Hydraulic modelling of the Lower Orange River (Republic of South Africa) and evaluation of integrated water resources management in the Orange-Senqu-Fish catchment

Jan Putteman, Bert Schepens

Promotoren: prof. dr. ir. Ronny Verhoeven, prof. dr. ir. Peter Troch
Begeleider: Dieter Meire

Masterproef ingediend tot het behalen van de academische graad van
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When the well is dry, we know the worth of water.

-Benjamin Franklin-

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Preface

The subject of this Master thesis is the Orange River in South Africa. A field trip to South Africa has been made possible for us by the Flanders UNESCO Science Trust Fund (FUST). Our local stay and agenda were organised within the FETWater framework. The FETWater programme ('Framework Programme for Research, Education and Training in the Water Sector') aims to support training and capacity building networks in integrated water resources management in South Africa. The processing of the on-site collected data was performed at the Hydraulics Laboratory of Ghent University (Belgium). The content of our thesis consists of two main components, these are the development of a hydraulic model of the Lower Orange River, and the evaluation of integrated water resources management within the river catchment.

We would like to thank Prof Ronny Verhoeven and Prof Peter Troch for the productive cooperation and for the time they have invested in our thesis. We owe many thanks to Dana Grobler, who took care of us during our stay in South Africa. Dana spent many hours helping us at his office in Stellenbosch. We wish him, his wife Toni and their children all the best. Many thanks to all the employees of the Hydraulics Laboratory for helping us and entertaining us with South African boboti and pancake breaks. In particular we thank PhD student Dieter Meire for helping us with our modelling problems, and we wish him success with the continuation of his research. Although Liesbet De Doncker was out of office on maternity leave since February, we want to thank her for teaching us the basic STRIVE skills. We wish her and her family good luck for the future. Kerst Buis from the Ecosystem management research group (University of Antwerp) provided us with some good advice on the hydraulic modelling, which we appreciate a lot. Thanks to our dear colleague students Michaël, Steven and Bruno for discussing problems, sharing frustrations and having fun at the laboratory. We wish them all the best in their post-university life.

We owe thanks to many people for helping us during our stay in South Africa: The employees of the BlueScience office at Stellenbosch, Bernice (Caledon Villa Stellenbosch), Ben Benade (EkoImpak Kimberley), Annette Wentzel (FETWater), Danie De Waal, Maithland Seaman and Marie Watson (Free State University Bloemfontein), Marica Erasmus (DWA), Jackie van Bosch (DWA Bloemfontein), Hanzel Murphy (DWA Gariep), Henry Lourens and Gawie van Dyk (DWA Kimberley), Brunk Du Plessis, Nicolene Fourie, Celiwe Ntuli, Francinah Sibanyoni and Eddy van Wyk (DWA Pretoria), Janine Adams (Nelson Mandela Metropolitan University, Porth Elisabeth), Piet Huizinga (retired environmental engineer), Jason Hallowes (SADC Johannesburg), Lucky Dlamini and Charlotte McBride (South African Weather Service) and Manie Maré and Susan Swart (WRP Pretoria).

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Chapter 1 presents an overview of the most important features of the river and its catchment, such as tributaries, climatic conditions and natural run-off. The content of this chapter should be interpreted as a general background to the following chapters on integrated water resources management.

Chapter 2 discusses on the present infrastructure in the Orange River, consecutively in a downstream direction. The Orange-Senqu-Fish system is a highly regulated system. Many dams, weirs and irrigation schemes have been constructed within the catchment. A proper understanding of the present infrastructure will help to understand the human impacts on the environment.

Chapter 3 presents a brief summary of the National Water Act (NWA). The NWA provides a legal framework for the implementation of a sustainable water management in South Africa. The NWA prioritises basic water requirements for both man and nature.

Chapter 4 describes the current water management system in South Africa, and emphasises the need for and the requirements of a new management system. A sustainable water management system needs to provide equitable water access and encourage a conscious use of water.

Chapter 5 analyses the impacts of the regulated flow regime on the riverine ecosystem. The natural flow regime is compared with the artificial regime, and the consequent impacts on the environment are evaluated. Requirements for a more environmentally sound flow pattern are described.

Chapter 6 discusses on the black fly problem. Black flies can reach pest densities due to the altered hydrological regime. Black fly pests result in a huge economical damage. Several black fly control programmes are evaluated.

Chapter 7 analyses the ecological condition of the Orange River mouth. The Orange River mouth is designated a Ramsar wetland. However, this wetland is severely deteriorated due to anthropogenic impacts. Several rehabilitation measures are evaluated.

Chapter 8 to 13 discuss on the development of a hydraulic model of the Lower Orange. The basic structure of the hydraulic model is described in detail. Several methods for lateral inflow evaluation are discussed. Calibration of the model is performed by adjusting the Manning's roughness coefficient. The accuracy of the model is evaluated by comparing the validation runs to the recorded flow data.

Chapter 14 describes some recommendations for further research. A lot of data was collected within the framework of this Master thesis. Not all data has been processed. A continuation of the research presented in this thesis will be prove to be useful.

Chapter 15 presents the general conclusions on this Master thesis.

Chapter 16 is conceived as a user manual to the attached DVD. This DVD contains the complete hydraulic model. All data required for a successful continuation of the research is included.

Keywords

Orange River, integrated water resources management, STRIVE, hydraulic model

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Abstract—**This article evaluates the water resources management in the Orange-Senqu-Fish catchment in South Africa. Social, economic and environmental issues are discussed. Furthermore, the hydraulic module of the STRIVE package is adapted to the Lower Orange River and methods for lateral inflow evaluation are implemented. The resulting hydraulic model is calibrated and validated.**

Keywords— **Orange River, integrated water resources management, STRIVE, hydraulic model**

I. Introduction

THE Orange-Senqu-Fish catchment is one of the largest catchments in southern Africa. The Orange River originates in Lesotho, and discharges into the Atlantic Ocean 2200 km further. The catchment includes 4 countries: South Africa, Lesotho, Namibia and Botswana. The river is subjected to very arid climatic conditions outside Lesotho. Increasing urban, industrial and agricultural water demands have resulted in the construction of dams, weirs, inter-basin transfer schemes and irrigation schemes along the Orange and its tributaries. Dams are also used for hydropower generation.

II. Legislative background and management policies

The establishment of a new South African political regime involves the incentive for a sustainable water management. The National Water Act (1998) provides a legal framework for managing all South African water resources in a sustainable way. The supply of water for basic human needs and for the environment is considered a priority.

A new water management system ensuring equitable water rights and encouraging an environmentally conscious water use is needed. Trading of water rights is successful in urging to efficient water use. The 'Fractional Water Allocation and Capacity Sharing' system provides a base for a transparent participatory water management. Accurate hydraulic models are required in order to solve water allocation problems.

III. Environmental issues

A. Hydrological regime

The historical flow regime of the Orange River is characterised by strong variability, with (very) low discharges during the dry local winter and high discharges combined with flood events during the wet summer months. River regulation for supplying urban, industrial, agricultural and hydropower demands resulted in an artificial hydrological regime, characterised by a lack of flow variability and decreased total water volumes. This is illustrated by figure 1, representing the average of the lower 85 % mean monthly discharges recorded at Boegoeberg, before (1932-1966) and after (1978-1994) river regulation.

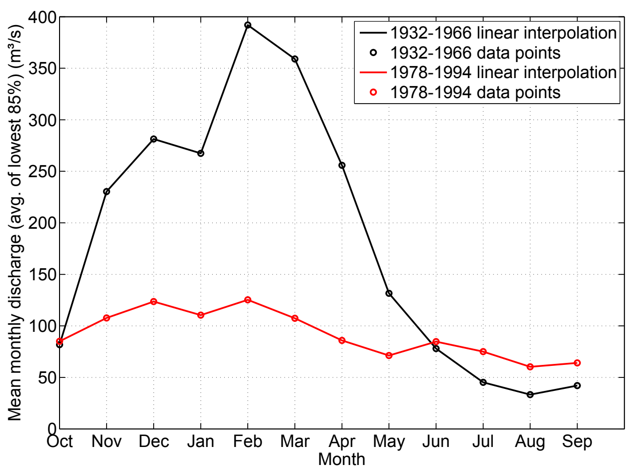


Fig. 1. Average of the lower 85 % mean monthly discharges at Boegoeberg. Discharge (m^3/s) versus month.

B. The riverine ecosystem

Flow regulation impacts on the viability of the riverine ecosystem. The impact of the artificial flow regime on the environmental condition has to be assessed, in order to be capable of suggesting more environmentally sound flow patterns. Dams impact on water temperature, water quality and sediment dynamics. Increased agricultural activity along the river also impacts on water quality and sedimentation processes. These factors, in combination with the altered flow regime, result in the deterioration of micro-habitats, algal blooms and an extreme expansion of *Phragmites* reeds. The present gentle flow regime harms many forms of life which have evolved to cope with severe hydrological conditions. At the moment, the riverine ecosystem is classified as largely modified. 20-year predictions indicate a negative trend of the environmental condition if no action is taken.

C. The black fly problem

Higher winter flows result in ideal conditions for black flies (*Simulium*) to reach pest densities. *Phragmites* reed proliferation favours the development of larvae. Black flies are well-known disease vectors. Their bites cause allergic reactions and often lead to secondary infections. Black fly pests results in health issues of both man and stock. Annoyance levels of black flies impact on tourism. Pests have major economic consequences. Several control programmes have been adopted in the Lower Orange. The application of Bti and temephos seems to be successful, without harming the environment.

D. The river mouth

The Orange River mouth (ORM) is the sixth most important southern African coastal wetland in terms of the number and diversity of birds supported. The ORM was designated a Ramsar wetland in 1991. Anthropogenic impacts during the last decades have severely degraded the condition of the ORM. The salt marsh component requires urgent rehabilitation measures. A more natural flow regime will allow regular mouth closure during winter and back-flooding of the salt marsh floodplains during spring.

E. Environmental requirements

Environmental water requirements need to be implemented in the operational management of the Orange river. The release of water should be varied in a way that mimics natural patterns. Short-term variability (days and weeks) and long-term variability (seasons) are of major importance.

IV. The hydraulic model

A. Introduction

One-dimensional unsteady surface water flow is expressed by the de Saint-Venant equations. An analytical solution of these equations is not possible, but the use of numerical models allows a numerical solution. In the scope of this study, discretisation is performed by the scheme of Preissmann where the equations are linearised using a Taylor expansion. A numerical solution of the resulting system is found by using the Double Sweep algorithm. Numerical solution is performed by the STream-RIVer-Ecosystem package (STRIVE), which has been developed by the Hydraulics Laboratory (Ghent University) and the Ecosystem management research group (University of Antwerp), using the existing FEMME software environment.

B. Adapting the hydraulic model to the Orange River

The river section between Vanderkloof Dam and Vioolsdrift was subdivided into 7 reaches. This river section is 1110 km long, and bridges a 943 m difference in altitude. The position of the extreme node of each reach coincides with a gauging weir. Recorded discharges are used as an upstream boundary condition and a weir rating curve determines the downstream boundary condition of each reach.

Lateral inflow or outflow of water depends on (a) rainfall events, (b) flood events, resulting in floodplain and groundwater interaction and (c) water abstractions, evaporation and evapotranspiration. A mathematical function for the detection of flood events and the calculation of the resulting lateral flow was developed. The numerical model also calculates lateral inflow from rainfall predictions, and takes into account the seasonal trend of the (c)-losses. Accurate lateral inflow determination is impossible for reaches enclosed by inaccurate gauging weirs. In this case, demand patterns obtained from other studies are used. However, lateral flow resulting from rainfall and flood events can not be implemented into the model in this case.

C. Calibration and validation

The hydraulic model is calibrated by adjusting the Manning's roughness coefficient. Although part of the recorded flow data is not very accurate, calibration is practically feasible for all reaches as the occurrence of remarkable flow events still can be linked to a point in time. It was concluded that the Manning's coefficient depends on water level (or discharge). This is illustrated by figure 2. In this figure, the higher (0.048) Manning's coefficient is more suitable for high discharges, while low coefficients (0.032 or 0.036) are suitable for lower discharges. After calibration, validation runs are performed in order to assess the accuracy of the model.

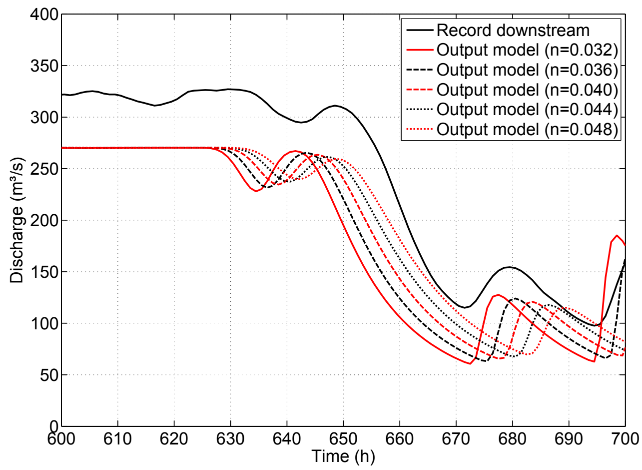


Fig. 2. Influence of Manning's roughness coefficient on the simulated hydrogram (reach 1, March 2009). Discharge (m^3/s) versus time (h).

V. Conclusion

Increasing water demands will result in higher environmental impacts. This emphasises the need for the urgent implication of a sustainable water management. Hydraulic models can serve as a useful tool for planning water releases in order to supply urban, industrial, agricultural and environmental water demands along the river. The hydraulic model developed in the framework of this Master thesis can be used for future research, in order to suggest and evaluate environmentally sound water releases.

Nederlandstalige samenvatting
-Summary in Dutch-

Onderstaande tekst vormt een beknopte samenvatting van de inhoud van deze Master thesis. Gezien de omvang van de thesis spreekt het voor zich dat deze samenvatting slechts de grote lijnen van deze thesis weergeeft, en men voor meer details de hoofdtekst dient te raadplegen.

Algemene inleiding Het bekken van de Oranjerivier (EN: Orange River) is het grootste rivierbekken in Zuid-Afrika. De Oranjerivier ontspringt in het Drakensberg gebergte in Lesotho op een hoogte van ca. 3300 m. Vanaf de bron stroomt de rivier over een afstand van 2200 km westwaarts, tot ze uitmondt in de Atlantische Oceaan. De Oranjerivier is niet bevaarbaar, tenzij voor kleinere boten die voor visvangst en recreatie gebruikt worden.

Meer dan de helft van het rivierbekken is gesitueerd in Zuid-Afrika. Verder strekt het rivierbekken zich uit over delen van Lesotho, Botswana en Namibië. De Oranjerivier vormt de internationale grens tussen Zuid-Afrika en Namibië.

Teneinde te kunnen blijven voorzien in de grote vraag naar water voor landbouw, industrie en watervoorziening in steden en dorpen werden de voorbije decennia verschillende stuwdammen en stuwen gebouwd in de Oranjerivier. Deze infrastructuurwerken verstoren het natuurlijke stromingsgedrag van de rivier, met zware gevolgen voor het ecosysteem in en rond de rivier.

De Oranjerivier staat ook bekend als de 'Gariep rivier', wat 'grote rivier' betekent in de inheemse Nama taal. 'Oranjerivier' is de oorspronkelijke Afrikaanse benaming die de rivier kreeg in koloniale tijden. Het deel van de Oranjerivier dat in Lesotho gesitueerd is wordt daar 'Senqu rivier' genoemd.

De Oranjerivier heeft meerdere zijrivieren. Verschillende zijrivieren leveren slechts een sporadische en geringe bijdrage tot de debieten in de Oranjerivier. De Vaal rivier is één van de grootste zijrivieren en in het kader van deze thesis van bijzonder belang.

Met 'Upper Orange' wordt het deel van de rivier stroomopwaarts van de samenvloeiing van de Oranjerivier en de Vaal rivier bedoeld. 'Lower Orange' verwijst naar de riviersectie stroomafwaarts van dit punt.

Het deel van het rivierbekken gesitueerd in Zuid-Afrika, Namibië en Botswana kent een zeer droog klimaat. In Lesotho heerst daarentegen een vochtig klimaat. Naarmate men de Oranjerivier verder stroomafwaarts volgt, wordt men blootgesteld aan steeds strengere (drogere) klimatologische omstandigheden. Deze bevinding vindt men terug in de gemiddelde jaarlijkse neerslag: in de hoger gelegen delen van Lesotho overschrijdt deze makkelijk 1000 mm, terwijl deze in de Kalahari halfwoestijnen nog slechts 150 mm bedraagt. De jaarlijkse verdamping in het rivierbekken binnen Zuid-Afrika varieert van 2100 mm tot 2700 mm. De natuurlijke run-off binnen het rivierbekken bedraagt 11500 miljoen m^3 per jaar.

Verschillende dammen en stuwen werden sinds de jaren '60 en '70 gebouwd in de bedding van de Oranjerivier en haar zijrivieren. Het Lesotho Highlands Water Project (LHWP) is een project dat de watervoorziening van het industriële hart van Zuid-Afrika (de Gauteng provincie) moet verzekeren. Verschillende stuwdammen, stuwen en watertunnels werden reeds in gebruik genomen. Men transporteert grote volumes water vanuit Lesotho richting de grote steden Pretoria en Johannesburg. De term inter-basin transfer verwijst naar dit soort projecten, aangezien water van het ene rivierbekken naar een ander bekken wordt getransporteerd. Twee grote stuwdammen (Gariep Dam en Vanderkloof Dam) bevinden zich in de Upper Orange (Zuid-Afrika). Beide werden gebouwd voor irrigatiedoeleinden en het opwekken van elektriciteit. Bovendien wordt een deel van het water dat gestockeerd wordt in het reservoir van de Gariep Dam via een tunnelschema getransporteerd naar de Eastern Cape provincie. Vanderkloof Dam is de stuwdam die het verst afwaarts gelegen is in de Oranjerivier. Bijgevolg regelt Vanderkloof Dam het stromingspatroon van de 1400 km lange riviersectie (voornamelijk Lower Orange) gelegen stroomafwaarts van deze dam. Verschillende stuwen werden voor irrigatiedoeleinden gebouwd stroomafwaarts van Vanderkloof Dam. Al deze infrastructuurwerken hebben geleid tot grote waterafnames, waardoor het natuurlijke stromingspatroon van de rivier sterk gewijzigd werd.

