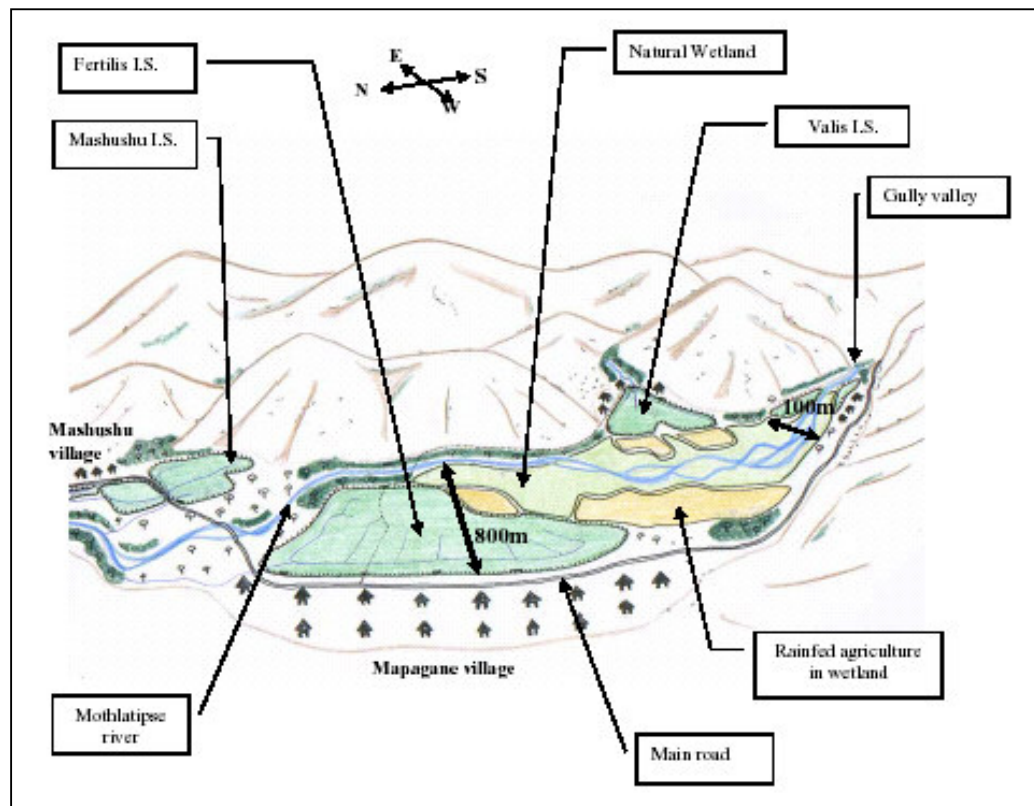


**Masters Thesis, Specialization in Environment Engineering,
Hydrology Elective**

**Effects of wetland degradation on the hydrological
regime of a quaternary catchment.**

Mohlapitse River, GaMampa valley, Limpopo Province, South Africa



Source: Chiron D, 2005

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Table of contents

Introduction	1
I] Context	2
1) <i>Problem Statement</i>	2
2) <i>The Mochlapitse river basin</i>	2
II] Land use study	4
1) <i>Step proposed</i>	4
2) <i>Method and data</i>	4
a - Data processing	4
b - Processing accuracy	5
3) <i>Results</i>	6
III] Mochlapitse river hydrological functioning	8
1) <i>Method and data</i>	8
a - Model description	8
b - Data inventory	10
c - Data quality	11
d - Data processing	13
2) <i>Model application</i>	14
3) <i>Results</i>	16
IV] Results analysis	19
Concluding remarks	21
Bibliography	23
Appendix	24

Table of Frames and Tables:

<i>Table 1: Land use evolution in the Ga Mampa valley</i>	7
<i>Table 2: Location of rainfall stations</i>	10
<i>Table 3: Availability of rainfall data</i>	10
<i>Table 4: Location of the gauging stations</i>	11
<i>Table 5: Availability of flow data</i>	11
<i>Table 6: Available rainfall data for the studied period</i>	13
<i>Table 7: Simulation of watershed flow (in mm) by the three models of watershed behavior, using the same precipitation time series P</i>	16
<i>Table 8: Cross-simulation matrix gathering the results of flows simulations for three models (M1 – M3) successively using three precipitation series (P1 – P4)</i>	16

Table of Figures:

<i>Figure 1: Path-Row reference</i>	4
<i>Figure 2: Satellite image of the 169/077 area, July 1996, bands 1 to 5 and 7</i>	4
<i>Figure 3: Class Domain</i>	4
<i>Figure 4: Sample set creation</i>	4
<i>Figure 5: Rainfall stations</i>	10
<i>Figure 6: Gauging stations map</i>	11
<i>Figure 7: Best adjustment criteria obtained for each calibration</i>	16
<i>Figure 8: Cross-simulation matrix for visual interpretation (mm of runoff)</i>	17
<i>Figure 9: Recording of cross-simulation matrix of drainage coefficient</i>	17

Table of Maps:

<i>Map 1: Hydrography of the Mohlapitse river</i>	2
<i>Map 2: Passage from the classified picture to the smoothed picture</i>	5
<i>Map 3: Passage from the classified picture to the smoothed picture</i>	5
<i>Map 4: Ga Mampa valley land use evolution, 1996</i>	6
<i>Map 5: Ga Mampa valley land use evolution, 1998</i>	6
<i>Map 6: Ga Mampa valley land use evolution, 2001</i>	6
<i>Map 7: Ga Mampa valley land use evolution, 2004</i>	6

Table of Charts:

<i>Chart 1: data continuity analysis by the simple mass method</i>	11
<i>Chart 2: Rainfall sums on 2 years in relation with altitude</i>	12
<i>Chart 3: Flow data as a function of time. 1970-2005</i>	13
<i>Chart 4: Rainfall data as a function of time. 1970-2005</i>	13
<i>Chart 5: ordered flows corresponding to the 1999-2005 precipitations, simulated for each model</i>	17
<i>Chart 6: same ordered flows (M1, M2 and M3 for P3) for high flows (first third)</i>	18
<i>Chart 7: same ordered flows for low flows (last third)</i>	18

Acronyms

ARC: Agricultural Research Council
CEMAGREF: Centre National du Machinisme Agricole, du Génie Rural, des Eaux et Forêts
CNEARC: Centre National d'Etudes Agronomiques en Régions Chaudes
CPWF: Challenge Program on Water and Food
CSIR: Council for Scientific and Industrial Research
DEM: Digital Elevation Model
DWAF: Department of Water Affairs and Forestry
ENSAR: Ecole Nationale Supérieure Agronomique de Rennes
ETM: Enhanced Thematic Mapper
ETP: EvapoTranspiration Potentielle (Potential EvapoTranspiration)
FSP: Food Stamp Program
GIS: Geographical Information System
GR4j: modèle du Génie Rural à 4 paramètres Journalier
GRET: Groupe de Recherche et d'Echanges
ILWIS: Integrated Land and Water Information System
INPG : Institut National Polytechnique de Grenoble
IWMI: International Water Management Institute
RHP: River Health Programme
SAAAC: South African Atlas of Agrohydrology and Climatology
WR90: Water Resources 1990 dataset
WRC: Water Research Commission

Introduction

For many years the effort to overcome water shortages in South Africa has resulted in some farmers utilizing wetlands for crop production. These wetlands are attractive units because of their rich soils and year round soil moisture, which is favourable for crops during both the “normal” dry season and the years of drought. However, wetlands serve many functions that are beneficial to the environment and to humans, and if used unwisely these benefits will disappear (Morardet S, Koukou-Tchamba A, 2004).

Wetlands are among the most threatened aquatic habitats in South Africa, with estimates of up to 50% having been lost countrywide. On-going threats to wetlands include human activities such as canalisation, drainage, crop production, effluent disposal and water abstraction. Loss of wetlands reduces biodiversity as the plants and animals that are adapted to wetland habitats are often unable to adapt to new environmental conditions, or to move to more suitable ones. Loss of harvestable resources also occurs when wetlands are lost. Reduction of water quality and flow regulation is a further consequence of loss of wetlands, and may result in greater extent or severity of flooding.

Of the more than 800 naturally occurring freshwater wetlands in South Africa, 14% have full protection within a national park, provincial nature reserve or wildlife sanctuary, while 4% are partially protected. South Africa currently has 16 wetlands designated as wetlands of international importance in accordance with the Ramsar Convention.¹

This paper is part of the Wetlands Project of the Challenge Program for Water and Food, and is based on the hypothesis that wetlands can be managed in a sustainable manner, achieving a balance between protection and agricultural production, thereby ensuring optimal use of wetlands (Morardet S, Koukou-Tchamba A, 2004). The focus of the study is facilitating sustainable wetland management and development by quantifying the effects of land use change (wetlands use) on the hydrological functioning of the river. In order to do so, satellite images were studied to analyse land use changes while a hydrological model, GR4j, was used to analyse changes in the hydrological function of the river. The last part of the report explores interactions between both, land use and hydrology, and concludes by answering the question: what is the link between wetland uses and hydrological river functioning?

¹ RHP- http://www.csir.co.za/rhp/state_of_rivers/state_of_crocsabieolif_01/Info_wetlands.html



- Mohlapitse river basin limit
- Temporary rivers
- Rivers
- Small scale irrigation schemes
- Untarred road
- Villages
- Culminant points
- Natural reserves

Mohlapitse river basin area: +/- 490 km²
 Length of the Mohlapitse river: +/- 50 km
 Few permanent tributaries
 Wetlands area: +/- 49 ha
 Elevation: from 675 m to 2050 m
 Mean annual precipitation: 630 mm

Source: Chiron D. 2005

Map 1: Hydrography of the Mohlapitse river

I] Context

1) *Problem Statement*

The International Water Management Institute (IWMI) is a non-profit, scientific research organization specializing in water use in agriculture and integrated management of water and land resources. IWMI works with partners in the South to develop tools and methods to help these countries eradicate poverty and ensure food security through more effective management of their water and land resources.

