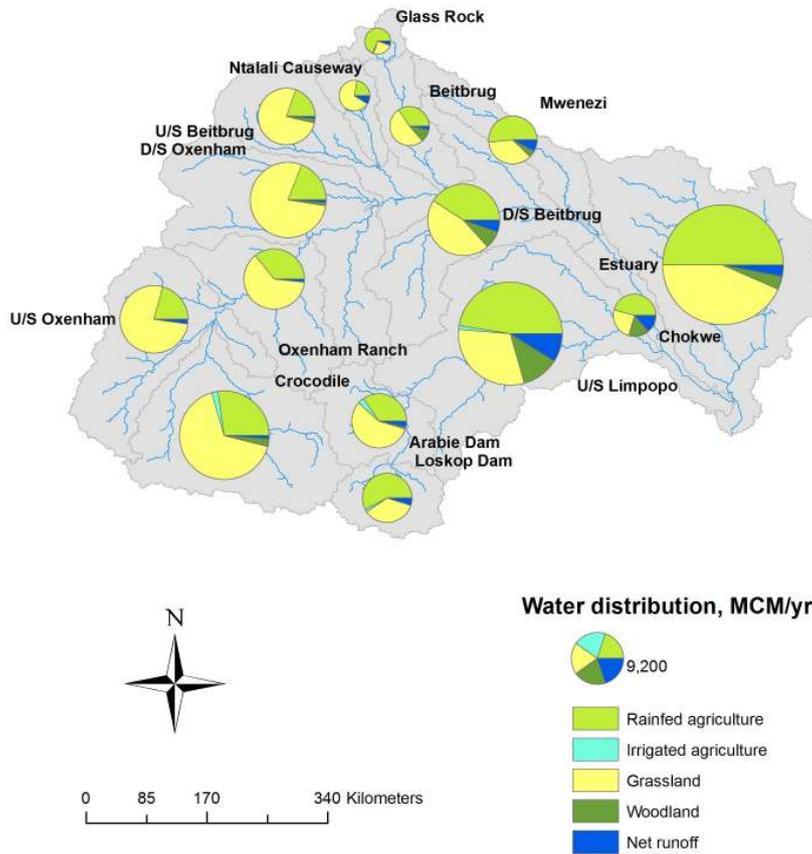
Figure 12.   Summary of major water uses in catchments of the Limpopo Basin.

The annual runoff increases with annual precipitation (Figure 13), but the data show considerable scatter.

7   Example use

We give here two examples of using the spreadsheet to model the impact of change, firstly that of climate change, and secondly that of a large increase in the areas used for irrigation. A broad reduction of rainfall in the range of 5-10% has been predicted for the summer rainfall region of South Africa (http://www.environment.gov.za/ClimateChange2005/ What_does_it_mean_for_South_Africa.htm). Another study suggests that Limpopo Basin is likely to experience between 5-10% decrease in rainfall (http://www.aiaccproject.org/ meetings/Johannesburg_03/Sessions%20A%20thru%20E/B2_Parida_AF42.ppt). Here we have considered 7.5% decrease of rainfall in all catchments. The rather obvious consequence for the discharge at Chokwe is a decline of about 27% in mean annual flow (Figure 14).

Table 3. Annual percentage runoff ratios (runoff/precipitation) for catchments in the Limpopo Basin.

| Catchment	Location	Runoff ratio (%)
Crocodile	Crocodile	1
Limpopo	U/S* Oxenham	2
Limpopo	Oxenham Ranch	1
Limpopo	D/S* Oxenham	2
Tuli	Ntalali Causeway	2
Limpopo	U/S Beitbrug	2
Umzingwane	Glass Block	2
Limpopo	Beitbrug	2
Mwenezi	Mwenezi	3
Limpopo	D/S Beitbrug	1
Olifant	Loskop Dam	3
Olifant	Arabie Dam	0
Olifant	U/S Limpopo	1
Limpopo	Chokwe	2
Limpopo	Mouth	2
Whole Basin		2
* U/S = upstream; D/S = downstream.		
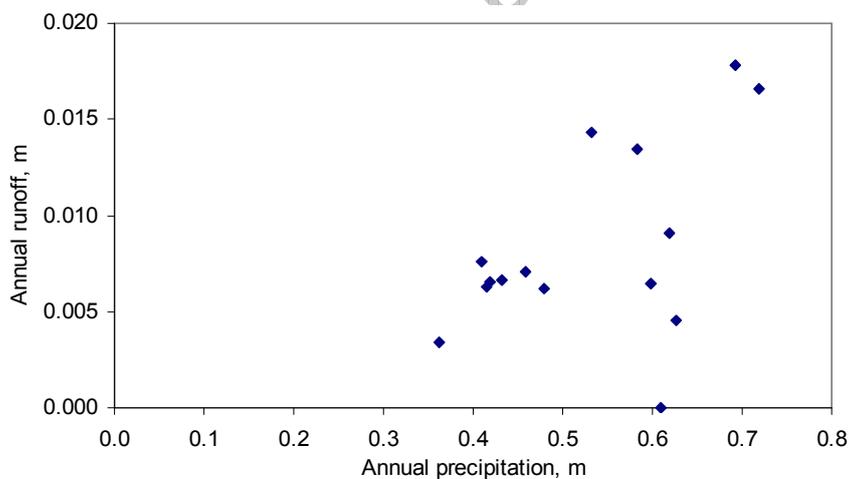
Figure 13. Runoff (annual averages 1990-2004) in the catchments in the Limpopo Basin.