National Water Act (1998) Het is duidelijk dat het ecosysteem geassocieerd met de Oranjerivier erg te lijden heeft onder de menselijke invloeden. Bovendien is het zo dat de verschillende rassen in Zuid-Afrika lange tijd ongelijke rechten hebben gekend, wat resulteerde in een ongelijke toegang tot drinkbaar water. Na het einde van het apartheid regime heeft zich een nieuw politiek klimaat gevestigd, waarin de belangen van het gehele volk en de natuurlijke rijkdommen van het land centraal zijn komen te staan. Men tracht te streven naar een duurzaam waterbeheer, waarvoor de basisbehoeften van mens en natuur het uitgangspunt vormen. Gezien de toenemende vraag naar drinkbaar water en de steeds groter wordende ecologische impact van deze waterafnames dringt zich een nieuwe vorm van duurzaam management op. De National Water Act (NWA) creëert in Zuid-Afrika een wettelijk kader voor duurzaam en efficiënt waterbeheer. Het basisidee van de NWA is de erkenning dat water een schaars en kostbaar goed is dat aan elke inwoner van Zuid-Afrika moet toebehoren. Bovendien stelt deze wettekst dat een integraal waterbeheer die een verhoging van de levenskwaliteit van elke inwoner, zonder onderscheid, beoogt het ultieme doel moet zijn. Deze nieuwe vorm van waterbeheer vraagt input van de bevolking door actieve publieke participatie bij het opstellen van nieuwe beheersmaatregelen. Gezien het belang van de NWA voor een duurzaam waterbeheer werden de belangrijkste passages uit deze wettekst ter vervollediging van deze thesis besproken in hoofdstuk 3.

Watermarkten als onderdeel van een nieuw duurzaam waterbeheer Aangezien de vraag naar water ruimschoots het aanbod overtreft in Zuid-Afrika, is een efficiënt en maatschappelijk verantwoord mechanisme voor de verdeling en toekenning van waterrechten noodzakelijk. De eisen die gesteld worden aan zulk mechanisme volgen uit de vernieuwde National Water Act (1998).

Het huidige (te vervangen) management systeem 'Priority-based River and Reservoir Operating Rule' (PRROR) werd ontwikkeld in de jaren '80. Dit systeem bestaat uit 2 numerieke modellen die de gevolgen van verschillende waterallocatie scenario's kunnen simuleren. In feite houdt men enkel rekening met de distributie en allocatie van water voor de mens, zonder hierbij randvoorwaarden m.b.t. ecologie van de rivier te hanteren. Het PRROR systeem kent rechten voor de afname van irrigatiewater toe op basis van rechten om grond te bewerken voor landbouw. Het is dus zo dat enkel mensen die vruchtbare grond bezitten wettelijk aanspraak kunnen maken op irrigatiewater. Deze politiek bevordert illegaal watergebruik, wat uiteraard nefast is voor de nauwkeurigheid en efficiëntie van dit soort modellen. Bijgevolg treft men in de praktijk nog steeds een situatie aan waarbij rijke (voornamelijk blanke) boeren aanspraak maken op het merendeel van de waterabstracties voor irrigatiedoeleinden. Het is duidelijk dat deze aanpak leidt tot een onevenwichtig verdeeld en inefficiënt watergebruik.

In de vernieuwde NWA krijgen de basisbehoeften voor mens en natuur een prioritaire status. Watergebruik voor economische doeleinden wordt als zijnde van secundair belang behandelt. Bovendien dient men efficiënt watergebruik aan te moedigen. Men dient af te stappen van het concept van 'technische efficiëntie' van waterallocatie, waarbij men de terugstroom van water (EN: return flow) naar de rivier tracht te beperken. Aangezien return flows ecologische behoeften bevredigen is een louter streven naar dit soort efficiëntie te vermijden. De efficiëntie van water management dient in de toekomst gedefinieerd te worden als de maximale output die men kan verkrijgen, waarbij output zowel sociale, economische als ecologische belangen omvat. Er zijn verschillende methodes om een duurzaam water management te verkrijgen. De meest doelmatige strategie blijkt het in praktijk brengen van een watermarkt mechanisme waardoor waterrechten verhandeld kunnen worden. Dit mechanisme stimuleert een bewust watergebruik, aangezien niet gebruikte waterrechten kunnen doorverkocht worden, en voor extra waterrechten ook extra betaald moet worden. De (lokale) overheden dienen een snelle transactie van deze waterrechten tegen verlaagde administratieve kosten mogelijk te maken. Momenteel heeft zich reeds een actieve watermarkt gevestigd langsheen de Lower Orange. Een vernieuwd management systeem dat heet 'Fractional Water Allocation and Cacity Sharing' (FWACS) zal geïmplementeerd worden. Het FWACS systeem bestaat uit 3 onderdelen: de allocatie van water (EN: fractional water allocation), capaciteitsverdeling (EN: capacity sharing) en het verdelen van verliezen (EN: proportioning of losses). Run-off wordt -na in mindering brengen van ecologische behoeften- volgens het fractional water allocation principe onder de verschillende watergebruikers verdeeld. Het is duidelijk dat numerieke modellen en communicatiesystemen een belangrijke rol spelen in het bepalen van tijdsvensters en hoeveelheden van waterafnames. De capaciteit aan beschikbaar water in de reservoirs van stuwdammen wordt onder de toekomstige verbruikers verdeeld (capacity sharing). Elke gebruiker kent de hoeveelheden water waarover hij/zij beschikt en bepaalt zelf wanneer hij/zij deze gebruikt. Beide voornoemde principes zijn transparant naar de gebruikers toe en laten een eenvoudige verhandeling van waterrechten toe. Waterverliezen (bv. door verdamping) worden over de verschillende gebruikers verdeeld (proportioning of losses). Het is duidelijk dat het FWACS systeem een aantal grote investeringen vereist, zoals betrouwbare modellen, communicatiesystemen naar de bevolking toe en een goed werkend controleapparaat dat op de waterabstracties toeziet. In het bijzonder zijn hydraulische modellen erg belangrijk voor het oplossen van het waterallocatievraagstuk. Verder in deze thesis wordt dan ook dieper ingegaan op de ontwikkeling van deze modellen.

Ecologische aspecten van de rivier De grote vraag naar rivierwater heeft geleidt tot de uitvoering van grote infrastructuurwerken in de Oranjerivier en haar zijrivieren. Regulatie van de rivier door de mens heeft geleid tot een zeer artificieel stromingsregime dat sterk verschillend is van het natuurlijke regime. Het is belangrijk om een duidelijk beeld te krijgen van de ecologische impact van dit artificiële stromingsregime teneinde meer natuurvriendelijke beheersmaatregelen voor de stuwdammen voor te stellen.

Het natuurlijke stromingsregime bestaat uit hoge debieten gecombineerd met wassen (de eerste normaliter in november) gedurende de natte zomermaanden, afgewisseld door lage debieten gedurende de lokale winter. Elektriciteitsgeneratie, watervoorziening voor dorpen, steden en irrigatie heeft vrij constante debieten gedurende het hele jaar tot gevolg. Regulatie van de rivier heeft geresulteerd in volgende impacten op het hydrologisch regime:

- Gebrek aan seizoensgebonden variatie;
- Te hoge winterdebieten;
- Gebrek aan kleine wasgolven (deze worden tegengehouden door de stuwdammen);
- Reductie van jaarlijkse water volumes;
- Gebrek aan korte-termijn variatie.

Stuwdammen hebben een rechtstreekse impact op de watertemperatuur en waterkwaliteit stroomafwaarts. Water voor elektriciteitsgeneratie is immers afkomstig uit het temperatuurinerte hypolimnion. Bovendien werkt een dam reservoir als bezinkingsbekken voor opgeloste stoffen, zware metalen etc. Het hypolimnionwater bevat zeer weinig opgeloste zuurstof of is zelfs anoxisch. Return flows van de landbouw hebben een belangrijke invloed op de waterkwaliteit in de rivier, aangezien zij nutriënten, zouten, chemicaliën en micro-elementen lozen in de rivier.

Vroeger werd de Oranjerivier gekenmerkt door haar hoge turbiditeit. De gebouwde stuwdammen gedragen zich als bezinkingsbekkens voor het sediment aanwezig in de rivier. Bovendien resulteren verminderde debieten in een kleiner sedimenttransport. De ingebruikname van oevers van de rivier voor landbouw leidt tot erosie van de vruchtbare landbouwgrond met een verhoogde sedimentatie tot gevolg, gezien de verminderde sedimenttransportcapaciteit van de rivier. Onnatuurlijke sedimentatie vernietigt verschillende micro-habitats. Bovendien ontstaan eilandjes in de rivier, versterkt door pioniervegetatie. Deze eilandjes kunnen zich goed handhaven gezien het huidige gebrek aan wasgolven.

De rietsoort *Phragmites australis* kent een enorme recente expansie in de Lower Orange. Het mildere hydrologische regime in combinatie met de mechanische beschadiging van oevers creëert ideale leefomstandigheden voor deze pionierplant. Dit riet versterkt en bevordert de vorming van eilandjes in de rivier. Bovendien beperkt ze de stroming van water tot een nauwe geul. De resulterende morfologische veranderingen van de rivierbedding zullen leiden tot grote overstromingen en bijhorende schade tijdens de eerstkomende grote wasgolf, aangezien de rivierbedding in haar huidige staat niet meer aangepast is aan hoge debieten. Bovendien heeft de expansie van *Phragmites australis* nog verschillende andere directe en indirecte negatieve gevolgen voor mens, economie en natuur. De gewijzigde hydrologische omstandigheden in combinatie met toegenomen nutriëntgehaltes resulteren in excessieve algenbloei, zowel in het reservoir van de Vanderkloof Dam als stroomafwaarts in de rivier. Zulke algenbloei kan leiden tot een daling van het zuurstofgehalte en de vrijstelling van toxische stoffen. Oevervegetatie lijdt sterk onder de ontwikkeling van landbouw en nederzettingen langsheen de rivier.

De Oranjerivier stelt van nature uit hoge eisen aan de levensvormen die erin voorkomen, aangezien zeer droge periodes met bijna geen debiet werden afgewisseld door extreme wassen die met een hoge turbiditeit gepaard gingen. Verschillende levensvormen hebben zich in de loop der tijd aangepast aan deze strenge leefomstandigheden. Het spreekt voor zich dat het milderen/wegnemen van deze specifieke leefomstandigheden nefast is voor de gezondheid van de aanwezige populaties. 3 soorten invertebraten zijn inmiddels uitgestorven in de Lower Orange. Daarentegen zijn de gewijzigde leefomstandigheden ideaal voor *Simulium* muggen (EN: black flies), wat resulteert in een ongewenst hoge densiteit van deze muggen.

De Lower Orange is van bijzonder belang voor de bescherming van zeldzame en endemische vissoorten. Het gewijzigde hydrologische regime heeft echter een grote rechtstreekse en onrechtstreekse impact op de micro-habitats van deze soorten. Bovendien wordt vismigratie fysisch belemmerd door dammen en stuwen. Zowel de Orange-Vaal Smallmouth Yellowfish als de Orange-Vaal Largemouth Yellowfish zijn van groot belang voor de recreatieve vliegvisserij, welke een belangrijke bron van inkomsten betekent voor de toeristische sector langsheen de Vaal en de Oranjerivier. De Largemouth Yellowfish is omwille van zijn zeldzaamheid en formaat bijzonder gegeerd bij hengelaars. Deze soort is echter ernstig bedreigd en verdere beschermingsmaatregelen dringen zich dan ook op.

Momenteel wordt de rivier geclasseerd in de ecologische klasse D (sterk gewijzigd ecosysteem). Indien geen structurele veranderingen van het rivier management plaatsvinden voorspelt men voor de komende 20 jaar een negatieve tendens, waarbij een klasse D/E bereikt zal worden, waarbij klasse E staat voor een sterk gedegradeerd ecosysteem. Bij het bepalen van een meer natuurvriendelijk hydrologisch regime dient men enerzijds rekening te houden met de variabiliteit van de debieten, zodanig dat men een stromingsregime bekomt dat lijkt op het natuurlijke regime. Men moet trachten om een mix van droge periodes en periodes van hoge debieten te verkijgen. Anderzijds dient men te verzekeren dat de waterstroming voor elektriciteitsgeneratie en andere doeleinden minder abrupt aanvat en stopt, aangezien dit een zeer artificiële situatie is die in de natuur niet voorkomt.

***Simulium* muggen of black flies** Zoals reeds vermeld heeft de instelling van een artificieel hydrologisch regime geleid tot plaag densiteiten van *Simulium* muggen (EN: black flies). Deze densiteiten traden in de natuurlijke situatie slechts sporadisch op. Een milder hydrologisch regime heeft echter geleid tot jaarlijkse bovennatuurlijke densiteiten van deze muggen (in het bijzonder *Simulium chutteri*). Deze black fly plagen hebben een grote impact op mens en economie. Daarom wordt dit ecologisch probleem afzonderlijk besproken.

De enorme uitbreiding van *Phragmites* rietvegetatie oefent een positieve invloed uit op de ontwikkeling van black fly larven. Bovendien laten de kunstmatig hoge winterdebieten overleving van deze muggen toe, met een snellere voortplanting tot gevolg. De toename van organisch materiaal dat door de rivier wordt getransporteerd is eveneens gunstig voor deze muggen, aangezien zij zich hiermee voeden. De natuurlijke predatoren van black flies lijden sterk onder het artificieel hydrologisch regime.

De beten van deze muggen leiden tot hevige irritatie en mogelijke secundaire infecties. Black flies zijn bekende dragers en overbrengers van ziektes, zowel voor de mens als voor dieren. De verspreiding van ziektes naar vee met vervolgens een vermindering van de algehele conditie of sterfte van het vee ten gevolge van deze muggenplagen resulteert in grote economische verliezen. Black fly plagen zijn eveneens zeer hinderlijk voor de mens, wat resulteert in een grote impact op de toeristische sector en een vermindering van de efficiëntie van arbeiders tewerkgesteld in industrie en landbouw.

Sinds de jaren '60 werden verschillende bestrijdingsmethodes toegepast met wisselend succes. Tijdens de eerste bestrijdingscampagnes maakte men gebruik van DDT. Men is hiervan afgestapt wegens de verwoestende ecologische impact. Periodiek afsluiten van de stroming in de rivier in mei en augustus is succesvol, maar slechts toepasbaar nabij dam of stuw. Bovendien houdt deze methode geen rekening met de vraag naar water voor verschillende doeleinden. Voor een meer wetenschappelijk onderbouwde manipulatie van de stroming rekening houdend met levenscycli, populatiedynamiek en specifieke microhabitats van de black flies en hun predatoren gelden eveneens dezelfde bezwaren, hoewel deze methode succesvol is. In de jaren '80 begon men gebruik te maken van een biologisch larvicide (Bti) en een chemisch larvicide (temephos). Beide larvicides zijn selectief en resulteren in een veel kleinere ecologische impact dan DDT. Momenteel worden Bti en temephos met succes toegepast. Niettemin komen black fly plagen nog steeds voor ten gevolge van menselijke fouten en een gebrekkige kennis van de dynamiek van bepaalde black fly populaties.

Ecologische aspecten van de monding De monding van de Oranjerivier is het zesde meest belangrijke wetland langsheen de Atlantische kustlijn van zuidelijk Afrika op vlak van aantallen en diversiteit van vogels die hier regelmatig worden waargenomen. Desalniettemin hebben een slecht rivier management en on-site menselijke invloeden gedurende de voorbije decennia een grote ravage aan het lokale ecosysteem aangericht.

Kunstmatig hoge winterdebieten zorgen ervoor dat de monding van de rivier zich vrijwel nooit meer sluit. Indien de riviermond zich toch sluit wordt deze artificieel (mechanisch) doorbroken. Het sluiten van de riviermond is een natuurlijk proces dat ervoor zorgt dat de vlaktes rond de riviermonding overstromen. Bovendien bepaalt de staat van de monding (open/gesloten) in welke mate mariene invloeden kunnen binnendringen.

Van bijzonder ecologisch belang zijn de zilte moerassen ten zuid-oosten van de monding. Hiervan verkeren ongeveer 300 ha in erbarmelijke staat, ten gevolge van een slecht beheer. Na de extreme wasgolf van 1988 was de dominante zilte vegetatie *Sarcocornia pillansii* grotendeels verwoest. In natuurlijke omstandigheden kan de vegetatie hiervan snel herstellen. Menselijke invloeden hebben echter geresulteerd in te hoge zoutgehaltes van bodemsediment en grondwater van deze zilte moerassen, waardoor natuurlijke rehabilitatie van deze vegetatie niet mogelijk is. Verschillende constructies belemmeren de indringing van zoet water uit de riviergeulen in de moerassen. Aangezien de riviermond zich niet meer kan sluiten kan overstroming van deze gebieden niet meer optreden. Het gebrek aan zoet water in deze moerassen zorgt ervoor dat de aanwezige hoge zoutgehaltes niet kunnen dalen. Toevoer van water door overstroming of de aanwezigheid van geulen kan de zoutgehaltes terug op een aanvaardbaar peil brengen, zodat natuurlijke rehabilitatie van de vegetatie mogelijk wordt. Rehabilitatieprogramma's dienen zich dan ook te focussen op de factoren die de aanvoer van water belemmeren.

In 1991 werd de riviermonding erkend als Ramsargebied, gezien zijn belang voor verschillende populaties zeldzame en endemische vogelsoorten. Niettemin leidde de verslechterende conditie van dit gebied tot een sterke daling in de aantallen aanwezige vogels. Bijgevolg werd dit gebied in 1995 op de Montreux Record geplaatst, teneinde op deze manier de aandacht te vestigen op de nood aan rehabilitatiemaatregelen. Momenteel voldoet de riviermonding nog steeds aan de Ramsarvereisten, hoewel niet alle condities van de oorspronkelijke erkenning meer vervuld zijn.

Het hydraulisch model 1D niet-permanente stroming in een open kanaal wordt beschreven door de de Saint-Venantvergelijkingen. Aangezien deze niet-lineaire partiële differentiaalvergelijkingen niet analytisch kunnen worden opgelost, dient men gebruik te maken van een numerieke oplossingsmethode. Discretisatie gebeurt met behulp van het Preissmannschema waarbij de vergelijkingen gelineariseerd worden door middel van een Taylor ontwikkeling. Deze vergelijkingen worden vervolgens opgelost door het Double Sweep algoritme.

De numerieke oplossing van de de Saint-Venantvergelijkingen gebeurt door middel van een computer model. In deze studie is gebruik gemaakt van het STream-RIVer-Ecosystem pakket (STRIVE), dat ontwikkeld werd door het Labo voor Hydraulica (Universiteit Gent) en de Ecosystem management research group (Universiteit Antwerpen). Dit pakket beoogt de geïntegreerde modellering van rivierecosystemen, en is gebaseerd op de reeds bestaande FEMME omgeving. In deze Master thesis wil men de hydraulische module van STRIVE aanpassen aan de Oranjerivier. Later kan men aan deze hydraulische module bijkomende modules koppelen, bv. om waterkwaliteit numeriek te modelleren.