The *Challenge Program for Water and Food (CPWF)* is a partnership between national and international research institutes, NGOs and river basin communities. Its goal is to identify and encourage practices and institutional strategies that improve water productivity – or to grow more food with less water.

This report is part of the *Sustainable Management of Wetlands in Southern Africa for Poverty Alleviation* project, part of the CPWF. This project aims to address the lack of scientific data needed to provide ecologically sound options for wetland-based livelihood strategies in southern Africa. An initial inventory of wetland resources in three countries will be made, followed by detailed hydrologic, agronomic, biophysical, socio-economic, and institution investigations at representative sites.

2) *The Mohlapiitse river basin*

The Mohlapiitse River basin covers 490km² mainly composed of the Mohlapiitse River (50km long), bushveld in the mountains and cultivation in the valley (Chiron D, 2005). The Mohlapiitse River descends from an elevation of 2050m above sea level to 675m at the gabion dam of Fertilis, 3/5 of the way through its run. From this point, the slope average is around 0,6% down to the Olifants River confluence. Some 3 to 5 permanent tributaries are connected to the Mohlapiitse River and 10 to 15 small-scale irrigation schemes use the water of these rivers.

The river runs quickly to the end of the abrupt mountains then flowing in a sinuous, stony riverbed from the north to the south. The minimum width of the riverbed ranges from 10 to 30 m and with a maximum of 50m to 100m at the natural wetland level (cf. Appendix 1). At the downstream Ga Mampa area, there is a gully mountain, which likely has hydrological consequences. In fact, the gully section reduces the water flow and allows the stony riverbed to recharge itself with water while the upstream aquifer grows quickly during the rainy season (cf. Map 1).

The Ga Mampa Valley history can be told in five main steps (Chiron D, 2005):

The local population of the Ga Mampa Valley lived near the river and practiced rain fed agriculture (sorghum). At the beginning of the 20th century, white farmers came and evicted the local population leaving the valley under cultivation by white farmers up to 1959. The local population took refuge in the mountains and provided labour for the white farms.

In 1964, the government created natural reserves in the mountains while the local population returned to the river that the white farmers had left. During the 1960s, the natural wetland covered an area downstream of Fertilis and Valis of more than 90 ha. Irrigated agriculture dominated and rain fed (wetland access) production was rare in the

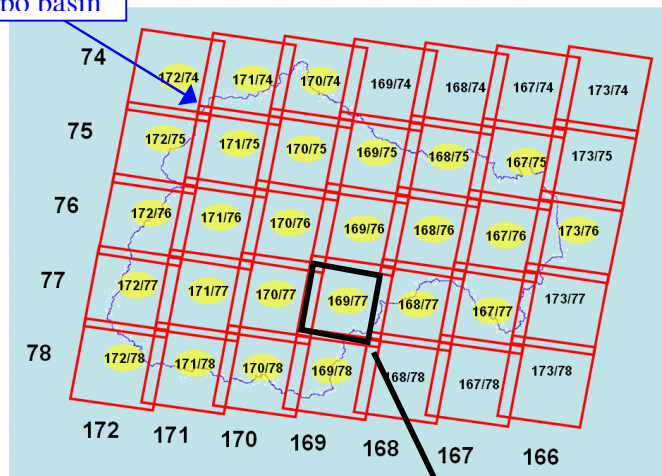
valley. The Fertilis irrigation scheme grew by 10 more farmers with an area of 92 ha. At this point, farmers began occupying the natural wetland at Fertilis and Vallis downstream.

In 1994, with the end of the apartheid era and the dawn of new political programmes, civil servants responsible for the irrigation scheme retired or were removed (cf. Appendix 2). The government decided to transfer the irrigation management to the black community. However, most of the Ga Mampa citizens were unaware that they had to manage the irrigation scheme by themselves. The irrigation management was transferred to farmers too quickly which resulted in the decline of the irrigation scheme including deterioration of hydraulic equipment. This combined with decreasing water supply, stray animals, difficulties organizing farmers, and the 1995 flood, caused some farmers to discontinue winter crop production while others opted to cultivate the wetland. This 'migration' corresponds to the first significant wetland conquest in the mid 1990s. As a result, fallow land area has increased inside the irrigation scheme while part of the wetland was transformed into cultivated land. At the end of the 1990s, the natural wetland had been reduced by a quarter with about 70ha of wetland remaining.

In 1999, a local Extension Officer found funds to build a gabion weir for the Fertilis and Mashushu irrigation schemes. Farmers participated by providing the stones, but these dams were destroyed by the 2000 flood. The 2001 season was a bad one for farmers and with a similar fate in 2002 most farmers lost money. Following these bad years, farmers asked the wetland committee for plots in the wetland signaling the second natural wetland conquest.

In 2004, the wetland was divided into two parts: 1) the remaining natural wetland; and 2) the cultivated wetland. More than half of cultivated area is devoted to coriander production during the winter and maize during the summer (cf. Appendix 3,4,5 and 6).

Limpono basin



Band 1: 0.45 - 0.52 μm (blue)
 Band 2: 0.52 - 0.60 μm (green)
 Band 3: 0.63 - 0.69 μm (red)
 Band 4: 0.76 - 0.90 μm (near infrared)
 Band 5: 1.55 - 1.75 μm (mid-infrared)
 Band 7: 2.08 - 2.35 μm (sw-infrared)
 Band 6: 10.4 - 12.5 μm (thermal infrared)
 Band 8: 0.52 - 0.90 μm (panchromatic)

R 4 (NIR)
 G 3 (Red)
 B 2 (Green)

Source: IWMI-data storehouse pathway

Figure 1: Path-Row reference

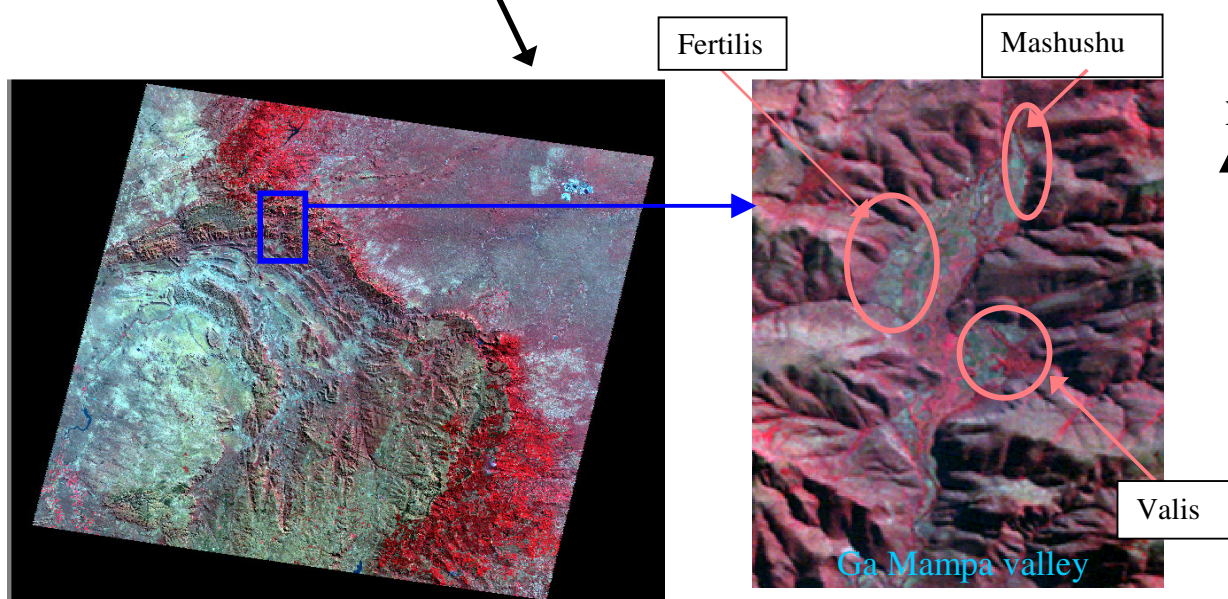


Figure 2: Satellite image of the 169/077 area, July 1996, bands 1 to 5 and 7

Source: DWAF

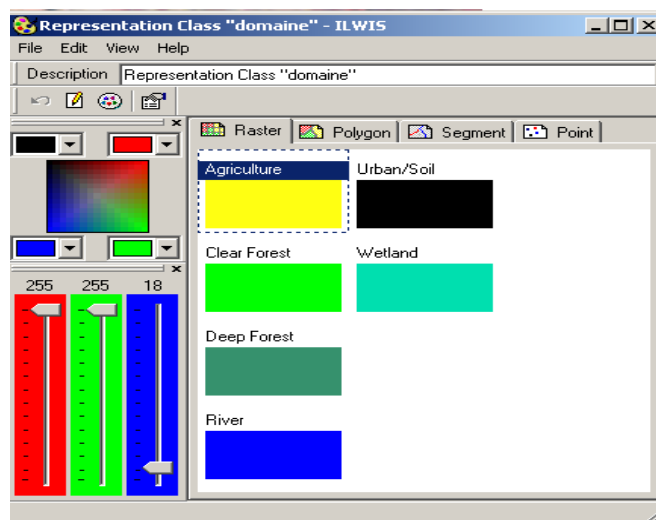


Figure 3: Class Domain

Source: ILWIS

II] Land use changes study

1) *Step proposed*

The purpose of this study is to quantify—or at least observe—changes in wetland use. Various satellites images will be processed in order to identify six classes of land use based on the visual characteristics of each area. A five-day field study will then validate the land use categories of each area. The resultant characterization or zoning will be used to generalize about land use in all the satellite images, followed by a comparative, longitudinal analysis of Ga Mampa Valley land use.