The second example is that of the planned dam at Mapai on the Lower Limpopo in Mozambique. The dam is listed in AQUASTAT as being for irrigation and is planned to have a capacity of 11,200 mcm. Here we assume that it will serve an irrigated area of 1,000 km^2. We hasten to emphasise that this is not a prediction of how the dam will be used, it is merely a demonstration of the use of the water-use account spreadsheet. The impact on flows at Chokwe is seen in Figure 15. It may be noted that the entirely hypothetical large diversions from such a dam limit flows dramatically but do not prevent the floods of 2000 (much of the contribution to which came from the Oliphants River).

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We warn that these examples are for demonstration, they are not a prediction of what will actually happen.
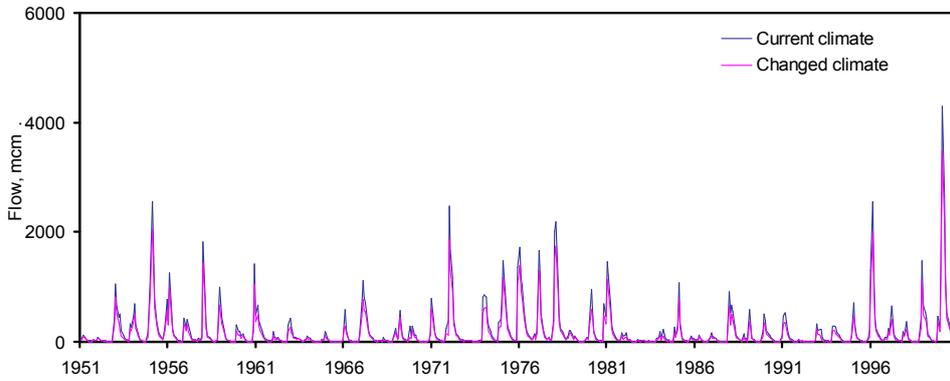

Figure 14.   Discharge at Chokwe with modelled decreased flow as a result of a 7.5% decrease in rainfall caused by climate change.
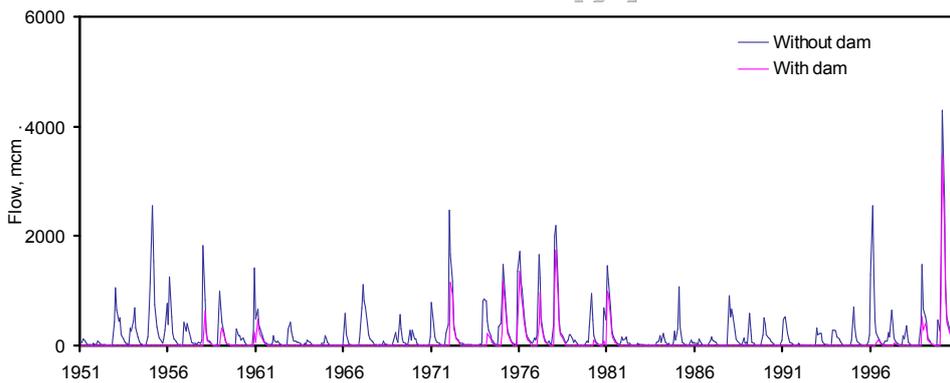

Figure 15.   Discharge at Chokwe with modelled changed flow as a result of the development of the Mapai dam.

8   Conclusions

A very simple spreadsheet model with few adjustable parameters has produced plausible runoff and river flow behaviour in the Limpopo Basin. If required it could be further developed. This would entail developing more complete and error-free climate and stream flow data, as well as data of land use and crop coefficients.

The flow gauge data in several gauges in the Limpopo basin imply runoffs greater than that estimated by other means. They also imply river flows in other locations greater than those believed to occur. Some gauges therefore appear to be in error. Basing runoff and flows on other runoff estimates appears to be a sounder approach than is relying on the river gauges.

The Limpopo Basin has low rainfall, mostly in the summer half of the year, leading to peak river flows usually in the late summer. Perhaps because of the modest availability of water, there is little irrigation, mostly in the southern part of the Basin.

We evaluated preliminary scenarios that simulate the impact of climate change and dam development on water availability and flow in the lower part of the Basin. The results suggest that climate change and the upstream development will have a large impact on water availability in the lower Limpopo Basin, and hence on the wetlands. However, the large dam appears not to be sufficient to control very large flood events such as occurred in 2000.

9   Acknowledgements

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