Teneinde een beter inzicht te krijgen in de structuur en werking van het STRIVE pakket, wordt eerst de algemene basisstructuur van het pakket uiteengezet. Bovendien is een goed inzicht in de werking van STRIVE onmisbaar indien men het hydraulisch model van de Oranjerivier ook daadwerkelijk wil gaan gebruiken.

Het hydraulisch model werd ontwikkeld voor de riviersectie tussen Vanderkloof Dam en Vioolsdrift. Deze sectie van 1110 km werd onderverdeeld in 7 panden. Het totale hoogteverschil over deze riviersectie bedraagt 943 m. De grenzen van deze panden vallen samen met stuwen waarvoor uurlijkse debietmetingen beschikbaar zijn. Als opwaartse randvoorwaarde wordt voor elk pand het verloop van de opgemeten debieten in de tijd gebruikt. Als afwaartse randvoorwaarde maakt men voor elk pand gebruik van de ijkingscurve van de afwaartse stuw. Voor elke stuw is immers een tabel beschikbaar waarin het verband tussen waterpeil en debiet wordt aangegeven. Door curve-fitting kan men een wiskundig verband bepalen dat het debiet uitdrukt in functie van het waterpeil. Opgemeten dwarssecties van de rivier werden gebruikt om de geometrie van de verschillende panden te definiëren. Door elke opgemeten sectie werd een best-passende trapezium getekend die vervolgens in het model werd geïmplementeerd.

Enkel voor het eerste pand, tussen Dooren Kuilen (Vanderkloof) en Marksdrift was voldoend nauwkeurige data beschikbaar waaruit een schatting van de optredende verliezen en eventuele laterale instroom kon worden gemaakt. Wasgolven gaan gepaard met berging en interactie met het grondwater. Bijgevolg zullen de debieten die uit het pand stromen tijdelijk kleiner zijn dan de instromende debieten. Men heeft dus tijdelijk een 'verlies' van water, dat na het einde van de wasgolf beschikbaar komt als 'laterale instroom'. Daarom werd een mathematische functie opgesteld die automatisch wasgolven detecteert, en aan de hand van de debiettoenames/afnames in de opwaartse knoop van het pand zelf de in rekening te brengen laterale instroom of uitstroom berekent. Aangezien hevige regenval steeds in een laterale instroom in het pand resulteert, werden verbanden opgesteld die uit de te verwachten neerslag de hoeveelheid laterale instroom kunnen voorspellen. Ook dit is een geautomatiseerd proces. Tenslotte volgen irrigatiewaterafnames, evaporatie, evapotranspiratie en return flows een seizoensgebonden trend, aangezien zij afhankelijk zijn van de heersende klimatologische omstandigheden. Uit de beschikbare data werd voor elke maand een gemiddelde laterale uitstroom gedefinieerd, die eveneens automatisch in rekening wordt gebracht bij berekening van de modelresultaten.

Voor de overige panden was de meetdata niet nauwkeurig genoeg om zelf een inschatting van laterale in-en uitstroom te kunnen maken. Daarom werd gebruik gemaakt van data die in het kader van enkele Zuid-Afrikaanse studies werd verzameld. Men heeft voor de belangrijkste abstractiepunten langs de rivier berekend wat de maandelijkse vraag naar water is. Bovendien geven deze studies ook gemiddelde waarden voor evaporatie en evapotranspiratie. Deze data werd in het model geïmplementeerd als volgt: voor elke abstractie (punt of diffuus) bestaat een bestand waarin de gemiddelde maandelijkse abstractiedebieten staan. Deze debieten worden als de laterale uitstroom in de knopen corresponderend met de abstractiepunten ingelezen door het model. Diffuse abstracties worden uitgespreid over de knopen die in de bijhorende zone gesitueerd zijn. De nauwkeurigheid van de meetdata van de panden 2 t.e.m. 7 bleek onvoldoende om een wetenschappelijk onderbouwde inschatting van de laterale instroom/uitstroom te wijten aan wasgolven en regenval uit te voeren.

Calibratie en validatie van het model De calibratie van het model wordt voor elk pand uitgevoerd door aanpassing van de Manning coëfficiënt. Men vergelijkt verschillende simulaties met de opgemeten debieten in de afwaartse knoop van het pand, en bepaalt hieruit de meest optimale waarde van de Manning coëfficiënt. Tijdens het calibratieproces werd vastgesteld dat de Manning coëfficiënt een functie is van het waterpeil. Het is dan ook sterk aangeraden om dit verder te onderzoeken in een vervolgfase van deze thesis. Men merkt op dat minder nauwkeurige meetdata geen bezwaar vormt voor het bepalen van de Manning coëfficiënt, aangezien opmerkelijke pieken of dalingen in debiet nog steeds kunnen worden waargenomen.

Voor elk pand worden vervolgens enkele validatiesimulaties uitgevoerd teneinde de juistheid van de eerder uitgevoerde calibratie te controleren.

Het gecalibreerde hydraulisch model is ter beschikking gesteld op een DVD in bijlage van dit rapport.

Aanbevelingen voor verder onderzoek Deze Master thesis is opgevat als het eerste werk in een serie van meerdere. In het kader van dit thesisonderzoek werd immers meer data verzameld dan verwerkt kon worden. Daarom geven de auteurs van dit rapport graag enkele aanbevelingen voor verder onderzoek, zodat toekomstige laatstejaarsstudenten dit onderzoek vlot kunnen verderzetten:

- **Verdere calibratie van de Manning coëfficiënt:** tijdens de calibratie van het hydraulisch model bleek dat de Manning coëfficiënt afhankelijk is van het waterpeil. Bovendien is het mogelijk dat de Manning coëfficiënt seizoensgebonden variaties vertoont ten gevolge van de groei van macrophyten. Er dient dus verder onderzoek uitgevoerd te worden naar de factoren die de Manning coëfficiënt bepalen, en de opgestelde verbanden kunnen in het hydraulisch model geïmplementeerd worden om zo de nauwkeurigheid te verbeteren.

- **Vergelijking met ecologisch verantwoorde hydrologische regimes:** de nieuwe National Water Act voorziet een legaal kader voor de implementatie van watervereisten van het ecosysteem ('instream (or environmental) flow requirements'). Deze instream flow requirements leggen een distributie van watervolumes vast die gedurende een bepaalde periode van het jaar verwezenlijkt moet worden teneinde het ecosysteem in een vooraf vastgelegde toestand te onderhouden. In feite vormen zij dus de schakel tussen biologische aspecten en de praktische uitwerking van meer duurzame operationele procedures. Men kan de evolutie van de hydrologische condities in de rivier analyseren en dit via instream flow requirements linken aan de resulterende impact op het ecosysteem. Ook kunnen knelpunten voor het verwezenlijken van een meer natuurvriendelijk hydrologisch regime blootgelegd worden. In een laatste stap kan men voorstellen doen voor een duurzaam hydrologisch regime, waarbij men eveneens rekening houdt met de eisen van de verschillende stakeholders langsheen de rivier.

- **Nieuwe infrastructuur en hiermee gerelateerde management scenario's:** de constructie van een nieuwe dam in de Lower Orange is momenteel een hot topic onder Zuid-Afrikaanse ingenieurs. Indien voldoende stroomafwaarts gesitueerd kan een nieuwe dam de operationele verliezen drastisch beperken, aangezien deze dam al het water dat niet gebruikt werd opvangt. Een dam in de nabijheid van de riviermonding kan bovendien een meer natuurlijk hydrologisch regime in de riviermonding bewerkstelligen zonder hierbij de watergebruikers langsheen de gehele Lower Orange te beïnvloeden. Literatuurstudie over de ideale locatie van deze dam moet worden uitgevoerd. Ook kunnen suggesties gedaan worden voor duurzame stromingsregimes die gunstig zijn voor de riviermonding.

- **Waterkwaliteit en temperatuur:** in het kader van dit thesisonderzoek werd volgende recente data verzameld voor 7 meetpunten binnen het bereik van het hydraulisch model: geleidbaarheid, ionensamenstelling, alkaliniteit, pH, stoffen in suspensie, nitraat en stikstof, fosfor. Bijkomende modules die het transport en de dynamiek van deze stoffen beschrijven kunnen aan het numeriek model toegevoegd worden en gekoppeld worden aan de hydraulische module. Verder dient men na te gaan of voldoende gegevens beschikbaar zijn betreffende watertemperatuur en of ook dit aspect aan het numeriek model kan toegevoegd worden.

- **Integraal waterbeheer:** in deze thesis werden reeds verschillende aspecten van het huidige waterbeheer aangehaald. Aangezien verschillende onderwerpen onbesproken bleven verdient het aanbeveling om de evaluatie van integraal waterbeheer in het Orange-Senqu-Fish bekken verder te zetten.

Contents

List of Figures

List of Tables

List of abbreviations

ARC-OVI	Agricultural Research Council - Onderstepoort Veterinary Institute
Bti	Bacillus thuringiensis Berliner var. Israelensis de Barjac (serotype H-14)
DA	Department of Agriculture
DDT	dichlorodiphenyltrichloroethane
DHI	Danish Hydraulic Institute
DMS	dimethylsulfide
DO	Dissolved Oxygen
DWA	Department of Water Affairs
EC	Electrical Conductivity
EFR	Environmental Flow Requirement
EMC	Ecological Management Class
EWR	Environmental Water Requirements
FWA	Fractional Water Allocation
FWACS	Fractional Water Allocation and Capacity Sharing
IFR	Instream Flow Requirement
IQR	InterQuartile Range
IUCN	the International Union for Conservation of Nature
IWRM	Integrated Water Resources Management
LHWP	Lesotho Highlands Water Project
LOR	Lower Orange River
LOROS	Lower Orange River Real-time Operating System
LORS	Lower Orange River System

LOWMA	Lower Orange Water Management Area
MAR	Mean Annual Run-off
MSL	Mean Sea Level
MW	Mega Watt
NA	Republic of Namibia
NIB	Nkwaleni Irrigation Board
NWA	National Water Act
NWRS	National Water Resources Strategy
ORBCP	Orange River Blackfly Control Programme
ORM	Orange River Mouth
PRROR	Private-based River and Reservoir Operating Rule
R	Rand (South African currency)
RSA	Republic of South Africa
UNESCO	United Nations Educational, Scientific and Cultural Organization
WMA	Water Management Area
WRC	Water Research Commission
WRPM	Water Resources Planning Model
WRYM	Water Resources Yield Model
WUE	Water use efficiency

Chapter 1

Description of the Orange River catchment

1.1 Introduction

The Orange River catchment is the largest catchment in South Africa. In fact, this is the largest river basin south of the Zambezi. The Orange River rises in the Drakensberg mountains in Lesotho at an altitude of about 3300 m, from where it starts flowing to the west. The water flows for approximately 2200 km, until it reaches the Atlantic Ocean. The Orange River is non-navigable, except for boats for fishing and recreational purposes.

More than half of the catchment is inside the Republic of South Africa, with the remainder in Lesotho, the Republic of Botswana and the Republic of Namibia. In particular, the Orange River forms the international border between South Africa and Namibia.

In order to meet agricultural, urban and industrial demands, several dams and weirs have been constructed along the river. These dams disturb the natural river flows, impacting on the environmental condition of the river.

The Orange River is also known as the Gariep River, which means 'great river' in the original Nama language. In Afrikaans, the Orange River is referred to as Oranjerivier. The part of the Orange River flowing in Lesotho is known as the Senqu River.

1.2 The Orange and its tributaries

Figure A.1 (Appendix section) shows a map of the Orange-Senqu river catchment. This catchment extends over four countries: South Africa, Lesotho, Namibia and Botswana. As can be seen on the map, the central part of the RSA contributes the most to the total area of the river basin. The catchment area also includes the utmost southern part of Botswana, more than half of the Namibian surface area south of Windhoek and the whole of Lesotho (table 1.1).

Table 1.1: Orange River catchment area

South Africa	$580{\cdot}10^3$ km^2 (59 %)
Namibia	$260{\cdot}10^3$ km^2 (26 %)
Botswana	$120{\cdot}10^3$ km^2 (12 %)
Lesotho	$25{\cdot}10^3$ km^2 (3 %)
Total catchment area	$985{\cdot}10^3$ km^2 (100 %)

Below, a more detailed description of the catchment in each country is presented. Some attention is paid to the tributaries of the Orange River, although this description will be confined to the most significant tributaries.

1.2.1 Lesotho

The Orange River originates in Lesotho, where it is better known as the Senqu River. Its source is situated in the Lesotho highlands, near mount Thabana Ntlenyana. In these high rainfall areas, the water is drained by the Senqu River. These upper reaches of the Senqu River can be considered as the origin of the Orange River. As soon as the Senqu River crosses the Lesotho border and enters the RSA, it is known as the Orange River. The Caledon River forms for most of its length the north-western border between Lesotho and the RSA. Two main tributaries of the Senqu River are the Malibamutso River and the Senqunyane River, which will be of importance in section 2.1.

1.2.2 Republic of South Africa

Within South Africa, the Orange River catchment can be subdivided into the Integrated Vaal River System and the Larger Orange River system. One should notice that the Vaal River System is operated almost independently from the Orange River system. Of course, both systems are connected at the confluence of the Orange and the Vaal River, where surplus water from the Vaal River system joins the Orange River. The Vaal River system will only be described briefly, as this part of the catchment is of minor concern for the presented study.

Integrated Vaal River system

The Vaal River is one of the major tributaries of the Orange River. The confluence of these rivers is located in the Siyancuma rural area, near Kimberley. The Vaal River originates in the vicinity of Ermelo, which is located approximately 200 km east of Johannesburg. The stream length measured from the source up to the confluence is more than 1000 km. Although the Vaal River has several major tributaries, only the Riet River will be of further importance for this report.

Larger Orange River system

The **Upper Orange River** has been defined as this part of the Orange River upstream of the Orange-Vaal confluence, as well as the Riet-Modder catchment. Although the Riet and Modder rivers are tributaries of the Vaal, these rivers are considered to be part of the Upper Orange River system as several water transfers take place from the Orange River to the Riet-Modder system. These water transfers are being established by the appropriate infrastructure (section 2.2).

The Kraai and Caledon rivers can be described as the main tributaries to this part of the Orange. The Kraai River is draining from the north Eastern Cape. The Kraai-Orange confluence is located at Aliwal North. The Caledon River determines the north-western border of Lesotho. Near Qibing (RSA), the Caledon River starts diverging from the Lesotho border. From then on, the Caledon starts flowing through the Free State Province (RSA), until she reaches the Orange River at Bethulie. The confluence of both rivers is situated a few kilometers upstream of Lake Gariep.

The **Lower Orange River** can be specified as the river section downstream of Marksdrift, until it reaches the Atlantic Ocean at Alexander bay. This part of the river is mainly situated in the Northern Cape Province. The most downstream section of the Lower Orange River determines the border between Namibia and the RSA.

The major tributaries draining into this part of the river are being described below, consecutively from upstream to downstream. The Ongers River joins the Orange some 35 km upstream of Prieska. This river drains the northern part of the Karoo semi-desert. Hartbees River joins the Orange at about 80 km downstream of Upington. Both the Ongers and Hartbees are characterized by their seasonal flow, however this seasonality is smoothed down due to dam storage. The Molopo River historically joined the Orange approximately 120 km downstream of Upington. Since at least 1000 years, the flow from the Molopo is not reaching the Orange River as sand dunes near Noenieput (RSA) have blocked its course. The Molopo and its tributaries drain this part of the Northern Cape Provence situated north of the Orange as well as the southern parts of Botswana.

1.2.3 Namibia

The Fish River is located in Namibia, and can be considered as Namibia's major tributary to the Orange River. The Fish originates south of Windhoek. This river flows mainly in a southern direction, until it reaches the Orange after 636 km. The Orange-Fish confluence is situated some 100 km upstream of the Orange River mouth. Although the Fish is Namibia's largest river within the Orange catchment, one cannot rely on the Fish for satisfying downstream water demands because of the highly sporadic character of this river.

1.2.4 Botswana

The international boundary between Botswana and the Republic of South Africa is determined by the Molopo and Nossob rivers. The confluence of the Molopo and Nossob is located at the utmost southern tip of Botswana. The Molopo originates in Botswana, while the Nossob River originates in Namibia. These rivers are not considered to make a meaningful contribution to the surface water resources.

1.3 Climate

1.3.1 Classification

The climate of South Africa can be characterized using the Köppen-Geiger climate classification, which is one of the most widely used climate classification systems. Two climate classes are applicable to the South African climate. Class B comprises dry climates, where the potential evaporation and transpiration exceed the precipitation. Class C includes moist subtropical mid-latitude climates, characterized by warm and humid summers with mild winters. Both classes can be subdivided into the following minor types (table 1.2).

Table 1.2: Köppen-Geiger climate classification [1].