2) *Methods and data*

DWAF has provided seven Landsat 7 ETM satellite images of the 169/077 area (cf. Figure1). Only dry season images will be utilized because most available data are from that season. Satellite images from the following dates are available:

- 2 July 1996,
- 8 July 1998,
- 10 September 2001,
- 24 July 2004.

a- **Data processing**

For each photo the first step is to combine the six bands with ILWIS software, (cf. Figure2). The resulting images are “classified” in comparison to a “sample set”. The sample set consists of “domain” which is a list of classes with their name, their symbol and their colour (cf. Figure3). The next step is to locate the domain directly on the satellite image by selecting pixels on the image that correspond exactly with land cover for example, forest or river (cf. Figure4).

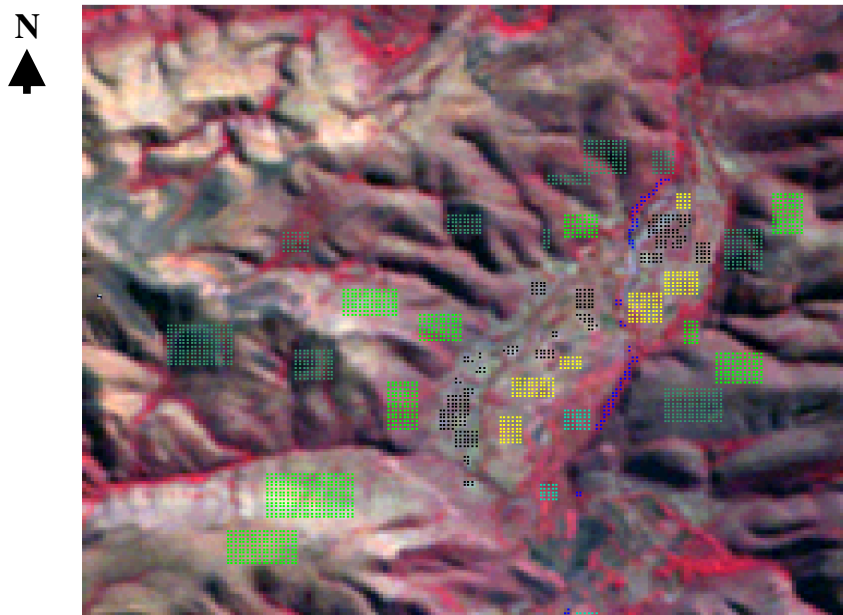
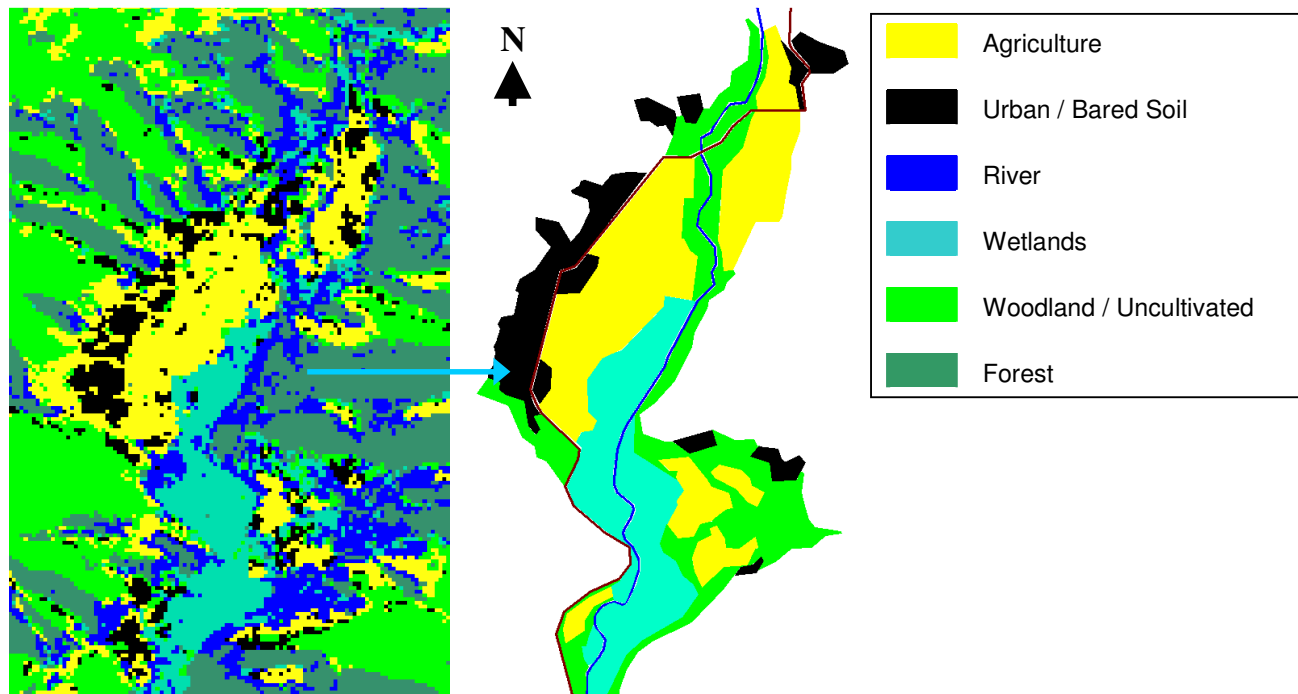


Figure 4: Sample set creation

This method is useful as it creates a new sample set for each photo, providing greater precision. Indeed, from one image to another pixel colour can change, indicating a change in class of land use.

The image is then classified by the software, which calculates—for each pixel and according to its characteristics—its most likely class. The six chosen classes are generalized to the entire satellite image (cf. Map 2). Images are then “smoothed” with Map info for questions of legibility (cf. Map 3).

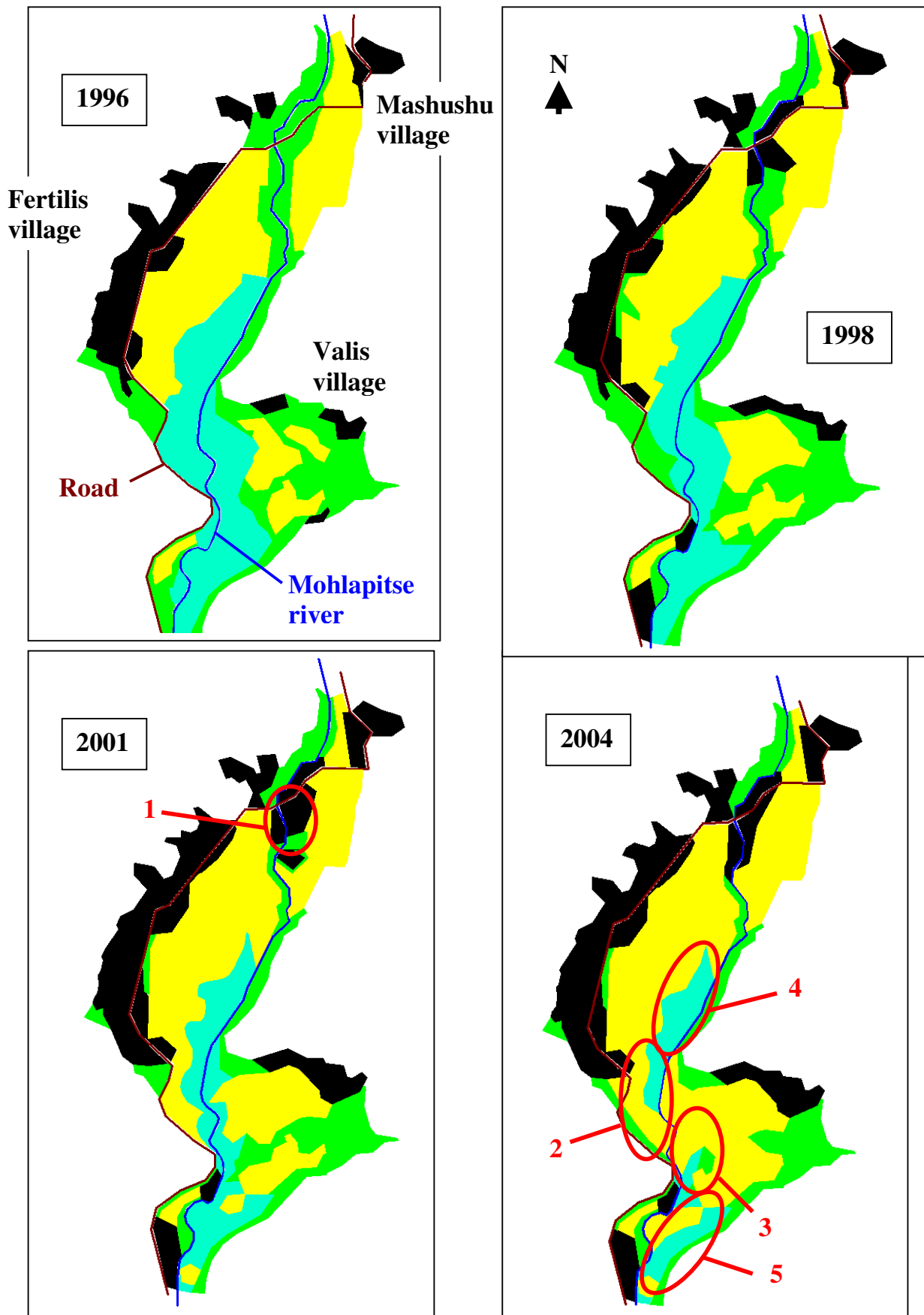


Maps 2 and 3: Passage from the classified picture to the smoothed picture

The smoothed map of 1996 was created from the classified satellite image along with the topographical map of 1997. Indeed, the topographical map indicates the precise delineation of wetlands, rivers, and cultivated and urban areas, a good place to start. The other maps are created from the corresponding classified satellite image as well, but starting with the smoothed anterior picture (1998 map creation started with the 1996 smoothed map) in order to keep coherence and uniformity in the land use evolution.

b- Processing accuracy

The fieldwork was used to confirm geographical coordinates of different land use in order to do a precision test on the classified picture of July 24, 2004. The coordinates for thirty-nine points near Fertilis have been classified (forest, river, wetland). Researchers superposed these points on the classified image and verified that the class of these points corresponded to the classified image. Test results were precise to 82%, a good result considering the GPS precision (10 meters) and the pixel size.