1st	**2nd**	**3rd**	**Description**
B			Arid
	W		Desert
	S		Steppe
		h	Hot
		k	Cold
C			Temperate
	s		Dry summer
	w		Dry winter
	f		Without dry season
		a	Hot summer
		b	Warm summer
		c	Cold summer

Figure 1.1 presents an overview of the Köppen-Geiger classification for the entire Orange-Senqu River basin. On the right-hand side of the map, one can see Lesotho with its (mainly) temperate C-climate. The Orange River rises in the mountains of Lesotho, where large volumes of water are inserted into the Orange River due to snow melt and the local humid summers. Once the river has left Lesotho, it encounters a very arid B-climate. In particular, this means that the evaporation fairly exceeds the precipitation. The climate

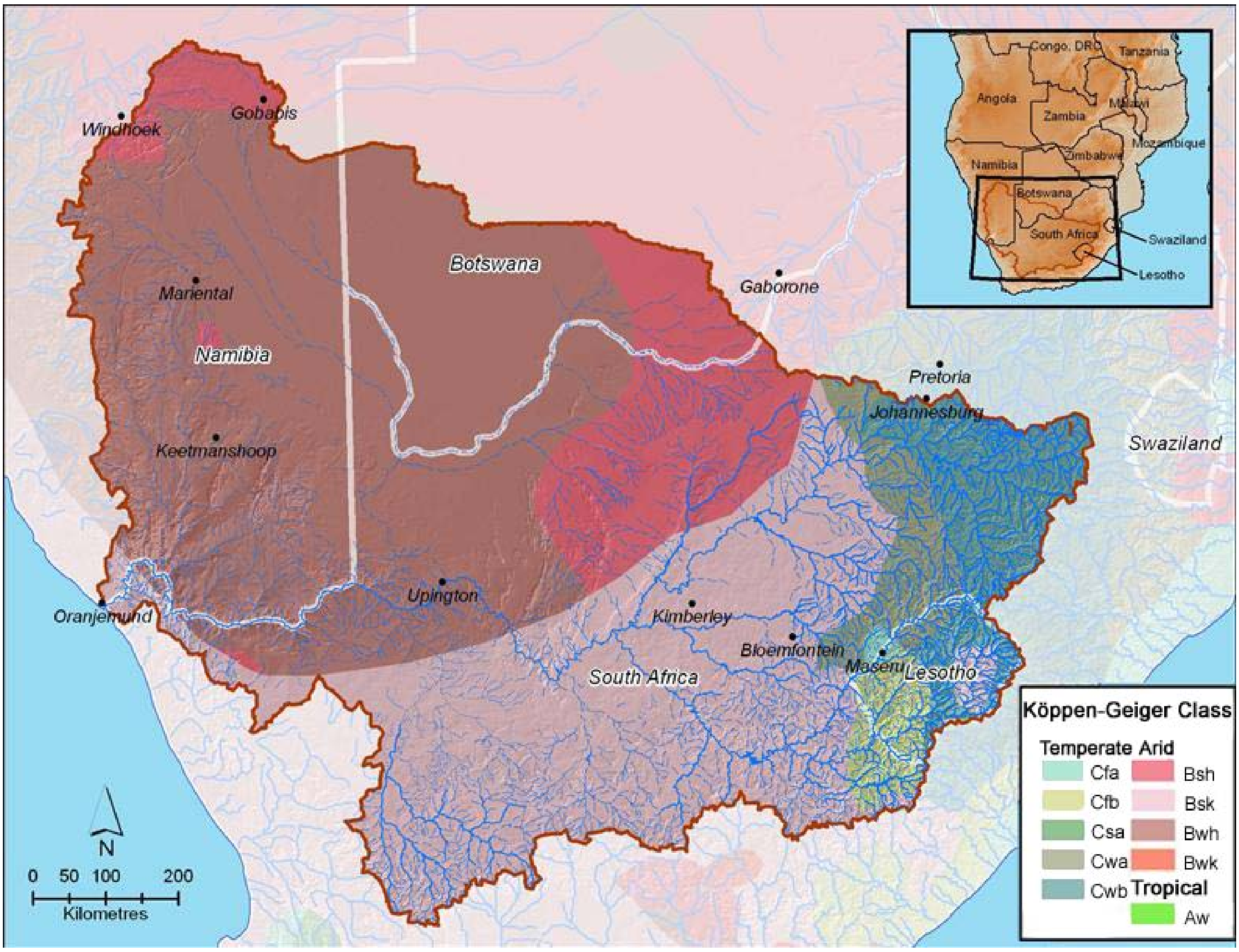


Figure 1.1: Köppen climate classes in the Orange-Senqu basin [1].

downstream of Upington is the most severe, reflected by semi-desert areas.

1.3.2 Rainfall

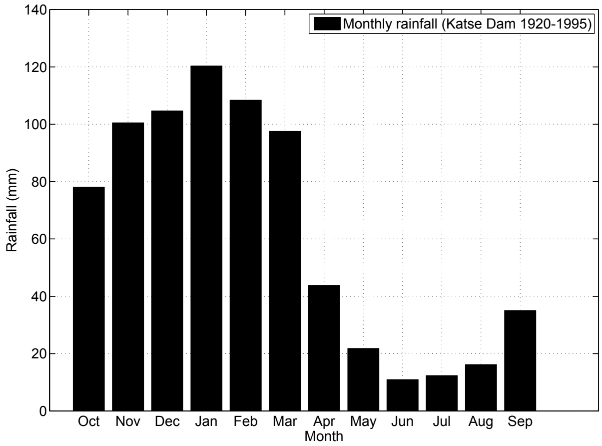
As mentioned above, several climate classes can be encountered in the Orange River catchment. Figure 1.2 illustrates this conclusion by showing the average monthly rainfall for 3 locations in the Orange-Senqu catchment. Katse Dam is located in the Lesotho Highlands. Vanderkloof Dam is situated approximately 1400 km upstream of the Orange River mouth. Naute Dam is constructed on the Fish River, and is exposed to the same arid conditions as the downstream part of the Orange which forms the international border with Namibia.

In fact, the climatic conditions become more arid when moving in downstream direction, as reflected by the decreasing maximum monthly values. This finding is also confirmed by table 1.4, where the annual precipitation from Vanderkloof Dam to the river mouth is represented. However, all 3 bar graphs show the same trend, i.e. a humid local summer (mid-October to mid-February) and autumn (mid-February to April) and a dry local winter (May to July) and spring (August to mid-October).

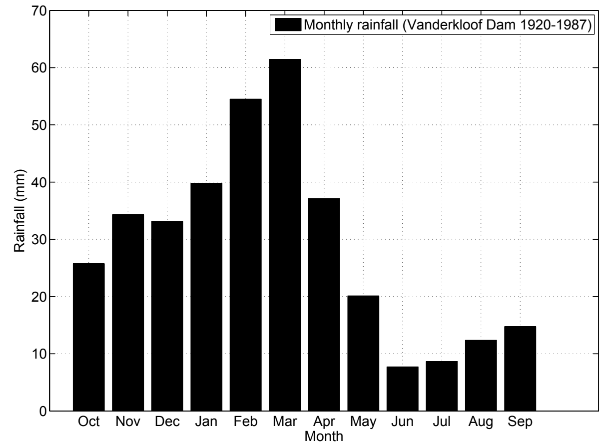
The average yearly rainfall values have been summarized in table 1.3. The average rainfall at the Drakensberg Mountains (near the source of the Senqu) fairly exceeds 1000 mm per year.

Table 1.3: Average yearly rainfall at Katse Dam, Vanderkloof Dam and Naute Dam.

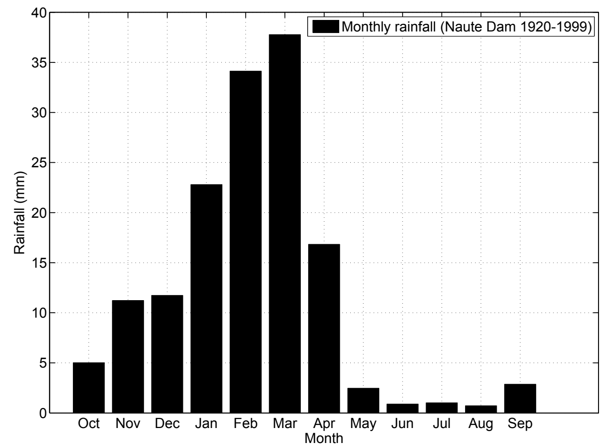
Location	**Average yearly rainfall** (mm)
Katse Dam	750
Vanderkloof Dam	350
Naute Dam	148



(a) Katse Dam (1920-1995)



(b) Vanderkloof Dam (1920-1987)



(c) Naute Dam (1920-1999)

Figure 1.2: Average monthly rainfall (mm): Katse Dam, Vanderkloof Dam, Naute Dam.

The variability of precipitation should be recognized as a critical factor for the understanding of the local climate. On a long time scale, this means that periods of drought alternate with higher rainfall periods. For example, 1984 fell in a drought period, reflected by a yearly rainfall of 433 mm at Katse Dam. In contrast, a yearly rainfall of 1005 mm has been recorded in 1975 (above-normal rainfall period) at Katse Dam. On a short time scale, the variability expresses itself for example in the occurrence of flood periods. These flood events are of particular ecological importance, e.g. a flood removes the sediment by flushing the river. The last big flood (until now, 2010) occurred in 1988. During February, heavy rainfall has been measured all over the river catchment. This resulted in immense flooding of the river, with peak discharges up to 8300 flowing through the river. Figure 1.3 compares the measured rainfall during February 1988 with the average rainfall for February at Katse Dam and Naute Dam.

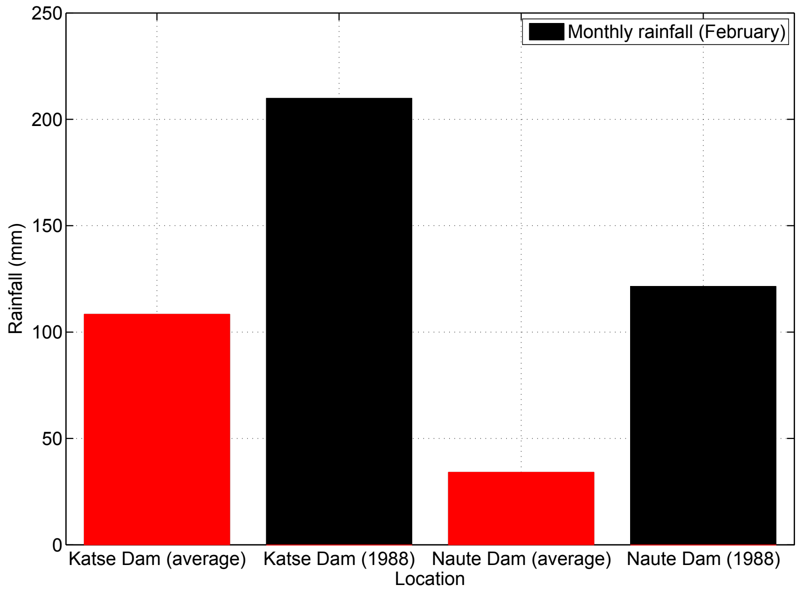


Figure 1.3: Average monthly rainfall (mm) compared with the February 1988 rainfall (mm) for Katse Dam and Naute Dam.

1.3.3 Evaporation

As stated above, the part of the Orange downstream of Vanderkloof Dam flows through an arid Köppen class B landscape. This is reflected by table 1.4, where the gross evaporation (i.e. rainfall has not been subtracted) fairly exceeds the precipitation. This river section is of particular importance for the continuation of this report, as the modelling section of this study will deal with this part of the river. Contrary to the precipitation distribution, the annual evaporation is quite constant. In other words, the total annual evaporation only shows little variation when comparing different years. The annual evaporation also remains steady along the river length downstream of Vanderkloof Dam. The evaporation data illustrated in table 1.4 has been measured by a Symon's evaporation tank. This tank was adopted many years ago as standard in South Africa.

Table 1.4: Symon's pan evaporation and precipitation downstream of Vanderkloof Dam [2].

From	**To**	**Gross evaporation** (mm/a)	**Precipitation** (mm/a)
Vanderkloof Dam	Orange/Vaal	2200	300
Orange/Vaal	Boegoeberg	2340	230
Boegoeberg	Kakamas	2590	150
Kakamas	20°E Meridian	2700	100
20°E Meridian	Vioolsdrif	2600	100
Vioolsdrif	Orange/Fish	2400	50
Orange/Fish	River mouth	2100	50

Figure 1.4 shows the average monthly evaporation at Vioolsdrift (ca. 300 km upstream of the river mouth). As the evaporation data is correlated with temperature data, the highest evaporation losses could be expected during summer, while the lower evaporation values could be expected during winter, which is indeed confirmed by figure 1.4.

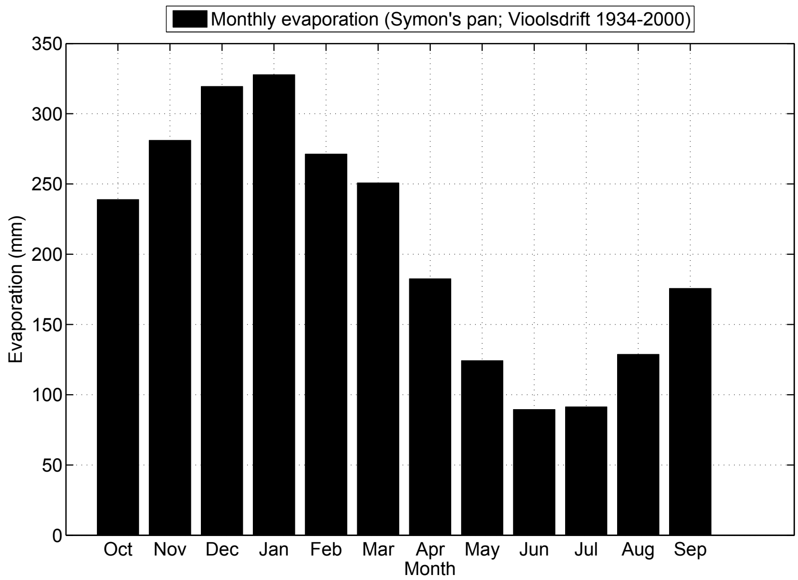


Figure 1.4: Average monthly Symon's pan evaporation (mm) at Vioolsdrift.

1.3.4 Natural run-off

The natural run-off of the entire Orange-Senqu basin (Vaal included) amounts to 11 500 million m^3 per year. The catchment downstream of the Orange-Vaal confluence only contributes 800 million m^3 per year, which is approximately 7% of the total run-off. The run-off originating from the catchment downstream of the Orange-Vaal confluence is highly erratic due to the arid climate in this region. This means that one cannot rely on this run-off to support the downstream water demands, as no major storage infrastructure has been constructed on this part of the river.

Table 1.5 illustrates the contribution of each subcatchment to the total run-off water volume. One should notice the small area and the large MAR value of the Lesotho Highlands subcatchment, indicating the humid local climate. The Namibian semi-desert area only contributes little to the total run-off, which again is accounted for by the local climate.

Table 1.5: Mean annual run-off (MAR) of the Orange-Senqu subcatchments (1920-1987)[3].

Subcatchment	**Catchment area** (km^2)	**Natural MAR** (10^6 m^3/a)
Riet-Modder	20 114	401.73
Lesotho Highlands	24 752	4065.41
Caledon	15 245	1216.82
Upper and Lower Orange	185 504	1668.72
Namibia Fish	95 680	529.67
Vaal system	129 567	3601.72
Total	**470 862**	**11 484.07**

1.4 Conclusion

This chapter presents an overview of the most important features of the river and its catchment, such as tributaries, climatic conditions and natural run-off. The content of this chapter should be interpreted as a general background to the following chapters on integrated water resources management (IWRM).

Chapter 2

Infrastructure inventory

This paragraph discusses on the present infrastructure in the Orange River, consecutively in a downstream direction. However, a description of the infrastructure for the whole Orange River catchment is beyond the scope of this report.

2.1 Lesotho

The Lesotho Highlands Water Project (LHWP) is a major water transfer scheme, undertaken by the Kingdom of Lesotho and the Republic of South Africa. This binational project transfers water from the Lesotho highlands to the Vaal River catchment [5] [6] [7] [8] .

This project has been developed in order to supply water to the Gauteng province. The surroundings of Pretoria and Johannesburg can be considered as a major population centre and industrial area. Before the completion of the first phase of the LHWP, the Gauteng water demands were satisfied only by using water directly from the Vaal catchment. This water supply proved to be insufficient to meet the increasing industrial and domestic demands. The possibility of a water transfer scheme from the Senqu to increase the flow into the Vaal was explored since the 1950's.

These water transfers create a benefit for Lesotho by enabling the generation of hydroelectric power. This project also provides an opportunity for undertaking ancillary developments such as the provision of water for irrigation and potable water supply in the Lesotho mountain regions. The LHWP also aims at promoting the general development of the remote and underdeveloped highland areas of Lesotho. Last but not least, Lesotho receives royal payments from the RSA for the transferred water.

The original construction scheme comprised 5 phases, which have been explained in table 2.1.

Table 2.1: Overview of the Lesotho Highlands Water Project [5].

Phase	**Construction component**	**Details**
Phase 1a	Katse Dam	185 m high
	Intake structure	70 m^3/s
	Transfer tunnel	Katse reservoir to Muela reservoir (45 km)
	Muela Dam	55 m high
	Hydropower station	At Muela
	Delivery tunnel	Muela reservoir to Vaal River basin (37 km)
Phase 1b	Mohale Dam	145 m high
	Transfer tunnel	Mohale reservoir to Katse Dam (32 km)
	Matsoku Diversion Weir	15 m high
	Transfer tunnel	Matsoku Weir to Katse Dam (5.7 km)
Phase 2	Mashai Dam	155 m high
	Tunnel/pumping main	Mashai reservoir to Katse Dam (19 km)
	Transfer tunnel nr. 2	Katse reservoir to Muela reservoir (45 km)
	Hydropower station	Upgrading of Muela plant
	Delivery tunnel nr. 2	Muela reservoir to Vaal River basin (37 km)
Phase 3	Tsoelike Dam	158 m high
	Tunnel/pumping main	Tsoelike reservoir to Mashai reservoir (4.3 km)
Phase 4	Ntoahae Dam	120 m high
	Tunnel/pumping main	Ntoahae reservoir to Tsoelike Dam (4 km)
Phase 5	Malatsi Dam	120 m high
	Tunnel/pumping main	Malatsi reservoir to Ntoahae Dam (4 km)

The different place-names have been indicated on the map of figure 2.1.

Figure 2.1: Lesotho Highlands Water Project: overview of construction sites [5].

At the moment, only phase 1 has been completed. Table 2.2 illustrates the results of a yield estimate study conducted in 1993. Although this study is slightly dated, it still gives an estimate of the extent of the flow deficits that will be encountered when implementing the remaining LHWP phases. During the planning phase of the LHWP project, one has estimated that a surplus of 1078 million m^3/a would be available even after full implementation of the LHWP, when neglecting the environmental demands of the river. However, the study under concern indicates that a flow deficit of 842 million m^3/a will occur when the LHWP is fully implemented and the environmental demands have been neglected in the calculation. Currently one is investigating the feasibility of the second phase of LHWP.

This phase will most probably be the last phase being implemented.

2.1.1 LHWP Phase 1a

The **Katse Dam** is one of the major developments in the Lesotho Highlands Water Project. This dam has been constructed on the Malibamutso River, which is a tributary of the Senqu River. The construction, which has been initiated in 1991, has been completed in May 1997. Less than one year later, the reservoir had been filled to the full supply level due to the abundant rainfall during this year and the previous season.

With a height of 185 m, it is the highest concrete arch dam in Africa. More specifications are presented in table 2.3.

Approximately 80 km of tunnels enable the transportation of water stored at Katse Dam to the Upper Vaal basin. The first section of this tunnel scheme is referred to as the **transfer tunnel**. This tunnel links Katse reservoir to the Muela reservoir and has a total length of 45 km. This tunnel has been excavated in basalt rock and has been concrete-lined for its entire length. With an internal diameter of 4.35 m, it can transfer a maximum discharge of 36 m^3/s. The water from Katse reservoir is transferred into this tunnel through a 98 m high intake tower.