Maps 4,5,6 and 7: Ga Mampa valley land use evolution

3) *Results*

Maps 4, 5, 6, and 7 are the outputs of processing the satellite images. These maps are quite accurate if not quite exact, and allow for useful study of land use change.

Some clarification is needed. Because the slopes are very steep and mountain areas have always been covered by a wild forest, only the valley areas are shown on the final maps.

Areas in black are urban or bare soil areas. Zone **1**, for example, is an area of abandoned soil that has slowly increased with time, but with some parts recuperated for agriculture since 2004. This area is also the riverbed. Indeed, in some very dry years, the drained riverbed (composed of white rocks) seems like a bare soil too. The woodland/uncultivated classification corresponds to wild vegetation such as abandoned cultivation, uncultivated field, scattered forest, downs, etc.

It was complicated to separate agriculture classification in two parts: permanent and temporary. Indeed researchers found that in some cases both classes corresponded to the same pixel, or got muddled with completely different classes such as forest. Therefore it was more relevant to keep just one class for agriculture.

Wetlands areas are very specific and clearly demarcated, so they are represented the most precisely.






The river is very narrow, so, the corresponding classification often includes the vegetation of the streambanks as well as the stream itself. The topographical map permitted exact position of the river (the bed of which did not move during the study period) and deduction of vegetation areas on the riverbanks.

So, what can we see?

- Slight enlargement of the urban/bare soil area,
- Reduction of the wild vegetation tract,
- Augmentation of the agricultural surfaces,
- Progressive disappearance of the wetlands (zones **2** and **3**), mostly converted to commercial agriculture.

These trends correspond to changes over time in the local livelihoods according to historical accounts. Some irrigation schemes have been abandoned, which explains the appearance of bare soils or of uncultivated areas in old abandoned agricultural areas, as well as the appearance of cultivation in wetlands. It is also to be expected that urban areas increase slightly in size and that wild vegetation areas disappear in favour of settlements and agriculture.

In order to quantify these changes it is possible to determine, by Map info, the created polygons surface area. Even if it is not a perfect fit, surfaces indicated on Table 1 are close enough to the observed to appreciate global land use surface evolution.

Legend	
	Agriculture
	Urban / Soil
	River
	Wetlands
	Woodland / Uncultivated

	1996	1998	2001	2004	Trend
Wetlands	0.90	0.82	0.66	0.43	-
Agriculture	1.82	1.87	2.16	2.51	+
Urban/bare soil	0.95	1.13	1.36	1.36	+
Woodland/uncultivated	1.43	1.28	0.92	0.80	-
Total	5.10	5.10	5.10	5.10	

Table 1: Land use evolution in the Ga Mampa valley

The surface area accounted for in this table (5.10 km²) is only the zone represented on the final maps. This zone is where most of the land use changes have taken place, while the other areas where change could have been happened are either very small or have evolved in a similar way.

The most striking change shown by this table is the reduction of half of the wetland areas and the corresponding increase for agriculture. The most worrisome is not necessarily the quantity of disappearing wetlands but what they become. Some areas, as in zone **3**, have not maintained even a small strip of wetland alongside the stream, suggesting that agriculture has encroached on the banks of the river. Except in zone 4, the river is totally deprived of its wetlands. As wetlands capture and prevent a good deal of pollution from entering the river, these functions are seriously reduced if not completely missing. It is reasonable then to expect significant increases in the quantity of pollution entering the river.

The slight decrease in woodland areas also deserves attention. If current trends continue, (nearly 3/5 of the area is already agriculture or urban), Ga Mampa Valley will soon be exclusively agricultural and urban areas. This would mean greatly reduced infiltration because even though mountain areas might stay forested, the abrupt slopes limit infiltration. The majority of rainfall would be lost as run off into the stream and not kept on the valley floor.

The results show that today, wetland areas 4 and 5 do not touch each other. This is of great concern because wetlands are crucial ecological niches and their reduction to many little blocks could promote the loss of species that require larger habitat. Not only is wetland loss a concern, but so too fragmentation of persisting stands.

III] Mohlapitse river hydrological functioning

The purpose of this study was to quantify the impact of changes in the wetlands (i.e., from natural to cultivated) on the hydrology of the river. The history of the valley provides three study periods:

- 1970/1990: natural wetlands, active irrigation schemes,
- 1990/2000: transition,
- 2000/2005: cultivated wetlands, unserviceable irrigation schemes.

The GR4j rainfall-runoff model was used to evaluate the change in hydrological functioning between each time period. The model was calibrated separately for each period and then run using the actual rainfall of the two other periods in order to assess the impact of land-use changes. The difference between the simulated flows and the actual observed flows for each period might be interpreted, among other possible reasons, as a consequence of land use change.

1) Method and data

a- Model description

The model used was GR4j, (modèle du Génie Rural à 4 paramètres Journaliers) developed by Nasciemento (1995) and modified by Edijanto and al (1999). It is a rainfall-runoff model with few parameters, developed for utilisation on scarce data catchments.

Nasciemento (1995) version description of the GR4j model is presented here, followed by the Edijatno *and al.* (1999) modifications.

- Rainfall interception:

Rainfall falling on the catchment undergoes potential evapotranspiration ETP (cf. Appendix 7). Net rainfall, P_n is determined by:

- if $P \geq E$ then $P_n = P - E$ and $E_n = 0$
 - if $P < E$ then $P_n = 0$ and $E_n = E - P$
- With E_n , net evapotranspiration

- Soil reservoir:

If net rainfall is greater than zero (i.e., $dP_n > 0$), the part that goes to the soil reservoir is dP_s and the other part dP_n is conveyed towards the outlet:

$$\begin{aligned} dP_n &= (S/A)^2 \cdot dP_n \\ dP_s &= [1 - (S/A)^2] \cdot dP_n \end{aligned}$$

Where S is the level in the soil reservoir and A the maxim capacity of this reservoir. The soil reservoir level variation is $dS = dP_s$ and the level is updated following:

$$S_{t+1} = \frac{S_k + \tanh(P_n / A)}{1 + (S_k / A) \cdot \tanh(P_n / A)}$$

If all the rainfall is lost through evaporation, the rest E_n of ETP is used to evaporate the water contained in the soil reservoir, at a rate, which is a function of the level in the soil reservoir.

- Separation of the drainage components:

Rainfall is separated into two parts. A pseudo-direct drain is routed directly to the river via a unit hydrograph and represents 10 % of the effective rainfall; the other part of the effective rainfall (90 %) is routed by a unit hydrograph and a routing reservoir.

- Unit hydrograph:

The two drainage components experience a progressive delay through the action of the unit hydrograph, which enables simulation of the rising limb of the hydrograph. A base-length C characterizes these hydrographs. The drain, which conveys the routing via the reservoir, is further retarded by a function $UH1$.

- Routing reservoir:

After it has been retarded by the unit hydrograph the principal drainage component is conveyed to the stream via a non-linear routing reservoir.

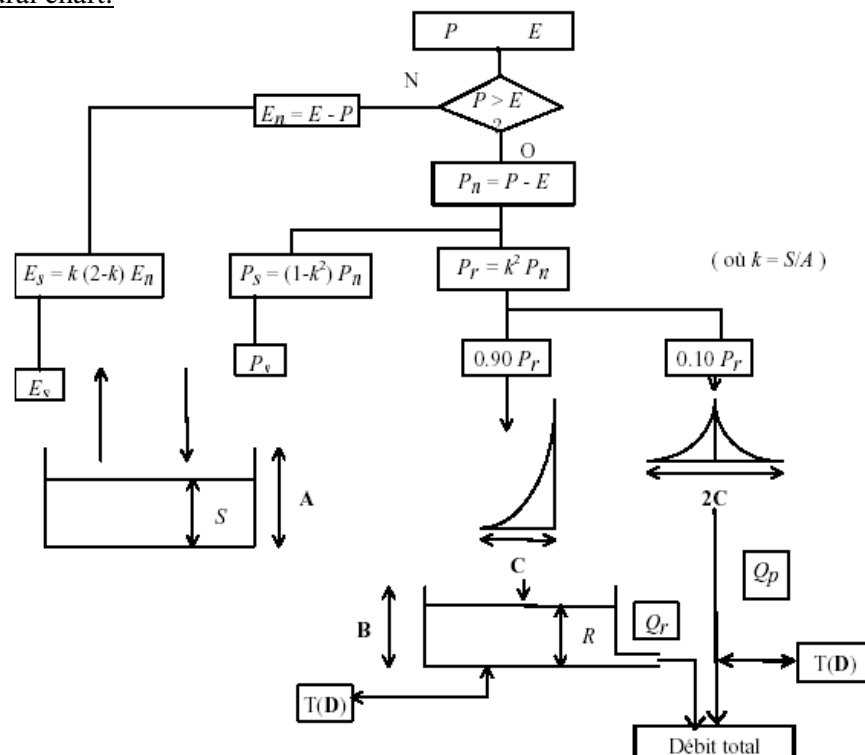
- Pseudo direct drain:

After it has been retarded by the unit hydrograph the pseudo-direct drainage component arrives directly at the catchment outlet.

- Deep drainage:

One term T enables simulation of deep infiltration to underground water.

Structural chart:



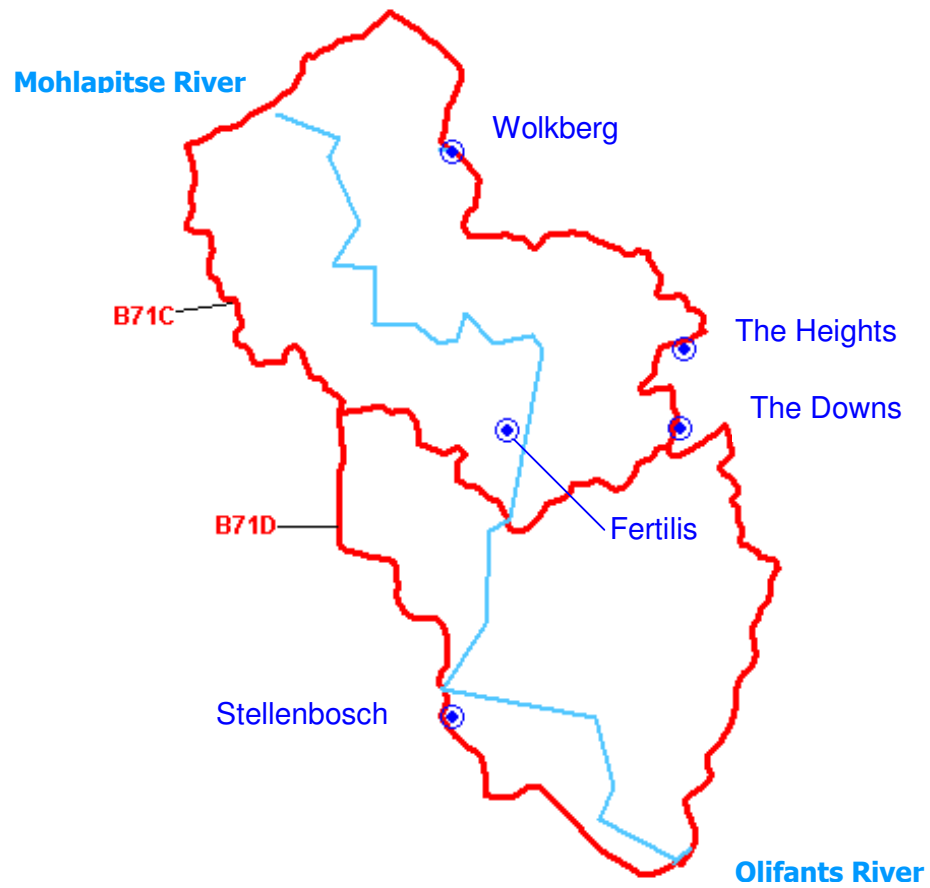


Figure 5: Rainfall stations

Source: McCartney & all, 2004

Parameters:

Three or four parameters are optimised:

- A: reservoir maximum capacity of production
- B: reservoir maximum capacity of routing
- C: unit hydrograph duration
- D: deep drainage parameter

Optimisation technique of parameters:

Local optimisation method 'pas-à-pas' = "stepwise" (Michel, 1989; Nascimento, 1995)

Data:

Rainfall and ETP data as input (ETP Penman for example); discharge time series are necessary for setting the model parameters.

Time step:

This model has been developed with a daily time step. Other models of the GR family are adapted for hourly, monthly and yearly time steps.

b- Data inventory

Rainfall

There are five rainfall stations on the Mafefe basin for which daily rainfall data are available (in millimeters) (Table 2; Table 3):

Station number	Station name	Coordinates (degree decimal)		Altitude (m)
		South	East	
0635873	Wolkberg	24.02	30.08	1580
0636135	Stellenbosch	24.25	30.08	795
0636157	Fertilis	24.13	30.10	780
0636276	The Heights	24.10	30.18	1250
0636308	The Downs	24.13	30.18	1350

Table 2: Location of rainfall stations

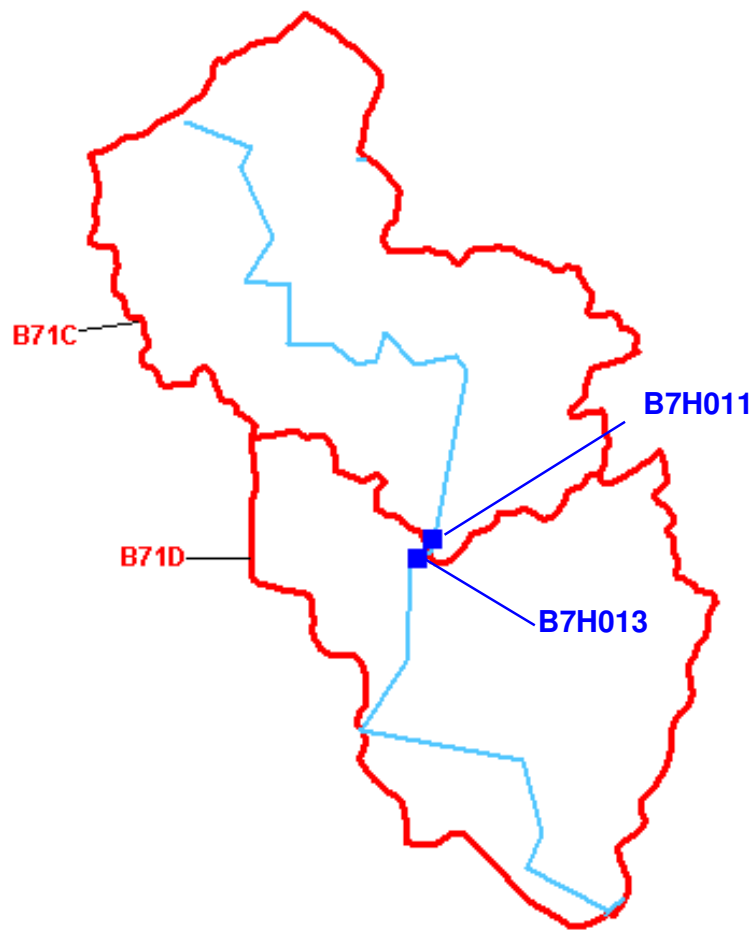
Source: DWAF

station	1913	1930	1946	1950	1959	1971	1973	1989	2005
Wolk									
Stellen									
Fertilis									
Heights									
Downs									



Source: South African weather service

Table3 : Availability of rainfall data



Source: McCartney & all, 2004

Figure 6: Gauging stations map

Flow

There is currently one gauging station on the Mohlaitse River, downstream of the wetland. A second gauging station, located very close to the first operated in the past (Table 4; Figure 6). Stream discharge daily data (in cubic meters per seconds) are available:

Station number	Coordinates		Altitude (m)	Basin surface area (km ²)
	South	East		
B7H011	24.1642	30.1058	750	263
B7H013	24.1731	30.1031	760	263

Table 4: Location of the gauging station

Source: DWAF

station	63/64				70/71				80/81				90/91				00/01			
B7H011																				
B7H013																				

complete year

incomplete year

Source: Department of Water Affairs and Forestry

Source: Department of Water Affairs and Forestry

Table 5: Availability of flow data

Evapotranspiration

A complete time series of daily evapotranspiration data for 2004 was available from measurements made at the Polokwane meteorological station. However, as this is located 80 km of the Ga Mampa valley, mean monthly values were calculated using the data time series available, from the SAAAC. These evapotranspiration data are Penman Monteith evapotranspiration, calculated using the approach outlined in FAO56 formula data.

c- Data quality

Rainfall

The simple mass graph represents the calculated rainfall for each station as a function of time. It permits visual assessment of discontinuities in the time series. Such discontinuities may be a consequence of human error or a change or breakdown in the equipment.

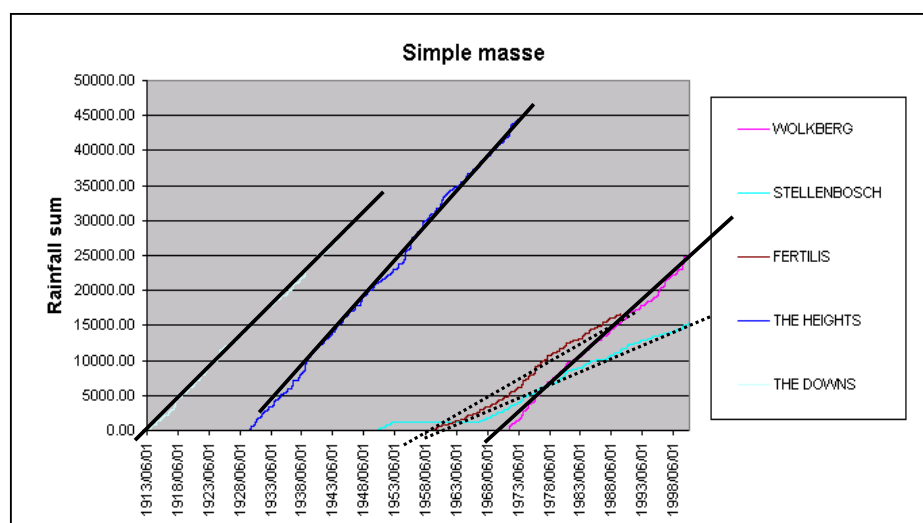
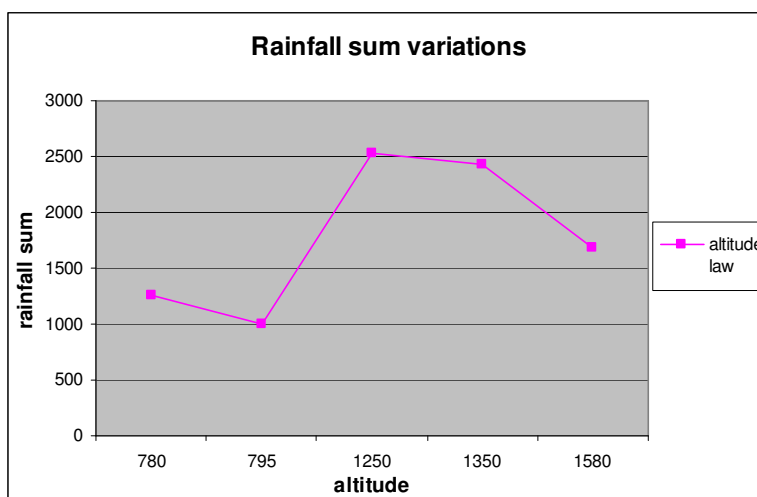


Chart 1: data continuity analysis by the simple mass method

Stellenboch and Fertilis are both located in the valley, where rainfall is typically lower than at higher elevations. This is represented by a smooth slope. The other stations have the same kind of evolution during the study.