At Muela, the water en route to South Africa powers an underground **hydroelectric station**. This hydropower station allows Lesotho to provide in its own electricity needs, as before the construction of this power station, electricity had to be bought from South Africa.

The underground power station has a capacity of 72 MW. Three 24 MW turbines transform the piezometric head of 300 m into electrical energy. The water exiting the power station flows into the Muela reservoir, impounded by the Muela Tail Pond (or Muela Dam).

Muela Tail Pond is a concrete arch dam situated on the Nqoe River. Table 2.4 shows more details on this dam.

The water can continue its way to South Africa by flowing into the inlet construction situated in the dam basin. This intake structure leads to the Delivery Tunnel, i.e. the second part of the tunnel scheme.

Table 2.2: Estimated water balance (1993) at Vanderkloof Dam for LHWP development level 5 and 1b [9] (Orange-Fish Tunnel and Orange-Riet Canal transfers have been included).

	Up to Phase 5 (10^6 m^3/a)		**Up to Phase 1b** (10^6 m^3/a)	
Details	**Demand**	**Balance**	**Demand**	**Balance**
Yield available at 90% assurance	-	**2530**	-	**3550**
River losses	800	**1730**	800	**2750**
Current irrigation demands	1496	**234**	1496	**1254**
Imminent irrigation development	362	**-128**	362	**892**
Future schemes	714	**-842**	714	**178**
Environmental demands at the river mouth	244	**-1086**	244	**-66**

The **Delivery Tunnel** is a 37 km long conveyance system. It consists of the 15 km long Delivery Tunnel South in Lesotho and the 22 km Delivery Tunnel North in the RSA. The Delivery Tunnel ends eight kilometers north of Clarens in the Ash River. The flow through the tunnel is recorded, as this information is used to calculate the allowance the RSA has to pay to Lesotho.

The water from the Delivery Tunnel is discharged into the Ash River. From then on, the water follows the natural watercourse into the Liebenbergsvlei and Wilge Rivers towards the Vaal Dam.

Water can also be released into the Little Caledon River through two outlet valves situated some 10 km before the outfall into the Ash River. This is referred to as the Little Caledon Bypass, enabling the diversion of approximately 50 % of the Lesotho water into the Caledon River down to the Welbedacht Dam, in order to supply the eastern, central and southern Free State as well as the Lesotho border under serious drought conditions.

2.1.2 LHWP Phase 1b

This phase of the LHWP is designed to increase the inflow into Katse Reservoir and to raise the average flow to South Africa from 16.8 m^3/s (Phase 1a) to 28.5 m^3/s. Through

Table 2.3: Katse Dam: specifications.

Type	Double curvature concrete arch
Height above foundation	185 m
Crest length	710 m
Total storage capacity	1950 million m^3
Active storage capacity	1519 million m^3
Full supply level (fsl)	2053 masl[1]
Reservoir area at fsl	35.8 km^2
Minihydro Plant Capacity	500 kW

Table 2.4: Muela Dam: specifications.

Type	Double curvature concrete arch
Height above foundation	55 m
Crest length	200 m
Total storage capacity	6 million m^3

this increase in discharges, use is made of (almost) the full theoretical capacity of the Phase 1a tunnel scheme.

The **Mohale Dam** (table 2.5) is situated on the Senqunyane River, which is a main tributary of the Senqu River. It is the highest dam of its type in Africa. The construction started in March 1998.

Table 2.5: Mohale Dam: specifications.

Type	Rock-fill embankment (concrete-faced)
Height above foundation	145 m
Crest length	600 m
Total storage capacity	947 million m^3
Active storage capacity	857 million m^3
Full supply level (fsl)	2075 masl
Reservoir area at fsl	21.2 km^2
Minihydro Plant Capacity	500 kW

[1] meters above sea level

The **transfer tunnel from Mohale to Katse** provides a connection between Mohale reservoir and Katse reservoir, allowing flow in either direction, in order to keep each dam at the optimum operating level. This tunnel is 32 km long and has a diameter of 4.5 m. The transfer tunnel has a theoretical capacity of 9.5 m^3/s.

In order to increase the water volumes delivered to South Africa, **Matsoku Weir** has been built. This investment has enabled an increase of the average flow to the RSA by 2.2 m^3/s.

Matsoku Weir is a mass gravity diversion weir with a height of 19 m and has a crest length of 180 m. The base flow passes the weir and continues its natural way, while the excess water during peak flows enters a tunnel. This tunnel is called the **Matsoku Tunnel**. It is 5.6 km long, and connects Matsoku with the Katse reservoir. This tunnel drains into the Katse reservoir some 16 km upstream of the dam.

2.2 South Africa

In the framework of the **Orange River project**, several water schemes have been developed [10]. The Orange River Project aims to provide both the Upper and Lower Orange WMA (Namibia included) with water. Water supply to users in the Eastern Cape Province has also been intended, in particular to the Fish to Tsitsikama WMA. The text below amplifies on the major infrastructure of the Orange River Project.

2.2.1 Upper Orange sub-system

Figure 2.2 illustrates an overview of the infrastructure in the Upper Orange sub-system.

Gariep Dam

The Gariep Dam (previously the Hendrik Verwoerd Dam) is situated along the Orange River, some 180 km south of Bloemfontein. Its storage reservoir is the largest in the RSA, extending over more than 370 km^2 at full supply level. The construction commenced in 1967, and was finished in 1971. Table 2.6 illustrates some technical details on the Gariep Dam.

The hydropower plant consists of 4 units, producing 90 MW of electricity each at a maximum discharge of 220 m^3/s. This hydropower station can therefore provide up to 360 MW

Table 2.6: Gariep Dam: specifications.

Type	Double curvature concrete arch
Height above foundation	90.5 m
Crest length	947.9 m
Total storage capacity	5348 million m^3
Active storage capacity	4710 million m^3
Hydropower capacity	360 MW

at a flow rate of more than 800 m^3/s. The piezometric head, which is the driving force for the electricity generation, is 55 m [11].

The water released from Gariep Dam moves on to the Vanderkloof Dam reservoir. Under normal conditions, only water from the hydropower plant is being released. In case of a flood event, 6 radial gates can release surplus water into 6 concrete chutes, with a maximum discharge of 8000 m^3/s. These chutes discharge the water further downstream of the dam, in order to prevent soil erosion at the base of the dam.

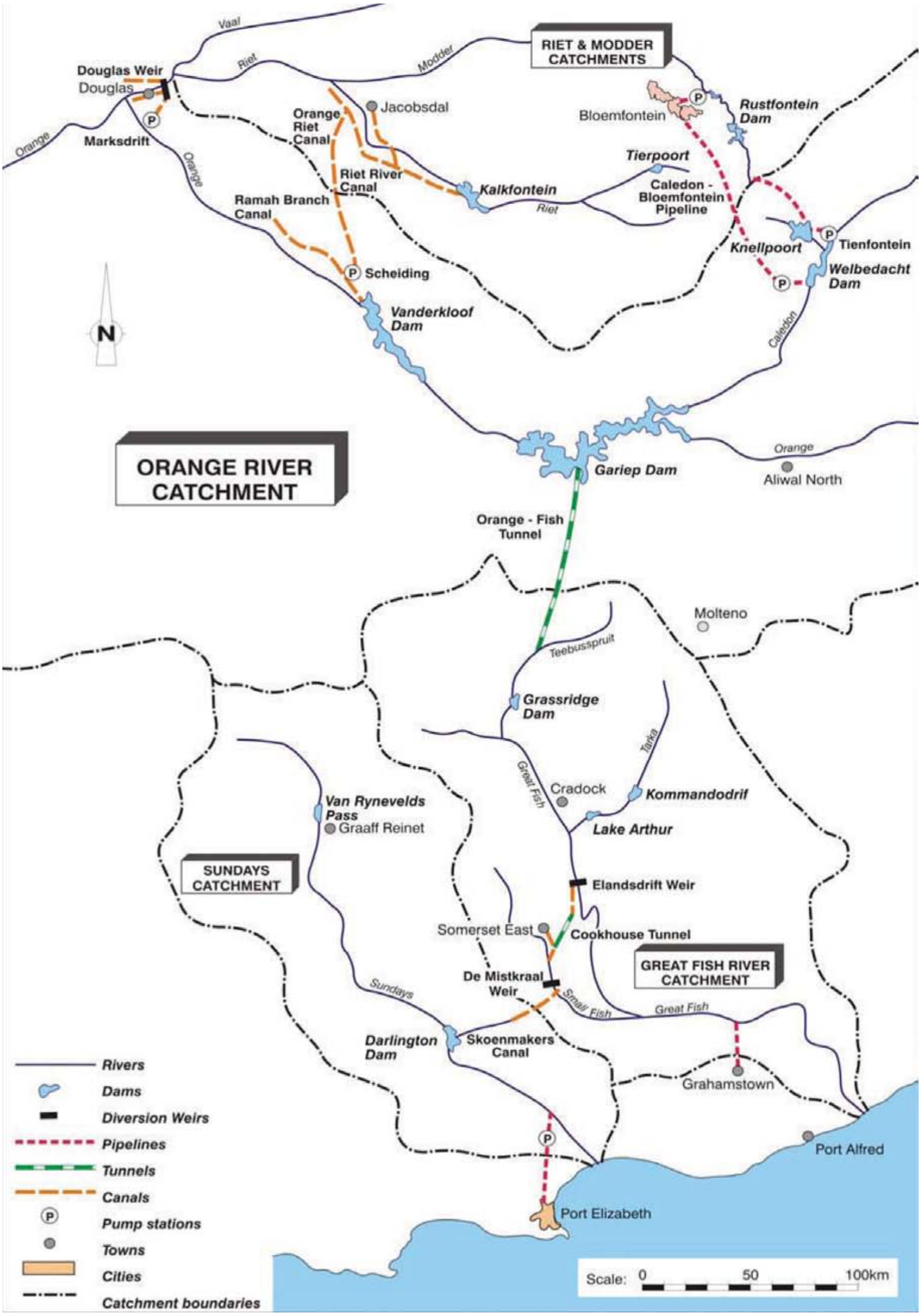


Figure 2.2: Transfer schemes for the Upper Orange River [4].

Orange-Fish transfer scheme.

The Orange-Fish tunnel transfer scheme (table 2.7) connects the Orange River to the Fish River catchment, in order to provide the Eastern Cape Province with water for irrigation, urban and industrial purposes. This tunnel is the longest continuous enclosed aqueduct in the Southern Hemisphere and the third-longest water supply tunnel in the world. The first tunnel excavations started in 1968. Construction was finished in December 1974.

Table 2.7: Orange-Fish transfer scheme: specifications

Length	82.8 km
Fall	1:2000
Internal diameter	5.3 m
Capacity	56 m^3/s

The tunnel inlet is located in the Gariep Dam reservoir, some 9 m above the original bed level of the Orange River, or 30 m below the full supply level of the dam. The inlet tower structure has a height of 77.7 m and an external diameter of 38 m. It is situated near Oviston, approximately 19 km upstream of the dam wall. The tower has intakes at six levels, so that relatively sediment-free surface water can be drawn off at different water levels. About a quarter of the flow in the Orange River entering Gariep Dam is diverted through the Orange-Fish tunnel.

Vanderkloof Dam

Vanderkloof Dam (formerly known as P.K. Le Roux Dam) is situated on the Orange River, some 124 km downstream of the Gariep Dam. It is currently the highest dam in South Africa. The construction of the Vanderkloof Dam started in 1971, and it has been completed in 1977. See table 2.8 for more details.

Table 2.8: Vanderkloof Dam: specifications.

Type	Double curvature concrete arch
Height above foundation	108 m
Crest length	760 m
Total storage capacity	3189 million m^3
Active storage capacity	2173 million m^3
Hydropower capacity	240 MW

Vanderkloof Dam serves several purposes. Obviously, the dam and its reservoir are a tourist attraction. A second function is the diversion of water to the Orange-Riet irrigation system. Vanderkloof Dam also provides flood control and flow regulation, and it supplies water for urban and irrigation use along the Orange River. Vanderkloof hydropower station, which is being operated by Eskom, transforms a piezometric head of 61 m into electricity. Two generators each have a full load capacity of 120 MW at a maximum water consumption of 217 m^3/s per turbine. This means that 240 MW can be produced, discharging more than 400 m^3/s. The hydropower plants are peaking power stations, as they are able to provide a swift response to the needs of the South African energy market [11].

Vanderkloof Dam receives the water that has been released from Gariep Dam. In fact, Vanderkloof Dam commands a gross catchment area of 89 560 km^2, most of which is controlled by Gariep Dam upstream. Nevertheless, run-off from the 18 920 km^2 intermediate catchment can be appreciable. In case of flood risk, the flood sluices which are positioned on the left flank of the dam, can discharge up to 8500 m^3/s.

The Vanderkloof Canals scheme comprises two main canals, i.e. the Orange-Riet Transfer Canal and the Ramah Canal, which have been described below.

Orange-Riet transfer scheme

The Orange-Riet transfer scheme drains water from the Vanderkloof Dam reservoir and transports it to the Riet River Catchment via the Orange-Riet Canal (table 2.9). Although the water is primarily intended for irrigation purposes, it is also being used to supply the urban requirements of Koffiefontein (including mining requirements), Ritchie and Jacobsdal. Construction has been completed in 1987.

Water is released from the Vanderkloof Dam into the Vanderkloof Main Canal. This canal is 14 km long and has a capacity of 57 m^3/s. At the Scheiding pump station, water from the Main Canal is pumped to a higher level (47 m higher) and discharged into the Orange-Riet Canal. The remainder of the Vanderkloof Canal is known as the Ramah Branch Canal, and has been discussed in the next paragraph.

Table 2.9: Specifications of the Orange-Riet Canal: length, capacity and the irrigated areas.

Length	112.6 km
Capacity (first 74.6 km)	15.6 m^3/s
Capacity (last 38 km)	13.2 m^3/s
Irrigation next to the canal	3787 ha
Riet River Settlement Jacobsdal	7812 ha
Scholtzburg Irrigation Board	637.1 ha
Ritchie Irrigation Board	96.8 ha
Lower Riet Irrigation Board	3937.1 ha

Ramah Canal

The remainder of Vanderkloof Canal, after passing the Scheiding pump station, is known as the Ramah Canal. This canal runs along the Orange River, and supplies water to the irrigation areas along the right bank of the Orange River. The Ramah Canal has 3 reaches, i.e. Ramah I, II and III, illustrated in table 2.10.

Table 2.10: Specifications of the Ramah Canal: length, capacity and the irrigated area.

Length (Ramah I)	17.3 km
Length (Ramah II)	48.9 km
Length (Ramah III)	21.2 km
Capacity (Ramah I)	9.6 m^3/s
Capacity (Ramah II)	4.2 m^3/s
Capacity (Ramah III)	1.48 m^3/s
Total irrigation area	5667 ha

Douglas Weir

Although Douglas Weir is situated on the Vaal River, it is discussed briefly in this section, as it is of importance in the rest of this study.

Douglas Weir is currently the last flow gauging station in the Vaal River upstream of the Orange-Vaal confluence. In order to successfully model the Orange River, one should consider Douglas Weir as a boundary condition of the model.

Douglas Weir was originally completed in 1896, and has been replaced by a higher concrete structure in 1976. This structure is a saw tooth shaped, broad crested storage weir. A Crump low notch is built on top of the storage weir on the right bank side. This notch has been added specifically in order to measure low flows, enabling a more accurate management of this part of the Vaal River and the surrounding irrigation schemes. The low notch limit is 8 m^3/s. However, this limit is exceeded regularly, resulting in water spilling over the broad crested saw teeth. Due to its specific geometry, the accuracy of spills over the weir up to 60 m^3/s is very low. So as to improve the accuracy of the flow measurements, one is investigating the possibility of a new weir downstream of Douglas Weir [12].

Orange-Vaal transfer scheme

The Orange-Vaal transfer scheme consists of a pumping station on the Orange River at Marksdrift, a rising main and a 22 km canal, known as the Bosman Canal, terminating at Douglas Weir on the Vaal River. This transfer scheme has a maximum capacity of 6 m^3/s.

It was initiated in 1984 as an emergency scheme in order to overcome problems of chronic water shortage and to lower the unacceptably high level of salinity of the irrigation water.

From Douglas Weir, water is discharged into a 24 km long canal on the left bank of the Vaal River, called the Douglas Canal, which leads to the Orange-Vaal confluence. On the right bank of the Vaal River, the Atherton Canal supplies water to the Atherton plots.

This scheme provides water to an irrigation area of 8113 ha.

2.2.2 Lower Orange sub-system

This section is particularly describing the irrigation schemes in the Lower Orange region. Certain amounts of water are also being drained directly from the river by the irrigators, however, these discharges are small compared to those drained by the formalised irrigation schemes. Figure 2.3 illustrates the locations of the infrastructure under concern.

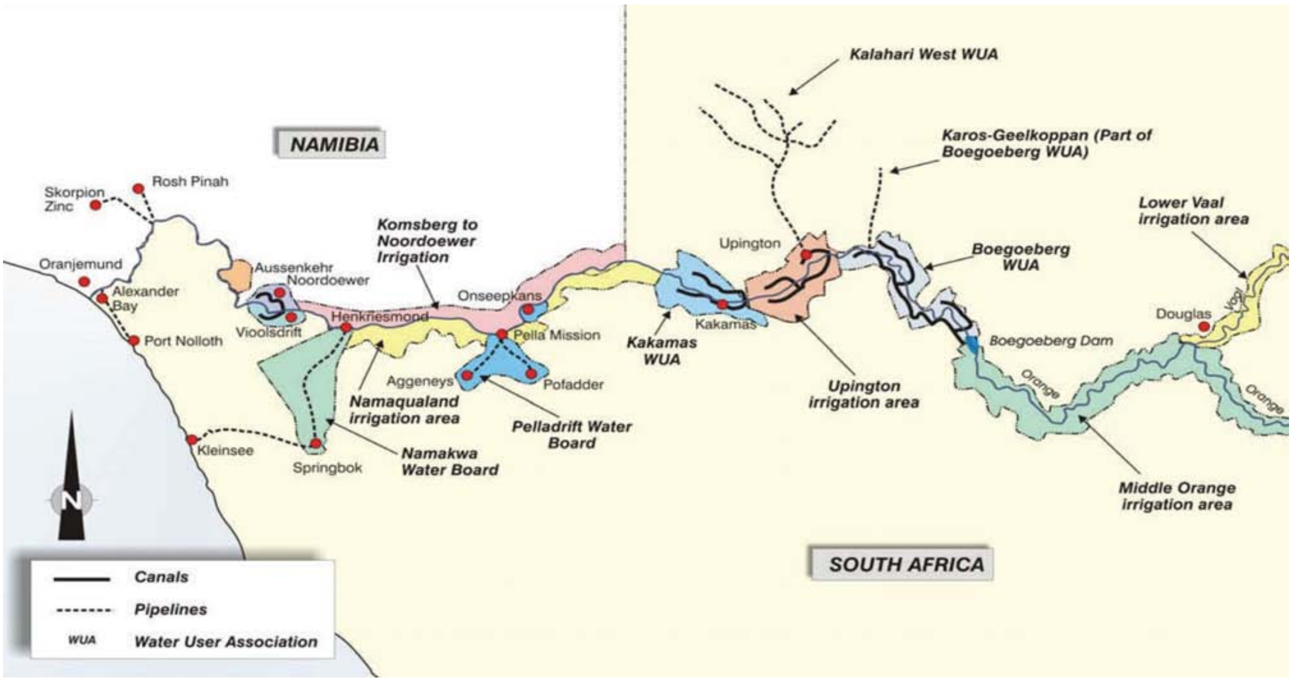


Figure 2.3: Water abstraction infrastructure in the Lower Orange River [4].