Representativeness of each rain gauge

Chart 2: Rainfall sums on 2 years in relation with altitude



It is understandable that the two stations located in the valley have lower values than those located at higher elevations. The apparent drop in total rainfall at the highest gauge may be caused by the fact that it is more exposed to wind.

Flow

Flow measurements are made daily at gauging station B7H013, using an automatic, recorder located in a cabin 20 meters upslope of the riverbank. The meter is read every 2 weeks. According to the DWAF, the data's accuracy is 5% and 10% for flows higher than 0.5 m³/s. The higher the flows, the less accurate the data. It may be that in case of high flows, the weir fills up, creating waves which distort the results. At very high flows, water overtops the station and the stage-discharge relationship becomes invalid. The station was constructed in 1970, so no data are available prior to this date.

There is another gauging station, B7H011, 2 kilometres upstream of B7H013, with very different data values. According to the DWAF, the B7H011 station data should not be used in a hydrological study. This station is a submersible road so all low flow values are erroneous and furthermore the rating curve is believed to be very inaccurate. Consequently only data from the station B7H013 was used in the current study.

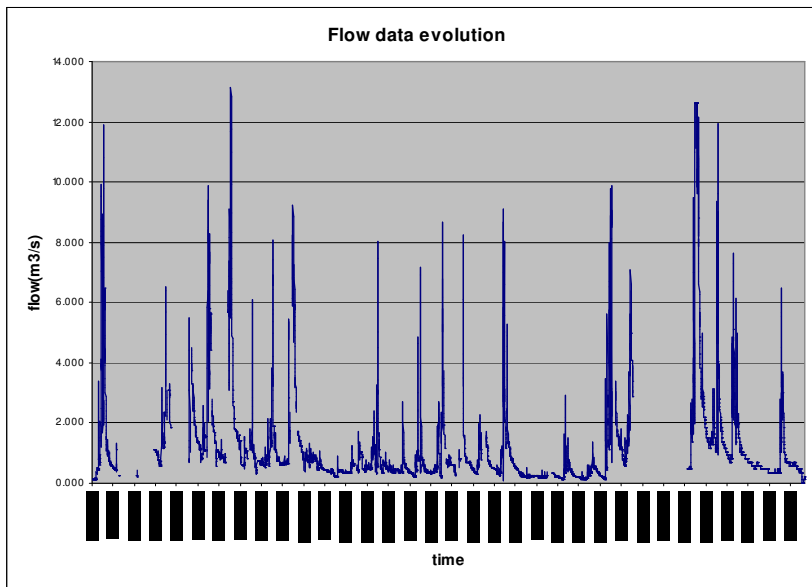
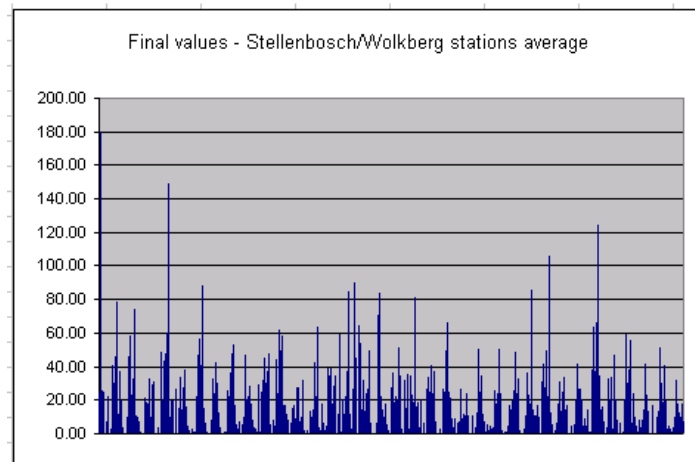


Chart 3: Flow data as a function of time. 1970-2005

Chart 4: Rainfall data as a function of time. 1970-2005



At first glance, there are no climatic trends visible on these charts. But do we have a period long enough to see that phenomenon?

d- Data processing

Rainfall

Station	1971	1973	1989	2005
Wolkberg				
Stellenbosch				
Fertilis				
The Heights				
The Downs				

Table 6: Available rainfall data for the studied period

Flow data are available for the period 1970 to April 2005. Only the Stellenbosch and Wolkberg rainfall stations have data covering this entire period. The simple mass plots show the same evolution for all the rainfall stations. Hence we can fill gaps in Stellenbosch record using data from the other stations. Stellenbosch is located in the valley and Wolkberg in the mountain. After trying different combinations with all available rain gauges, it was found that the average of Stellenbosch and Wolberg values is the closest to the monthly median values we have for the area (SAAAC). It also transpired that it is the one for which the model performance was best (i.e., based on Nash efficiency criteria).

Evapotranspiration

Daily data from the Polokwane meteorological station for 2004 were multiplied by a coefficient so that they correspond to the monthly data values of the SAAAC, which are more representatives for the study period. A different coefficient was used for each month. So, ARC values provided daily variation and the average monthly data provided the representative values for the whole catchment. In the model, because there is no time series, the same daily evapotranspiration values were used for each year. This is possible because, in vivo, evapotranspiration doesn't change significantly from year to year.

Flow

These data didn't require processing since there was no need to fill the gaps in the time series, because they were used for model calibration only. Missing data are indicated in the model by a negative value.

2) Model application

Three study periods: 1970-1990, 1990-2000 and 2000-2005 were investigated. For each one, a calibration period was selected. The period was selected knowing that the shorter it was the more precise the model would be (because of stability in land use change), that the longer it was the more representative it would be of the basin hydrological functioning during that period. Periods were also selected to minimise data gaps.

The simulation period selected were:

- 01/10/1974 – 30/09/1980,
- 01/10/1990 – 30/09/1996,
- 01/10/1999 – 13/04/2005.

The fact that the period 1999-2005 begins on a period of rising flow was not a problem because the first year of each calibration period is not taken into account for analysing the performance of the model since it is used by the model as a “warm-up” period.

The method consisted of calibrating a “before-variation” version of the model and using it as a virtual control watershed, along with observed rainfall, to reconstitute runoff after changes in land-use, assuming that there was no change in the watershed behavior between the first and the second period. Impacts of land-use change were then deduced by comparing the simulated and observed flows, with the hypothesis that the model fully captures the basin behavior under the conditions of the first time period. A review of such methods is given by Refsgaard et al., 1989 and Lørup et al., 1998. (Andreassian, V. et al., 2003)

The model parameters were calibrated for each period using the rainfall, the mean evapotranspiration and the observed flow as daily input data. Since the model operates on a daily time step, it was necessary not to delete data. Missing flow data were indicated by a negative value and so not taken into account in the calculations of model fit, although simulated flows model the gaps.

In addition to rainfall, evapotranspiration and flow, initial input data are:

- Basin surface area,
- The 4 parameters X1 to X4,
- Initial filling rates of the two reservoirs.

The model depends on the four calibrated parameters, which account for water balance (X1, capacity of production store; X2, water exchange coefficient) and water transfer (X3, capacity of the nonlinear routing store; X4, unit hydrograph time base). The small number of parameters prevents problems of overparametrization.

The four model parameters enable the model to be adapted to the specific basin being studied. Each basin has his own set of parameters, which characterise its hydrological behaviour. At the start of the optimisation the same initial values were used. These were the mean values derived from a huge number of catchments (here, $X1=5.8$; $X2=0$; $X3=4.5$ and $X4=-0.2$). During the optimisation, these values evolved until optimum values, which represent the “best” parameters for the basin being studied (that is to say the parameters for which simulated flows most nearly compare with observed flows and the model error is minimised).

The initial filling rates of the two reservoirs ($S0/X1$ represent initial filling rates of the production reservoir, $R0/X3$ the initial filling rates of the routing reservoir, the rate being the level divided by the maximum capacity), is used for the first time step of the simulation. The simulation begins with an arbitrary water quantity in the basin. Because there is no way to determine, *a priori*, these initial values, default values are used (i.e. reservoirs being more filled in the wet season than in dry season). This misrecognition is a source of error for the simulation (named “initialisation error”). The initialisation error decreases with time so one year is left as a “start-up” period for the model. During this first year, model errors are not taken in account (errors sum for best fitting of the model begins only after this first “start-up” year).

When all the input data have been entered the four parameters are optimised. This means finding the “best” parameter set so that the error between simulated and observed flow is minimised. To do this an excel solver was used, which optimise the parameters set using a number of different optimising criteria (i.e., Nash (Q), Nash (\sqrt{Q}) and Nash ($\ln(Q)$)). At the end of the optimisation, the parameter set is assumed to be the best possible for representing the catchment behavior.

Accuracy criteria indicate the extent to which a model is robust and precise. Figure 7 shows the accuracy criteria obtained for each calibration. According to the DWAF, the higher the flows, the weaker is the accuracy of the data. This explains why, for periods 1 and 2, the best model fit is indicated by Nash (\sqrt{Q}). This criterion is influenced most by the simulation of low flows in the model. Hence, if the low flows are simulated better, the model seems more precise if more emphasis is placed on these data. This is effectively the case for periods 1 and 2. Figure 7 shows that the 1990-1996 calibration is the worst and 1999-2005 is the best. So, during analyses of the results less emphasis was given to the results of period 2.

e-

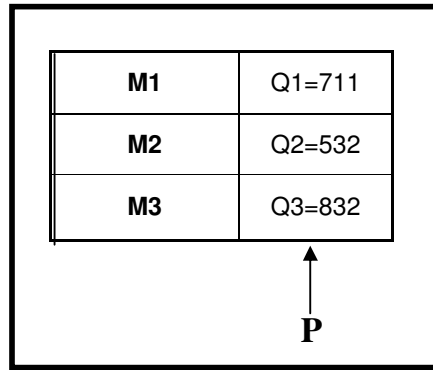


Table 7: Simulation of watershed flow (in mm) by the three models of watershed behavior, using the same precipitation time series P.

	P1	P2	P3
M1	711	504	493
M2	532	435	368
M3	832	616	588

Table 8: Cross-simulation matrix gathering the results of flows simulations for three models (M1 – M3) successively using three precipitation series (P1 – P3).

Critères d'efficacité (%)		1974-1980
Nash(Q)		54.1
Nash(VQ)		66.0
Nash(ln(Q))		63.9
Bilan		96.3

Critères d'efficacité (%)		1990-1996
Nash(Q)		46.8
Nash(VQ)		43.6
Nash(ln(Q))		27.0
Bilan		103.8

Critères d'efficacité (%)		1999-2005
Nash(Q)		80.2
Nash(VQ)		74.3
Nash(ln(Q))		56.5
Bilan		97.4

	Maximised criterion	
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Figure 7: Best adjudment criteria obtained for each calibration

3) Results

The approach adopted to analyse results was that described in “A new approach involving resampling of model simulations to assess trends in watershed behavior” (Andreasson et al., 2003).

1. Cross simulations as a basis for statistical testing

The method works in three steps:

1. The period of study is divided into n successive periods of equal length; each sufficiently long to enable proper calibration of the rainfall-runoff model. In the current study, 1970-2005 was the total period, with three subperiods, each of 5 (hydrological) years: 1974-1980, 1990-1996 and 1999-2005. Calibration of the GR4j model provided three successive models of watershed behavior (i.e., defined by three different parameters sets): M1, M2 and M3.
2. Observed rainfall time series are then used as input to the model in conjunction with the three optimised parameter sets to obtain the corresponding total streamflows simulated by the three models of watershed behavior (cf. Table 7 as an example). Note that direct comparisons of these model outputs are possible because they have been simulated with the same precipitation time series as input.
3. This operation can be repeated as long as independent precipitation time series are available, and the results can be displayed in matrix form. The more rows in the matrix, the more exhaustive the description of watershed behavior. In the current study a 3x3 square matrix was obtained (cf. Table 8), since the time series that were used for calibration were also used as precipitation input in the analysis of impacts. In this “cross-simulation matrix” in each cell (i, j) comprises the total streamflow simulated with the model Mj (representative of watershed behavior during period j) using precipitation Pi.

2. Visual analysis of cross-simulation matrices

A great deal in information on possible changes can be gained visually, by simply transforming the cross-simulation matrix figures into signs (plus or minus). Remember that for each row of the matrix, flows can be compared since they were simulated with the same precipitation input. In each row, the value found on the matrix diagonal was taken as a reference value, i.e., the value simulated by model Mi using precipitation Pi (since Pi is used to calibrate Mi, the value Qi, i seems the most logical reference for the comparison).

Thus, in case of an apparent positive trend, Qi,j is replaced with a plus sign. This happens for $j < i$, if $Q_{i,j} < Q_{i,i}$; and for $j > i$, if $Q_{i,j} > Q_{i,i}$. In case of an apparent negative trend, Qi,j is replaced with a minus sign. This happens for $j < i$, if $Q_{i,j} > Q_{i,i}$; and for $j > i$, if $Q_{i,j} < Q_{i,i}$. If $Q_{i,j} = Q_{i,i}$, replace Qi,j is replaced with a letter O. An example of recoding is shown in Figure 8.

The same cross-simulation matrix approach was used for drainage coefficients ($\Sigma Q / \Sigma P * 100$). This coefficient represents the percentage of rainfall water ending up in the river (cf. Figure 9) and so provides insight into infiltration and evapotranspiration within the catchment.

Matrix (mm of runoff):

	P1	P2	P3
M1	711	504	493
M2	532	435	368
M3	832	616	588



Is recorded as:

	P1	P2	P3
M1	0	-	-
M2	-	0	-
M3	+	+	0

Figure 8: Cross-simulation matrix for visual interpretation (mm of runoff)

Matrix (drainage coefficient):

	P1	P2	P3
M1	24.7	19.8	20.6
M2	18.4	17.1	15.4
M3	28.8	24.2	24.6



Is recorded as:

	P1	P2	P3
M1	0	-	-
M2	-	0	-
M3	+	+	0

Figure 9: Recording of cross-simulation matrix of drainage coefficient ($\sum Q / \sum P * 100$)

Results indicate that periods 1 and 2 present similar behaviour (i.e. similar magnitude of fluxes). Period 3 is clearly very different. The cross-simulation matrix of the total flows and the cross-simulation matrix of the drainage coefficients have exactly the same trend. In both, the most recent period is the one for which the river has the highest flows. This means that, for the same amount of precipitation, the Mohlapitse river basin generates more rapid response runoff in 1999-2005 than in the previous periods. As a result a proportionately, large quantity of rainfall water ends up in the river in period 3 than in the other periods. This could be attributable to either less infiltration or less evapotranspiration or faster routing of flows within the catchments and the river drainage system during this period or both.

With model runs simulating flow using the same rainfall input series (e.g., P1) it would be anticipated that trends in flow and drainage coefficients, would evolve in the same direction over time (i.e. between the three periods). However, this is not the case. Example for P1:

- 711 → 532 → 832 mm (for total flows),
- 24.7 → 18.4 → 28.8 (for drainage coefficients).

Given that changes in flow are being attributed to changes in land cover within the wetland it would be expected that changes in the flow and drainage coefficients would trend in a single direction. The fact that this does not occur may be attributable to the poor model calibration derived in the second period (i.e. the poor Nash of the second period). Consequently the results are probably distorted. Remembering that period 2 is a period of transition between 1 and 3 and observing that period 2 results are very similar to the period 1 results (i.e. more similar than to period 3) it was decided to compare period 1 and 2 (together) against period 3.

It was of interest not only to know that total flow volumes are greater in period 3 but also which kind of flow (i.e. low flows or high flows) comprises the additional water. Chart 5 represents ordered simulated flows, using the 1999-2005 precipitation as input, for each model (M1, M2 and M3).

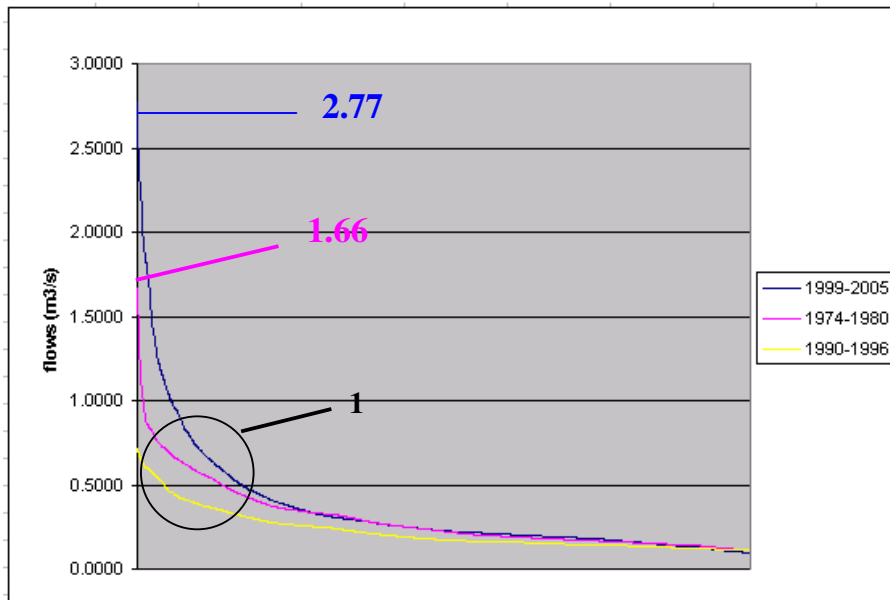


Chart 5: ordered flows corresponding to the 1999-2005 precipitations, simulated for each model

Starting from the hypothesis that the 1990-1996 calibration was too poor to represent reality it was decided to take account only of the periods 1974-1980 and 1999-2005. The graph then shows that the biggest differences in flow between the periods occur at high flows (cf. Chart 6). For example, for the same quantity of rainfall, the maximum flow generated in period 3 is 2.7708 m³/s while it was just 1.6650 m³/s in period 1. The graph also highlights a clear difference between the two curves (i.e. zone 1). The surface situated between the two curves represents, for the same precipitation, the difference in volume available for the river between period 1 and period 3. This difference occurs most particularly for high flows (i.e. greater than 0.4 m³/s). Although there is a difference between the two curves for low flows it is very small (cf. Chart 7). The minimum value for both periods is the same (0.10 m³/s).