Middle Orange irrigation area

This irrigation area consists of the riparian irrigators, situated from Hopetown to Boegoeberg. The area from Hopetown to the Orange-Vaal confluence is included in the Upper Orange sub-system. The area downstream of the Orange-Vaal confluence is located in the Lower Orange sub-system, and amounts to 15 434 ha. In the Middle Orange irrigation area, no common supply system has been developed, forcing the irrigators to directly abstract water from the Orange River on an individual basis.

Boegoeberg Dam and irrigation scheme

Boegoeberg Dam (table 2.11) was built in 1931. It is situated 164 km upstream of Upington. The initial capacity of 34.7 million m^3 has been reduced due to sedimentation. At the moment, this sedimentation process seems to have met an equilibrium state.

Table 2.11: Boegoeberg Dam: specifications.

Type	Concrete gravity storage weir
Height above foundation	9 m
Crest length	622 m
Total storage capacity	20.7 million m^3

Boegoeberg Dam supplies water to the Boegoeberg Canal scheme on the left bank. The main canal is 172 km long and has a design capacity of 9.76 m^3/s. Two siphons lead the water to the right bank of the river, discharging into the Noord-Oranje Canal and the Gariep Canal respectively. The Boegoeberg Irrigation Scheme nearly provides the whole irrigated area from Boegoeberg to Upington.

Upington Irrigation Board Canal and Gifkloof Weir

Gifkloof Weir is situated 18 km upstream of Upington. This weir provides water to the Upington Irrigation Board Canal which is located on the right bank of the Orange. Gifkloof Weir also diverts water to the left bank of the Orange. The left bank canal has a design capacity of approximately 10 m^3/s. Both banks of the river and the islands in the river are supplied with irrigation water via a network of siphons and secondary canals. The irrigation scheme under concern provides water to more than 6000 ha of land.

Keimoes Canal irrigation area

In the vicinity of Keimoes several irrigation boards have been developed with their own diversions, providing more than 5000 ha of land with irrigation water. Certain amounts of water are also being drained directly from the river by the irrigators, however, these discharges are small compared to those drained by the formalised irrigation schemes.

Kalahari rural water supply scheme

The Kalahari rural water supply scheme comprises the Kalahari West, Kalahari East and the Karos-Geelkoppan rural water supply schemes. This scheme provides water to the Kalahari semi-desert areas. A more detailed description of the scheme is beyond the scope of this text, as the discharges being drained from the river are small compared to the other schemes.

Neusberg Weir

Neusberg Weir (table 2.12) is situated on the Orange River, some 12 km upstream of Kakamas. It was completed in 1993. Neusberg Weir has been developed mainly for irrigation purposes. The construction of a weir at this location gives the benefit of being able to measure the flow accurately, before the Orange River encounters the Namibian border.

Table 2.12: Neusberg Weir: specifications.

Type	Storage weir
Height above foundation	5 m
Crest length	995 m
Total storage capacity	2 million m^3

Kakamas Irrigation Scheme

The Kakamas Irrigation Scheme is located near Kakamas and the Neusberg Weir. It consists of two schemes, namely the South-Furrow Canal scheme on the left bank of the river, and the North-Furrow Canal scheme on the right bank of the river. These canals have been constructed in 1898 and 1908 respectively, long before Neusberg Weir was built. Because problems were experienced creating sufficient flow in the main irrigation canals, Neusberg Weir was constructed.

The development of Neusberg Weir led to an increase of the capacity of the irrigation scheme. Being 3 m^3/s before the construction of Neusberg Weir, the maximum capacity of the South-Furrow scheme is 6.8 m^3/s, while the North-Furrow scheme can drain up to 7.5 m^3/s nowadays. Currently, the Kakamas Irrigation Scheme provides almost 7000 ha of land with water.

This scheme can be described as one of the most productive irrigation schemes in South Africa. The Kakamas irrigation water is being used for the production of high value table grapes, intended for local and international trade.

Rhenosterkop Weir

Rhenosterkop Weir is situated near Marchand, some 15 km downstream of Kakamas. This weir has been built between the left bank and Paarden Island, and has an intake capacity of 7.85 m^3/s.

Onseepkans irrigation area

A canal on the left bank of the Orange supplies the Onseepkans irrigation area with water. In total, 314 ha is supplied.

Pelladrift water supply scheme

Water is drained from the Orange at Pella Mission in order to supply Pofadder, Aggenys, Black Mountain Mine and Pella Mission. The average abstracted water volume amounts to 4.48 million m^3 per year, which is low compared to the other abstraction infrastructure.

Namakwaland irrigation area

The Namakwaland irrigation area extends between Henkriesmond and Pella Mission. The scheduled area amounts to more than 2400 ha.

Namakwa water board water supply scheme

In order to guarantee the water supply to the Namakwa area, this scheme has been constructed due to insufficient water resources from boreholes. Water is abstracted from the Orange River at Henkriesmond, so as to supply Springbok, Okiep, Nababeep, Steinkopf, Concordia, Carolusburg and Kleinsee.

Vioolsdrift and Noordoewer irrigation area

At Vioolsdrift Weir, water is led into a canal system supplying the Vioolsdrift (RSA) and Noordoewer (Namibia) irrigation areas. The main canal is located on the left bank of the river and is referred to as Vioolsdrift Canal, which has a capacity of 1.28 m^3/s. Part of the water is diverted into several siphon structures in order to supply the right bank of the river with sufficient irrigation water.

Alexander Bay

Water for irrigation purposes is used on the left bank of the river upstream of Oppenheimer Bridge, resulting in more than 700 ha of irrigated land. This irrigation water is abstracted directly from the river. The domestic and mining water requirements of Alexander Bay and Port Nolloth are satisfied by using water from the well points in the Orange River near Oppenheimer Bridge.

Namibian urban and mining from the Orange River

The alluvial aquifer at the river mouth satisfies the Oranjemund domestic water demands. The mining water demands at Oranjemund are satisfied by using seawater. Water is drained from the Orange at Noordoewer and Rosh Pinah in order to meet the domestic demands. The Skorpion Mine also uses the Orange River water.

Namibian irrigation

In addition to the Noordoewer irrigation area, irrigation water is also used at the irrigation farms and small mines, by using a mobile pump allowing a variable position depending on the water level of the river. Approximately 2600 ha of land are being irrigated by this kind of riparian water abstraction.

2.3 Flow gauging stations implemented in the model

Later in this report, a method for developing a hydraulic model is described. This model is calibrated by comparing the flow simulation results to the observed data of the flow gauging stations. For each reach, the position of the downstream node coincides with the position of a calibrated weir, i.e. a flow gauging station. The flow data of the flow gauging stations mentioned in table 2.13 has been used in the continuation of this report. The chainage is the distance measured from Vanderkloof Dam in a downstream direction.

Table 2.13: Weirs implemented in the hydraulic model.

Weir	**Chainage (km)**	**Coordinates**
Dooren Kuilen	1	29°59’28.00”S 24°43’13.00”E
Marksdrift	174	29°9’43.30”S 23°41’45.40”E
Douglas Weir	- (Vaal)	29°2’36.63”S 23°50’7.05”E
Irene	204	29°10’58.30”S 23°34’30.40”E
Prieska	355	29°39’6.20”S 22°44’45.30”E
Boegoeberg	471	29°1’48.30”S 22°11’14.20”E
Upington	635	28°27’28.50”S 21°14’21.20”E
Neusberg	708	28°46’13.66”S 20°44’29.00”E
Vioolsdrift	1100	28°45’28.80”S 17°43’17.70”E

2.4 Conclusion

The Orange-Senqu-Fish system is a highly regulated system. Many dams, weirs and irrigation schemes have been constructed within this river catchment. An overview of the most important infrastructure in the Orange-Senqu River is presented in this chapter. A proper understanding of the present infrastructure provides a surplus value to the chapters dealing with human impacts on the ecosystem and the implementation of abstraction points and boundary conditions in the hydraulic model.

Chapter 3

The National Water Act (1998)

3.1 Introduction

An outline of the National Water Act (NWA) with a summary of its most essential parts is inevitable to ensure the completeness of this report. This chapter is only a brief introduction to this text of law. Both purposes and measures are briefly explained. The importance of the Act should not be underrated and can only be well understood by empathising with the South African situation. In addition to its ecological importance, the Act contributes to the socio-economic life of most South Africans.

The aim of this Master thesis is to build a hydraulic model to optimise water allocation in the Lower Orange Water Management Area (LOWMA). In addition, the use of water (no matter whether it is used for irrigation, industrial and urban demands or any other purpose) and the Environmental Water Requirements (EWR) are also discussed in this report. In the Republic of South Africa (RSA), all water related matter is provided by the law of the NWA. This Act creates a legal framework that applies to all water users in South Africa. In other words, the NWA covers all statutory regulations that have to do with the subject matter of this thesis.

This chapter consists of two main parts. The first part (see section 3.2) represents the main goals of the Act. A better understanding of some principles can be achieved by examining the political and socio-economic situation after the end of the apartheid regime. In the second part (see section 3.3) some important chapters and sections of the Act are briefly explained. Only these parts that are applicable to this report will be discussed.

3.2 Purposes and principles of the Act

3.2.1 General thought

The NWA provides a framework for managing all South African water resources in an effective and sustainable way. This legal provision, which stipulates the rights and duties of every citizen, is still applicable as it was published in 1998 with the aim of fundamentally reforming the past laws regarding water resources. These former laws were not appropriate to South African conditions and above all they were discriminatory as they prevented equitable access to water [13].

As South Africa's water resources are under increasing pressure, the government has taken action to use those resources effectively and wisely. In order to build a sustainable future, the NWA was inevitable. The central idea behind the NWA is the recognition that water is a scarce and precious national resource that should belong to all the people of South Africa. Moreover, it recognises that the ultimate goal of water resource management is to achieve the sustainable use of water for the benefit of all South Africans [13]. The Act gives the Department of Water Affairs the power and the highly necessary tools to gather information that is needful to manage the water resources in an optimal way [14].

3.2.2 Importance of the NWA

Water is a fundamental element of life. No person, plant, animal or any other living organism can survive without it. Water is used by farmers to irrigate their fields and also by rural communities to irrigate their crops and support their stock. In addition, it provides recreation; it supports the environment, towns, cities, mines, industry, and power generation. People need water for drinking, cooking food, washing and for health issues. Water is a critical part of social and economic development to alleviate poverty.

South Africa is mainly a dry country, with a low average rainfall. South African rivers are generally small in comparison with other countries. Furthermore, a number of the larger rivers are shared with other countries as they act as an international border. Many of the existing water resources have been overused in the past or are altered significantly. Human impact has led to a decrease in the water quality in rivers and streams, groundwater and wetlands. Many areas are facing water shortages. In these areas the environment is under stress and some people do not have access to potable water or don't get their fair share of water [15].

The NWA is an important tool because it provides a framework to protect all South African water resources against overexploitation. It also ensures that there is water for social and economic development and what is more water for the future. The NWA stipulates the recognition that water belongs to the whole nation for the benefit of all people. This principle is of huge importance, certainly with the South African history in mind.

3.2.3 Benefits of the new NWA

The old Water Act was drafted in 1956 and is now revoked. The original intention was to apply the water rules of European countries to the South African situation. This was not appropriate because Europe has a lot of water in contrast with South Africa, which is dry with limited water resources. Moreover, the Act of 1956 ensured that water was mostly used by a small dominant community (mainly white people) that had privileged access to land and economic power [15]. Water was not yet recognised as a basic human right.

At the time when the old Water Act was written, population was much smaller and pressure on the environment and water resources was barely an issue. Agriculture was by far the most important focus of water policy. This was reflected by giving the right to use water to people who owned land and other properties [15]. Landowners could use any kind of water resource that they needed. Water was called private, over which the national government had limited control. This meant that people who did not own land (i.e. the majority of the population) were disadvantaged and did not have easy or assured access to (potable) water. Besides, the old Water Act focussed mainly on water use and dam development rather than on water protection, conservation and demand management [15].

3.2.4 Outline of the strategy and the main measures

Water belongs to all people

The NWA manages, protects and allocates water in a different way compared to former situations. The main principle implies the recognition that water is a natural resource that belongs to all people in South Africa. Based on this fundamental, the need for a more fair and equal distribution of water is acknowledged. Water is essential in only two ways:

water for basic human needs and for the environment [13]. The Act ensures that water for both basic human needs and the environment is 'reserved' before water is allocated for other use. Both quantities (i.e. flow, volumes and variability according to the natural flow regime) and qualities (i.e. water temperature, oxygen concentration, suspended solids, etc.) are taken into account.

Sustainable use for the benefit of all

Old apartheid ideals of privileged access have regulated water access and distribution for a long time. The NWA does away with these ideas. In order to achieve equitable and sustainable economic and social development, the Act promotes sustainable water use that is in the public interest. This results in a fundamental change in the management of water resources according to the NWA.

Water resources protected and managed as a whole

Promoting the integrated management of water resources with the participation of all stakeholders, the Act aims to protect, use, develop, conserve, manage and control all water resources as a whole. Rivers, dams, wetlands, the surrounding land, groundwater, as well as human activities that influence them, will be managed as one cycle. This means that all water in the water cycle will be treated as part of the common resource.

Participation

The goals of water resources management can only be achieved with an active public participation. The national government has a critical responsibility to ensure the effective participation of all stakeholders in water resources decisions that affect them. This is performed by the establishment of regional and local institutions, such as catchment management agencies and water user associations. Those institutions will facilitate the involvement of stakeholders in any important decision. This approach is in line with international trends towards IWRM (Integrated Water Resources Management) [15].

3.3 Contents of the NWA

3.3.1 General

This part is a brief summary of the contents of the NWA. The complete and extensive text of the Act is available at both [13] and [16]. The most relevant parts on the subject of this Master thesis are cited from [16]. It is important to mention that this text deals with only a few selected items of the whole Act. The Act is described in 17 chapters which can be divided in a few major sections. Figure 3.1 shows which items are covered in the NWA.

Chapter 1	Interpretation and fundamental principles	**Principles**
Chapter 2	Water management strategies	**How water will be protected, used, developed, conserved, managed and controlled**
Chapter 3	Protection of water resources	
Chapter 4	Use of water	
Chapter 5	Financial provisions	
Chapter 6	General powers and duties of Minister and Director-General	
Chapter 7	Catchment management agencies	**Institutional arrangements**
Chapter 8	Water user associations	
Chapter 9	Advisory committees	
Chapter 10	International water management	
Chapter 11	Government waterworks	**Infrastructure and land issues**
Chapter 12	Safety of dams	
Chapter 13	Access to and rights over land	
Chapter 14	Monitoring, assessment and information	**Monitoring**
Chapter 15	Appeals and dispute resolution	**Mechanisms to address appeals, offences and remedies**
Chapter 16	Offences and remedies	
Chapter 17	General and transitional provisions	

Figure 3.1: Structure of the NWA [15].

The most important aims of the Act are recapitulated below [16]:

- Recognising that water is a scarce and unevenly distributed national resource which occurs in many different forms which are all part of a unitary, interdependent cycle;
- Recognising that while water is a natural resource that belongs to all people, the discriminatory laws and practices of the past have prevented equal access to water and use of water resources;
- Acknowledging the national government's overall responsibility for and authority over the nation's water resources and their use, including the equitable allocation of water for beneficial use, the redistribution of water and international water matters;
- Recognising that the ultimate aim of water resource management is to achieve the sustainable use of water for the benefit of all users;
- Recognising that the protection of the quality of water resources is necessary to ensure sustainability of the nation's water resources in the interests of all water users;
- Recognising the need for the integrated management of all aspects of water resources and, where appropriate, the delegation of management functions to a regional or catchment level so as to enable everyone to participate.

3.3.2 Interpretation and fundamental principles

Sustainability and equity are identified as central guiding principles in the protection, use, development, conservation, management and control of water resources. These guiding principles recognise the basic human needs of present and future generations, the need to protect water resources, the need to share some water resources with other countries, the need to promote social and economic development through the use of water and the need to establish suitable institutions in order to achieve the purpose of the Act [16].

The purpose of the NWA is to ensure that the nation's water resources are protected, used, developed, conserved, managed and controlled in ways which take into account amongst other factors:

- meeting the basic human needs of present and future generations;
- promoting equitable access to water;

- redressing the results of past racial and gender discrimination;
- promoting the efficient, sustainable and beneficial use of water in the public interest;
- facilitating social and economic development;
- providing for growing demand for water use;
- protecting aquatic and associated ecosystems and their biological diversity;
- reducing and preventing pollution and degradation of water resources;
- meeting international obligations;
- promoting dam safety;
- managing floods and droughts.

To achieve this extensive purpose, the establishment of suitable institutions is necessary. These different organisations need to be set up according to an appropriately community, racial and gender representation [16].

As the public trustee of the nation's water resources, the national government must ensure that water is protected, used, developed, conserved, managed and controlled in a sustainable and equitable manner, for the benefit of all people and in accordance with its constitutional mandate. Without limiting this, the government is ultimately responsible to ensure that water is allocated equitably and used beneficially in the public interest while promoting environmental values. The national government has the power to regulate the use, flow and control of all water in the Republic of South Africa [16].

3.3.3 Water management strategies

In order to facilitate proper management of water resources, several strategies were developed. These different management strategies can be divided into two main parts.