Chart 6: same ordered flows (M1, M2 and M3 for P3) for high flows (first third)

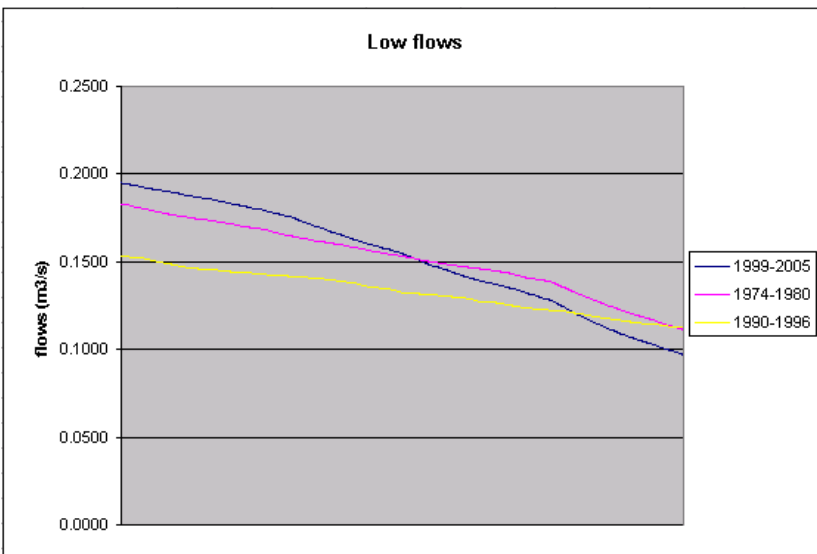
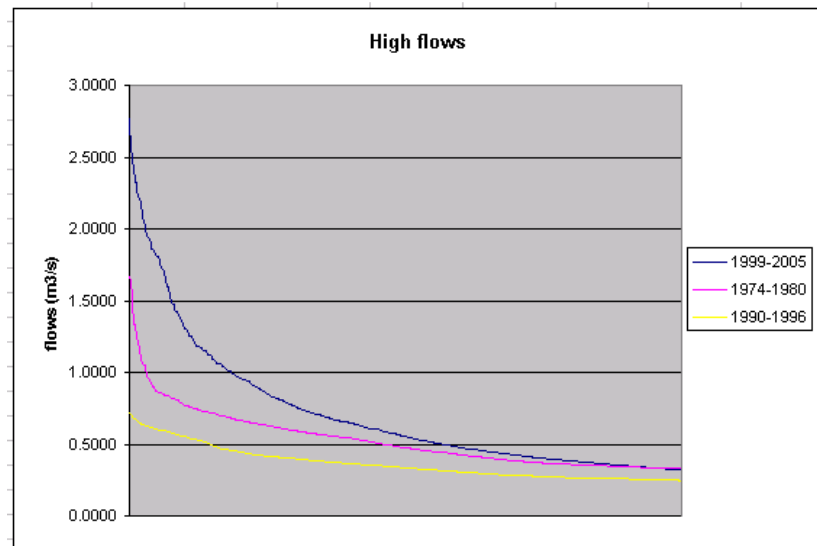


Chart 7: same ordered flows for low flows (last third)

IV] Results analysis

It has been shown (i.e. in the chapter II “Land use changes study”) that between 1996 and 2004, the Ga Mampa valley lost half of its wetlands. Often this loss occurred at very bad places like riverbanks. It is also apparent that agriculture is rising contrary to woodlands, which have decreased over time.

It has also been shown (i.e., in the chapter III “Mohlapitse river hydrological functioning”) that flows in the Mohlapitse river basin are greater now (i.e. 1999-2005) than they were in the past (i.e., 1974-1980); flows are higher and drainage coefficients have also increased. It is possible that this is a consequence of reduced evapotranspiration and/or lower infiltration within the catchment.

A common feature of many wetlands is that they reduce rapid runoff and store water. This often favours infiltration. Moreover, wetlands possess hydromorphic and endemic vegetation, which is very dense and, because water is readily available, this often promotes evapotranspiration. However, above all many wetlands are famous for their “sponge effect”, which means they keep water during high flows and so attenuate floods, and provide flow to rivers during dry periods and during droughts. This could be the reason why the Mohlapitse river has always been a very important tributary for the Olifants river during dry seasons.

Moreover, there is increasing need for more and more agricultural land and increasingly wetland area is being converted for agriculture. Often this involves draining the wetland soils with pipes and drainage channels, which lower the water table level and move the water more rapidly to the river.

If drained appropriately the land remains wet enough for agriculture but the wetland disappears. This phenomenon is clearly visible on the maps 4,5,6 and 7 presenting the land use change over time.

The hydrological modelling has shown that high flows have increased over time. Thus, it could be hypothesised that the decline in wetland area and the loss of the “sponge effect” could explain the increase in high flows.

Wetlands typically possess very dense vegetation that often grows *into* the stream. This vegetation acts like an obstacle to water drainage. In the first instance, this vegetation withholds water for its own consumption. Secondly, it slows water movement so providing greater time for infiltration and greater evaporation.

A decline in wetland area would imply a decrease in all the phenomena described previously and so would entail an increase in high flows, but also a decrease in low flows for disappearance of the “sponge effect” and the slow drainage of the sponge during the core of the dry season.

During high flow periods, there would not be wetland vegetation to retard runoff and to slow the speed of water movement. Wetlands loss would therefore equate to an increase in flows.

Benefits and limits of GR4j rainfall-runoff model

This study primarily comprised hydrological modelling. The GR4j model was used. The GR4j model was adapted for a first modeling exercise because it is very simple to use and requires only limited data inputs. The model runs using excel software and requires only four parameters to optimise. The model is however very robust. The only input data required are: precipitation, evapotranspiration mean values and observed flows.

However, because it is a simple model, there is limited possibility of adapting the model to specific catchments. The model had some problems reproducing the hydrological behavior of the study catchment (i.e., big differences between observed flows and simulated flows after the calibration especially for high flows because of the bad accuracy of the data). However, because no other models have been tried on this catchment (global conceptual or distributed), it is not possible to know if this problem is specific to the model or if it is the basin itself, which is difficult to model (e.g. because of data limitations). Nevertheless, it seems that, because of the lack of data, any other model could have been better so, the best results as possible have certainly been found in this study.

This first difficulty relates to the second, in that because the model errors are very high, determining trends in the watershed behavior is very difficult. Real changes (if they exist) may be of the same order of magnitude as the model simulation errors. The main intrinsic problem of the model (which is the same for all global conceptual models) is the difficulty of giving a physical interpretation to parameters. This makes the applicability of these models to non-gauged basins difficult (i.e., those which lack calibration data). Some researchers also think that the lack of spatial discretisation is a defect of global models, which limits their performance (Charles Perrin, personal communication).

Concluding remarks

In the case of this study, it would have been better to have more satellite images, especially old images. 1996 is almost certainly not far enough back in time for this study even if land use changes are mostly in the recent past.

The flow data contains too many gaps, some of which were for long periods of time. This could partly explain why the calibration in period 2, was not very successful. The 1999-2005 period represents the best optimisation period (i.e. as indicated by the Nash criterion) and is the period for which there are no gap on the flow data; 1990-1996 is the one which has most gaps and this is also the period with the worst Nash criterion. Furthermore, the rainfall data were also not continuous enough; in some records gaps of 1 year, occur. The more complete the data, the more precise the model is likely to be.

These constraints imply some improvements are possible to improve similar studies in the future. For the satellite processing chapter, it would be worthwhile to obtain satellite images regularly to be sure that studies will have complete data at regular time intervals and to do a very advanced research in order to find all archive data available and more precise pictures.

It is important that future studies use as complete rainfall data as possible. This requires greater analysis of rainfall patterns with altitude i.e., determine the best possible spatialization for the catchment, from the Digital Elevation Model obtained this year from the Government Printer and from the five rainfall stations available in the Mochlapitse river basin.

The most important is to obtain a verifiable data follow-up. The monitoring must be more robust in terms of both precision and regularity. It would be useful to upgrade the gauging station in order to have a good accuracy for the full spectrum of flows that occur, not only the low flows. The gauging station should be able to record very high flows if one day it is to be used for flood risk forecasting.

For a future wetlands study, it could be interesting too, in addition to the gauging station already existing downstream of the wetlands area, to have another gauging station located upstream of the wetland area. This will enable comparison of contemporary flows occurring immediately upstream and downstream of the wetlands and so to study precisely the impact of the wetlands on the flow regime.

This study suggests that, even if the Mochlapitse river wetland area is very small compare to the basin size (0.4 km² for 400 km²), it has a significant influence on the hydrological functioning of the river (cf. part “results analysis”). This suggests that the wetland is important both ecologically and hydrologically.

Conclusions derived from the second chapter “Land use changes study” show that the land use trend is conversion of the wetlands and woodland to agriculture areas. It could be very serious if this trend is continued in the future. In the long term, it is possible that continued wetland destruction will result in decreases in water quality, less reliable water supplies (especially during the dry season), increased severe flooding, lower agricultural productivity, and more endangered species.

The first step toward wetland rehabilitation for the Challenge Program on Water and Food (objective 2 of the FSP echel, wetland project) is to understand the relationships between wetland degradation and river hydrology.

This study aims to increase decision makers' awareness of wetland importance by illustrating those relationships.

The Ga Mampa valley illustrates possibilities for slowing wetland destruction by rehabilitating existing irrigation schemes.

In South Africa, a wetland rehabilitation programme already exists. The Departments of Environmental Affairs and Tourism, Water Affairs and Forestry, and Agriculture, together with partners in provincial and local government and civil society, especially the Mondi Wetlands Project, have jointly launched the Working for Wetlands programme. All rehabilitation interventions are undertaken within the context of improving the integrity and functioning of wetland ecosystems, and include measures that address both causes and effects of degradation. A guiding principle is that of raising awareness and influencing behaviour and practices impacting on wetlands, rather than focusing exclusively on engineering solutions.

Typical activities to rehabilitate a wetland include ²:

- The building of concrete, earth or gabion structures to arrest erosion, trap sediment and resaturate drained wetland areas
- Using structures and landscaping to reinstate diminished flood mitigation and water quality enhancement functions
- Plugging of artificial drainage channels
- Addressing offsite causes of degradation, such as inappropriate agricultural practices
- Re-vegetation and bio-engineering
- Eradicating invasive alien plants
- Raising awareness of wetlands among workers, landowners and the public
- Providing technical skills

² <http://www.nbi.ac.za/research/wetlandprog.htm>

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