The first part defines the national water resource strategy. This strategy provides the framework for the protection, use, development, conservation, management and control of water resources for the country as a whole. Moreover, it also provides the framework within which water will be managed at regional or catchment level. The national water resource strategy is binding on all authorities and institutions exercising powers or performing duties under this Act [16].

The second part deals with the so-called catchment or regional management strategies. In the process of developing these strategies, a catchment management strategy must seek co-operation and agreement on water related matters from the various stakeholders and impacted people. It must set principles for allocating water to existing and prospective users [16].

3.3.4 Protection of water resources

The protection of water resources is fundamentally related to their use, development, conservation, management and control. There exists a classification system to determine the class and resource quality objectives of all or part of the water resources considered to be significant. The purpose of the resource quality objectives is to establish clear goals relating to the quality of the relevant water resources. In order to determine resource quality objectives, a balance must be sought between the need to protect and sustain water resources on one hand and the need to develop and use them on the other. The different objectives may relate to [16]

- the Reserve (see further);
- the instream flow;
- the water level;
- the presence and concentration of particular substances in the water;
- the characteristics and quality of the water resource and the instream and riparian habitat;
- the characteristics and distribution of aquatic biota (i.e. plant and animal life);
- the regulation on prohibition of instream or land based activities which may effect the quantity or quality of the water resource;
- any other characteristic.

The Reserve consists of two parts: the basic human needs reserve and the ecological reserve. The basic human needs reserve provides for the essential needs of individuals served by the water resource in question and includes water for drinking, food preparation and personal hygiene. The ecological reserve relates to the water required to protect the aquatic ecosystems of the water resource. The Reserve refers to both the quantity and quality of the water in the resource and will vary depending on the class of the resource [16].

In the case that pollution of a water resource occurs or might occur as a result of activities on land, the person who owns, controls, occupies or uses the land is responsible for taking any measures to prevent pollution. If these measures are not taken, the catchment management agency concerned may itself do whatever is necessary to prevent the pollution or to remedy its effects and to recover all reasonable costs from the responsible people [16].

3.3.5 Use of water

As the Act is founded on the principle that the national government has overall responsibility for and authority over water resource management, including the equitable allocation and beneficial use of water in the public interest, any person can only be entitled to use water if the use is permissible under the Act [16].

Water use is defined broadly and includes taking and storing water, activities which reduce stream flow, waste discharges and disposals, controlled activities (activities which impact detrimentally on a water resource), altering a watercourse, removing water found underground for certain purposes and recreation [16].

3.3.6 Financial provisions

After public consultation a pricing strategy can be established. This price strategy may differentiate among geographical areas, categories of water users or individual water users. The achievement of social equity is one of the considerations in setting differentiated charges. Water use charges are to be used to fund the direct and related costs of water resource management, development and use. These charges may also be used to achieve an equitable and efficient allocation of water. In addition, they may also be used to ensure compliance with prescribed standards and water management practices according to the user pays and polluter pays principles. Water use charges will be used as a means of encouraging reduction in waste and provision is made to stimulate effective and efficient water use [16].

3.3.7 Catchment management agencies

The purpose of establishing catchment management agencies is to delegate water resource management to the regional or catchment level and to involve local communities within the framework of the national water resource strategy. The board of a catchment management agency will be constituted in such a way that interests of the various stakeholders are represented or reflected in a balanced manner and the necessary expertise to operate effectively is provided. Members of the governing board can be elected or nominated by the different water user groups [16].

Initial functions include the investigation of and advice on water resources, the coordination of the related activities of other water management institutions within its water management area, the development of a catchment management strategy and the promotion of community participation in water resource management within its water management area. Additional powers and duties may be assigned or delegated to agencies, such as to establish water use rules and management systems, to direct users to terminate illegal uses of water and to temporarily limit the use of water during periods of shortage. A catchment management agency may be financed by the state from water use charges made in its water management area or from any other source [16].

3.3.8 Water user associations

Although water user associations are water management institutions, their primary purpose, unlike catchment management agencies, is not water management. They operate at a restricted localised level and are in effect cooperative associations of individual water users who wish to undertake water related activities for their mutual benefit. Water user associations must always operate within the framework of national policy and standards, particularly the national water resource strategy [16].

Existing irrigation boards, subterranean water control boards and water boards established for stock watering purposes will continue in operation until they are restructured as water user associations [16].

3.3.9 International water management

Several bodies may be established to implement international agreements in respect of the management and development of water resources shared with neighbouring countries and on regional cooperation over water resources. The governance, powers and duties of these bodies are determined in accordance with the relevant international agreement, but they may also be given additional functions and they may perform their functions outside the Republic [16].

3.3.10 Government waterworks

Government waterworks which are in the public interest, are operated out of funds allocated by the parliament or from other sources. Examples of such waterworks include water storage dams, water transfer schemes and flood attenuation works. Certain procedural requirements must be satisfied before constructing a government waterwork, including a duty to obtain an environmental impact assessment and invite public comment, except for emergency, temporary or insignificant waterworks. Water from a government waterwork may be made available for allocation to water users and charges fixed for this water. Water in a government waterwork may also be made available for recreational purposes [16].

3.3.11 Safety of dams

Measures are taken to improve the safety of new and existing dams with a safety risk in order to reduce the potential for harm to the public, damage to property or to resource quality. To reduce the risk of a dam failure, control measures require an owner to comply with certain directives and regulations, such as to submit a report on the safety of a dam, to repair or alter a dam or to appoint an approved professional person to undertake these tasks. These measures are in addition to the owners' common law responsibility to ensure the safety of their dams [16].

Only dams of a defined size, dams which have been declared to be dams with a safety risk or dams falling into a prescribed category are affected. All dams with a safety risk must be registered [16].

3.3.12 Monitoring, assessment and information

Monitoring, recording, assessing and disseminating information on water resources is critically important for achieving the objects of the Act. The purpose of national monitoring systems will be to facilitate the continued and coordinated monitoring of various aspects of water resources by collecting relevant information and data, through established procedures and mechanisms, from a variety of sources including organs of state, water management institutions and water users [16].

National information systems will cover each a different aspect of water resources, such as a national register of water use authorisations or an information system on the quantity and quality of all water resources. In addition to its use by the Department of Water Affairs and water management institutions and subject to any limitations imposed by law, information in the national systems should be generally accessible for use by water users and the general public [16].

Also certain information relating to floods, droughts and potential risks needs to be made available to the public. Township layout plans must indicate a specific flood line. Water management institutions must use the most appropriate means to inform the public about anticipated floods, droughts or risks posed by water quality, the failure of any dam or any other waterworks or any other related matter. Early warning systems have to be established to anticipate such events [16].

Chapter 4

Water markets as part of a new management system

4.1 Introduction

Water management policies aim to regulate the use of water within the river catchment. In particular, these policies distribute the available flow volume among different stakeholders.

A significant change in water management policies was the result of the political alterations in South Africa. Since the end of the apartheid regime (in the early 1990's) major social and political changes have occurred in the Republic of South Africa (RSA). A new National Water Act (NWA), which was published in 1998, describes all legislation concerning the changed water policy (see chapter 3). A radical shift in the allocation, management and operation of water resources was inevitable in post-apartheid South Africa. The goal of this new policy is to obtain an optimal balance of equitable, efficient and sustainable water use in the catchments.

In this chapter, one tries to examine the concept of Fractional Water Allocation and Capacity Sharing (FWACS (see section 4.5)) as a new method of allocating and managing water rights. According to [17], this management system should ensure the achievement of the social and environmental requirements that are mentioned in the NWA.

4.2 The currently adopted management system

In order to understand the need as well as the advantages of a new management system, it is important to examine the existing water management methods that are applied in the RSA. The currently adopted methods and policy at the Department of Water Affairs (DWA) were developed in the 1980's. The water resources managing policy was founded on two modelling systems. These systems are the Water Resources Yield Model (WRYM) and the Water Resources Planning Model (WRPM). These models are capable of simulating many different operating policies governing the allocation of water in a multi-purpose multi-reservoir system [18]. Based on a modular system, these models assume that a water resources system can be represented by a flow network.

The modelling systems have been designed in order to handle a specific method of water management, which is a simple water apportionment (i.e. distribution and allocation) system. Without taking any environmental concern into consideration, water resources are divided among and supplied to the different users. The entire system is referred to as the Priority-based River and Reservoir Operating Rule (PRROR) system. This system discerns priorities given to different types of authorised water use, while reservoir and river operating rules stipulate the water restrictions faced by the water users under different conditions of water availability [17].

In the currently adopted PRROR system, the catchment is managed as it was a single system. Above all, the PRROR system is designed to manage the supply facilities in developed water resources systems [17]. This is still the main purpose of this managing system. The DWA is responsible for the allocation, apportionment and restriction of the various water users in the system.

Farmers are entitled to their water allocations by the PRROR system. In fact, these water entitlements (i.e. water rights) are related to the riparian rights of the farmers. In this way only farmers with land entitlements have officially the right to use water according to this system. Others have no title to the water that they need for irrigation purposes. This way of acting is obviously in contravention of the equity principle. Moreover, the modelling of the entire system is almost unfeasible as there are huge numbers of unauthorised water abstractions. The result of this policy is the existance of giant farmlands (see figure 4.1), possessed by rich farmers which are mostly white people. These farmers with landed property are entitled to use water from the rivers and reservoirs as they already have riparian entitlements (i.e. the right to farm those riparian lands). In this way, a poor farmer never gets a chance to start tilling land, let alone compete with those large landowners.

Figure 4.1: Extensive farming near Blouputs. Photograph: field trip September 2009.

The PRROR system is completely different from the proposed FWACS system (see section 4.5) as this former system was developed according to the old NWA. At that time, water resources systems were not yet as heavily developed. In addition, principles such as equity, efficiency and sustainability were not major concerns and efficient management was not a key issue [17]. Actually, the old NWA as well as the PRROR management system have been superseded and are no longer in accordance with the present situation in the RSA.

4.3 The need of a new management system

As mentioned above, the PPROR system of water entitlements is based upon riparian land entitlements. This led to an inequitable distribution of water rights. This management system favoured inefficient water use and a continuation of it can damage the long-term sustainability of water systems [17]. The 1998 NWA reformed the whole system and separated the water and land entitlements.

Only basic human needs and environmental sustainability are guaranteed as a right under the new Act. The rights of irrigators are seen as of secondary importance. According to this Act, the ownership of water in the RSA has changed from private to public. Furthermore, a water licensing system, which considers equity, efficiency and sustainability aspects, was introduced [19]. The National Water Resources Strategy (NWRS) recognises that with the present high level of water resources utilisation in the RSA, water use efficiency (WUE) must be substantially improved [19]. The current challenge is to explore new management mechanisms to improve the South African WUE, taking the environmental water requirements (EWR) into consideration.

The climatic conditions in the region of southern Africa are very specific and almost unique in the world. Only some parts of Australia are dealing with the same difficulties. These countries can be considered as predominantly semi-arid with a lot of water scarcities. The major problem is that in many cases the demands outstrip the supply capabilities of the existing systems [19]. Moreover, the RSA, along with Australia, has the highest regional variability of rainfall and run-off in the world [20]. The consequence of all these facts is that for a given level of water infrastructure (e.g. impoundments, transfer schemes etc. (see chapter 2)) the resulting yield is smaller in these parts of the world [21]. In addition, the existence and especially the unpredictable nature of wet and dry years, sometimes extending over several seasons, make the operation and management of water resources in South Africa both expensive and difficult [17].

4.4 Improving water use efficiency

4.4.1 Overall system efficiency

Up to now, most improvements on WUE in water resources management apply to technical WUE, which is a function of the percentage of water lost from the scheme not directly used by a water user [22] [23]. However, improvements in technical WUE when considering return flow contributions do not necessarily translate into water savings from the entire basin perspective [24] [25] [26] [27]. In fact, a significant portion of the applied water is still available for other users as return flow. Increasing the on-farm efficiency (e.g. by switching over from flood irrigation (see figure 4.2) to more advanced techniques such as sprinkler (see figure 4.3) and drip irrigation (see figure 4.4)) may lead to lower return flows available for environmental demands and thus an increased consumptive use of water (see section 4.8). According to this, the water that is available for the environment will be reduced. Technical WUE is actually only applying to increase efficiency in arable farming while environmental water requirements (EWR) are not taken into account.

Figure 4.2: Flood irrigation near Bucklands. Photograph: field trip September 2009.

Many hydrologists suggest that the overall system efficiency should replace technical WUE when looking at a basin scale (this means that all users, not only human but also the environment, should benefit from water use efficiency (WUE)) [24] [25] [28] [29] [30]. So as to leave no doubt, technical WUE can be useful but only when it forms a part of a general, overall (environmentally sound) WUE policy. Besides improvements in technical WUE, it is important to pay attention to mechanisms that could be used to improve system and allocation efficiency. In this respect WUE can be defined as achieving the maximum output (i.e. increasing the benefits of *all* water users, the environment included) per unit of water used in a catchment system [31] [32]. Regarding the existing boundary conditions (i.e. the climatic conditions, increasing water demands, limited water resources, etc.), the RSA is forced to have a try at maximizing all benefits of each drop of water.

Figure 4.3: Sprinkler irrigation near Bucklands. Photograph: field trip September 2009.

4.4.2 Requirements of a new management system

According to the DWA, there are options for improving WUE in South Africa [17]:

- The use of benchmarking, which in effect is a 'use-it-efficiently-or-lose-it' approach;
- The use of user charges (i.e. economic charges) to induce water use efficiency;
- The use of the water market to encourage permanent or temporary trading of water entitlements.

The first two approaches can be considered as punitive measures. According to several authors, these two measures wouldn't reach their aim in practice [32] [33] [34] [35] [36] [37] [38] [39] [40]. Some authors give preference to the transfer of water to the highest value use via the water market mechanism (i.e. trading of water rights). From the perspective of both the water manager and the water user, this seems to be the most attractive alternative in order to achieve allocation efficiency. Water entitlements, which need to be tradable,

Figure 4.4: Drip irrigation near Kotzeshoop. Photograph: field trip September 2009.

should follow the concept of a non-attenuated property right to promote a water market [41] [42] [43] [44].

It is important that all transaction costs that are associated with these trades (e.g. time, legal fees and other procurement costs) may not be prohibitive [44] [45]. By keeping these costs low, the water market should be accessible to the majority of the South African population.

Water entitlements need to be considered as a standard and should be defined in such a way that it allows easy transfer of water between different sectors. To meet these requirements, water use licenses should be defined as capacity shares [43]. The authors of [46] agree on the fact that capacity shares (i.e. the capacity of dam reservoirs is divided between the different users (see section 4.5)) are suitable for the definition of water contained in storage systems. In addition to that, they also suggest that a fractional water allocation (see section 4.5) should be used to apportion water that is either flowing into reservoirs or water from tributaries in undeveloped, run-off river systems.

4.5 Fractional water allocation and capacity sharing

The Fractional water allocation and capacity sharing (FWACS) system is a new water management method which consists of three divisions: water allocation, capacity sharing and proportioning of losses. These parts are discussed below in more detail:

- The first level of partitioning is that of the run-off, which is partitioned according to the overall run-off of the system. This part is called Fractional Water Allocation (FWA). The system has different common users (either agricultural, industrial or domestic) and one user which represents the total EWR of the entire (sub)system. After the EWR is put aside, users can obtain a certain proportion of the remaining run-off. The proportioning can be determined in different ways and should be discussed through stakeholder participation. It is obviously necessary to invest a lot of money in communication systems to inform stakeholders continuously about the water volumes they may take. Therefore, the implementation of a real-time hydraulic model in cooperation with an information and communication network is indispensable. The big advantage of the FWA system of proportioning run-off is that the allocations are relatively transparent and it is easy to trade the fractions of overall run-off between the different users [17]. Furthermore, one can deal easily with EWR in this type of allocation structure;

- Capacity sharing makes up the second level of proportional allocation. Now, the storage capacity of dams is divided between the different downstream users. Dams work as a storage structure for the water users who are thus able to secure an allocation to a piece of the storage on the system, i.e. the capacity share. The 'storage' refers to the live storage capacity of the system, enclosed by flood control level and dead storage level. Again these proportions can be allocated according to different criteria. It is possible to control assurance of supply by manipulating the ratios of inflow, dam size and water use. All users maintain their own 'imaginary' dam level and decide when they wish to use their water. Users can easily transfer water from one compartment to another. It may be concluded that the capacity sharing system is thus transparent and flexible;

- The proportioning of losses is the final element on the system. These losses are a result of evaporation and seepage in both the river and storage dam. In general, losses are calculated and distributed pro rata in accordance with the system of capacity sharing.

This management system provides a sound basis for defining water use entitlements and it acts as an enabling environment to encourage the development of a water market. In this way, FWACS can improve WUE while accounting for other matters as water quality, environment and equity considerations [17]. The entitlement system has to permit an exhaustive portioning of the resources among the different titleholders in order to meet the necessary conditions for water licenses (see section 4.4.2) [43]. Finally, one may conclude that FWACS is a valuable and highly flexible system that fulfils the requirements for non-attenuated property rights [47].

4.6 Comparison between the two management systems

The big differences between the PRROR and FWACS systems are listed below [17]:

- A disadvantage of the PRROR system is the lack of transparency. Water entitlements are not explicit nor exclusive as they are not well-defined. While assurance of supply is implied in the licenses of the PRROR system, it can not be guaranteed. On the other hand, entitlements are explicitly defined in the FWACS system. This system is very clear: everyone knows which amounts he can rely on. Users can ensure their assurance of supply by manipulating their own management;

- Where operating rules and water restrictions are determined by the DWA in the PRROR system, the FWACS system enables participatory management. Water users can, with DWA's advice and approval, manage the resources themselves;

- The transferability of water use entitlements between different sectors is very difficult in the PRROR system due to different levels of assurance. For example, the assurance level of irrigation allocations are much lower than those for domestic demands. The priority aspect of the PRROR system attributes different priorities to the various users. Therefore the trade process can be considered as highly uncertain. This problem is avoided in the FWACS system by defining the entitlements in the same way for all individual users;

- Due to the complex system of trading, each transaction in the PRROR system requires an expert to determine the transaction cost. This results in additional costs.

Therefore, the transaction costs in the FWACS system for both temporary and permanent trades are much lower;

- Last but not least, the environment is considered as a user of water resources according to the FWACS system. What's more, the EWR will now be assessed as even more important than the needs for irrigation. The ranking of the environment has actually been improved with respect to the farming and irrigation industry.

Recapitulating the criteria required for a water market to operate efficiently (see section 4.4.2), the currently adopted PRROR system seems not to meet these requirements. It is unfeasible to use the water market as mechanism to improve efficiency, without changing the management policy. People are not forced or even urged by the PRROR system to gain efficiency. The FWACS system, on the other hand, stimulates water users to increase the efficiency of their water use as they are permitted to sell their surplus of water. The PRROR system provides little or no incentive for adopting more efficient water use technologies. In almost all respects, the FWACS system is preferable to the PRROR one.

4.7 A case study on water market transfers

In 2004 there was a research to study the responses of water allocation in two irrigation areas by investigating how water markets can lead to more efficient water allocation and use [48]. This research was actually a sequel of an earlier study, performed in 1999 [49].The two concerning areas were the Lower Orange River (LOR), more exactly the Boegoeberg and Kakamas Irrigation Schemes, and the Nkwaleni Irrigation Board (NIB) along the uMhlatuze River (Nkwaleni Valley) in northern KwaZulu-Natal. Even though in both regions water is a scarce resource and production is entirely dependent on irrigation, the currently existing water market is completely different. Where in the LOR one of the highest incidences of market trading of water rights in South Africa take place, trading of water rights doesn't occur in the NIB. The aim of this study was to highlight the benefits from and institutional arrangements facilitating market trading of water rights along the LOR as well as the potential for and institutional changes necessary to facilitate the operation of water market along the uMhlatuze in the NIB [48].

4.7.1 Market trading of water rights along the Lower Orange River

A market for outer land water rights emerged along the LOR. Outer land is land adjacent to but inland from the canal, coupled to a river water right. Water transactions are driven by the desire of large scale table grape producers (see figure 4.5), with large holdings of high-potential arable outer land without water rights, to expand their operations. Statistical analyses of water transfers in the Lower Orange River showed that water rights were transferred to farmers with the highest return per unit of water applied, i.e. those producing table grapes [49].

Figure 4.5: Cultivation of table grapes near Boegoeberg. Photograph: field trip September 2009.

According to [50], an upward trend in real water prices exists. Prices, however, vary significantly from year to year. These changes are probably in response to the prices of export table grapes. The river flow has been reasonably stable from year to year and it is not expected that irregular water flow would have affected prices much [48].

The income from wine grapes in the LOR area is relatively low as this area is not as conducive to the production of exotic wines as is the Western Cape of South Africa. The study described in [50] indicates that water right buyers tend to be producers of the more lucrative table grapes and other crops with less field crops and other grapes.

Certainty of water rights is important for crops such as table grapes as the capital investment is very high for this crop. Another study [51] showed that farmers along the Orange River produce a low-income crop such as lucern for fodder along with a high-income crop such as table grapes. The reason for this combination is supply security. The low-value crop is grown for water supply security in the sense that in the event of water scarcity, water can be diverted from the low-value crop to save the capital investment in for example table grapes.

In the LOR area, an active water market has developed. This development was facilitated by the large number of willing sellers and the role played by the DWA. Their contribution exists of administering the market transfers, thereby reducing transaction costs and time. Improving the efficiency of water market trades could be achieved by delegating authority to the regional DWA offices to approve transfers, extending support to market transfers of canal water and ensuring that water abtraction is closely assessed as use of river water increases in the future [48].

4.7.2 Water allocation in the Nkwaleni Valley

The study found that no water market had emerged despite the scarcity of water in this area. No willing sellers of water rights existed. Demand for institutional change to establish tradable water rights may take more time since crop profitability in this area is similar for potential buyers and non-buyers. Transaction costs appear larger than benefits from market transactions. Farmers generally use all their water rights and retain surplus water rights as security against drought because of unreliable flow [48].

The majority of the farmers have the intention to purchase additional water rights. However, there are no willing sellers. This may be attributed to the fact that farmers in the Nkwaleni Valley generally prefer using their full water rights allocation in their farming operations. Irrigators may also prefer to retain excess water for water supply security [49]. In addition, the crops produced by potential buyers are not significantly more profitable than crops produced by non-buyers.

4.8 Transfer of consumptive versus diverted use of water

In South Africa, water rights refer to water diverted for irrigation. However, there exists a difference between the volume of water actually applied (diverted use) and the water taken up by plants (consumptive use). A significant portion of the diverted water is available for other users as return flow. The transfer of water rights to another user may negatively affect downstream users who are dependant on the return flow of the previous user.

A transfer of water rights has economic incentive implications. Whether diverted use or consumptive use is transferred has implications regarding to the incentive to conserve water and the price of water. If the prime cost of the diverted use of water (volumetric price) increases then a farmer may [48]:

- Shift to crops that are more efficient, or higher-valued;
- Continue with the same crop and acreage and apply less water;
- Employ more water-saving technology by, for example, moving from flood to drip irrigation.

According to some experts no water is saved by adopting water-saving technologies. An increased on-farm efficiency such as use of water-saving technology creates the illusion of water conservation when, in reality, the consumptive use of water may even increase [52]. In a hydrological system, water that is not taken up by plants will be returned to the basin or aquifer and be available for other users. This is the so-called return flow. If farmers are permitted to irrigate a larger area if they use water-saving technology then it may lead to lower return flow and increased consumptive use of water [48]. This is expected to happen in the RSA as farmers are indeed permitted to irrigate larger areas on condition that water-saving technologies are adapted. This results in a reduction of return flow and also in a reduction of the water available to the environment. The importance of return flows should not be underestimated.

4.9 Challenges associated with the implementation of FWACS

When the FWACS system is introduced, users need to know what their exact entitlement is and where it is coming from (either run-off or storage capacity). The management and information systems required for this system are far more demanding than those required under the PRROR former system. Following components are really indispensable for the succeeding of the FWACS system:

- A reliable real-time monitoring network has to ensure all information is sufficiently accurate. This information needs to be provided for the water allocation and accounting models;
- All information provided by the real-time network has to be stored in a comprehensive information management system;
- Water balances, flows and losses of the system need to be accounted for in a consistent scientific manner. Therefore, a new set of hydrological, hydraulic and water resources system models needs to be developed;
- An auditing and banking system has to make sure that trades are accounted for and that water and money should be exchanged simultaneously;
- The information needs to be accessible for all people. A brand new communication system has to be set up to provide all users with the required information to make informed decisions about their entitlements;
- The control of the used water amounts is an important issue. Nowadays water meters are either out of order or absent. Investing money in the installation of water meters is an essential condition to make this management system a success.

Even though the total costs associated with these implementations seem to be rather high, these issues are outweighed by the benefits generated in terms of improved water management, water savings and overall efficiency [17].

Several real-time systems have already been established in South Africa using the Mike Real Time Software developed by the Danish Hydraulic Institute (DHI). These systems include the Orange-Fish River System [53], the uMhlatuze Catchment [54], the Letaba Catchment, the Lower Orange River System (LORS) and the Crocodile East River [17]. In these particular areas, it has been demonstrated that real-time management can improve the scheduling of releases from the reservoirs and for that reason improve efficiency and reduce losses on these systems [53] [54]. These real-time systems should easily be extended to a full FWACS system by adding the auditing components [17]. The model that was built whitin the scope of this thesis is presented in chapter 8 to 13. This model can serve as an alternative for the existing model for the LOR that was built whit the commercial Mike Real Time Software.

4.10 Some criticisms on the FWACS system

Apart from all advantages of the FWACS system discussed before, some problems still need to be tackled. Both the DWA and individuals have levelled some criticisms. The most important are discussed below, some others are presented in [17].

FWACS may encourage market mechanisms that will not address the equity issues currently facing South Africa by entrenching an already existing inequity status quo [17]. If the DWA decides to move over to a water market system, it should also provide a kind of market contol, especially in the beginning. If not, poor farmers won't have a choice than selling their water entitlements. If this happens, the result will be the same as under the old Act and managemant system. To prevent that good intentions should lead to nothing, there is need of a mechanism of market control.

However, it could also be argued that FWACS provides good opportunities to address the equity issues. Moreover, it should be clear that a reallocation of water entitlements can cause a large impact from an economic and food perspective. Previously disadvantaged individuals will replace existing successful farmers and it will take his time for these new farmers to learn the existing skills and knowledge. This will obviously have a huge impact on the South African economic and food market. A smoother transition can be achieved by leasing arrangements of the entitlements (i.e. a developing farmer can leases his entitlements back to the established farmers in that particular area). In this way, the economy can become more equitable without the short-term economic impacts. It is also important to provide the community with information concerning the true value of the entitlements that it was given. The best method would be to introduce the FWACS system, educate all individuals receiving water use entitlements for equity purposes and then let the natural market forces take care of the allocation and economic efficiency [17].

4.11 Conclusion

South Africa urgently needs to improve its water use efficiency. Both from operational and planning perspectives, the South African water management policy needs to be changed. The management should be more decentralised where stakeholders become actively involved in all decision making processes. The Fractional water allocation and capacity sharing (FWACS) system will both encourage a participatory management and improve the overall efficiency. This fulfils the requirements discussed in the National Water Act (NWA).

The FWACS system can be supported by real-time systems such as the Mike Basin model. This or other models of same sort will improve the efficiency and prevent losses in both the short and long term. Moreover, this system encourages self-regulation and market mechanisms to sort out inefficiency rather than regulatory structures which require far more policing and enforcement [17].

Chapter 5

Environmental aspects pertaining to the riverine ecosystem

The Orange-Senqu River can be described as a highly regulated river, due to various dams and weirs built on the river, resulting in reservoirs and water abstractions which would not naturally occur. These human interventions impact on the environmental state of the river catchment. In order to achieve an integrated water resources management, one should be capable of diminishing the impacts on the environment. The goal is to establish sustainable operational procedures for the river catchment, which are beneficial for both man and nature. Indeed, one of the major challenges facing river management worldwide is the allocation of compensation flows, which not only satisfy the water demands of downstream users, but also maintain the river as a viable and healthy ecosystem [55].

This chapter describes the environmental impacts of the regulated river system, with emphasis on the Lower Orange. First, a historical flow data analyses is presented, so as to explain the present changes of the hydrological regime. Subsequently one can evaluate the impact of this artificial regime on the biota of the river catchment and examine the specific components of the hydrological regime which have been responsible for the change of the status of the biota under concern. Finally, when the impacts on the environment are well-known, one is able to propose general management procedures so as to improve the state of the environment.

The changed hydrological circumstances and their impact on the environment can be blamed for outbreaks of black fly pests. As this ecological problem has severe economic consequences (particularly for cattle breeding), it is described elsewhere. Besides, due to the annoyance level of black fly attacks, society is directly affected by this problem. It is obvious that this ecological problem should be interpreted in a wider context. Consequently, the black fly problem will be discussed separately in chapter 6.

5.1 Natural versus current hydrological regime

Before 1970 there was little damming of the river and the flow regime was considered natural. In 1971 the construction of Gariep Dam has been completed, and subsequently in 1977 Vanderkloof Dam was finished. Vanderkloof Dam is the last dam on the Orange (in a downstream direction), so this dam actually controls the flow pattern of the entire Lower Orange River. Several storage weirs have been constructed along the Orange, resulting in a rather local impact on the river, by permanently flooding the reach upstream of the weir. Of course, as these weirs are used for abstracting water from the river, they will also impact on the flow through the reaches downstream of the weir. However, the impact of these weirs is less significant than the impact of Gariep and Vanderkloof Dam. In order to examine the human impact on the hydrological regime, the flow data recorded before the construction of these 2 dams will be compared to the data recorded after the construction.

A historical flow data analysis is performed for the Boegoeberg Dam gauging station (downstream of Vanderkloof Dam), as monthly flow data for this station is available back to 1932. Although this gauging station may not be very accurate, especially at low flows, the data will be useful for evaluating and illustrating certain trends. A box-and-whisker plot is generally used for graphically depicting numerical data. The flow data recorded before the construction of Gariep and Vanderkloof dam is represented in figure 5.1 (i.e. the natural flow regime), and the data recorded after the construction of these dams is represented in figure 5.2 (i.e. the artificial flow regime). The use of flow data for the artificial regime has been restricted to 1994, in order to avoid interference with the impact of the first construction phase of the Lesotho Highlands Water Project. Unfortunately, only flow data for the 6-year period subsequent to the completion of the first phase of the LHWP is available, which is insufficient for data analysis.

For each month, the distribution of the monthly average discharge (for each year) is plotted by means of a box-and-whisker diagram. On each box, the central mark is the median, the edges of the box are the 25^{th} and 75^{th} percentiles, the whiskers extend to the most extreme data points which have not been considered outliers. These outliers can be described as

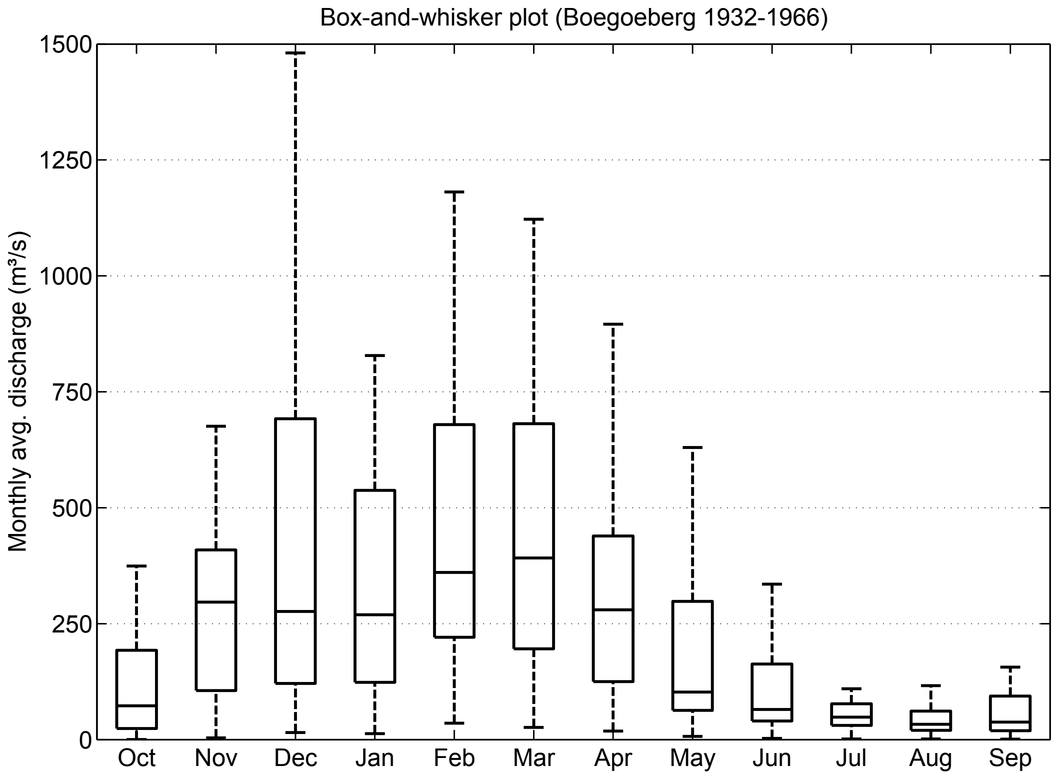


Figure 5.1: Box-and-whisker plot of monthly average discharge recorded at Boegoeberg from 1932 until 1966. Discharge (m^3/s) versus month.

the data points strongly deflecting from the cluster of data points. Points are considered as outliers when they are larger than $q_3 + 1.5(q_3 - q_1)$ or smaller than $q_1 - 1.5(q_3 - q_1)$, where q_1 and q_3 are the 25^{th} and 75^{th} percentiles, respectively. The outlier points are not represented in both box plots. Plotting these outliers would increase the vertical axis interval, which has been avoided for reasons of clarity.

By comparing the natural flow regime (figure 5.1) with the artificial regime (figure 5.2), one can draw the following conclusions:

- The **median** is a good standard for assessing the ‘average’ flow for each month. Historically, this value strongly varied during the year. Indeed, for the natural flow regime one can clearly distinguish the ‘wet’ months (November to April), charac-

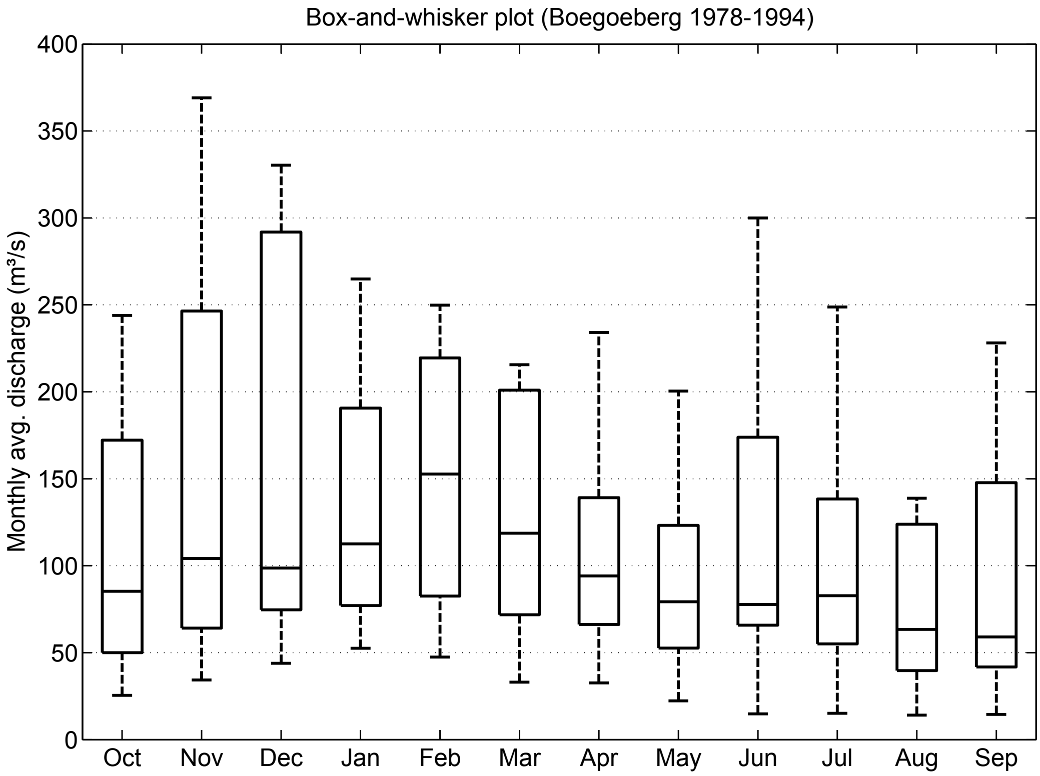


Figure 5.2: Box-and-whisker plot of monthly average discharge recorded at Boegoeberg from 1978 until 1994. Discharge (m^3/s) versus month.

terised by a median value exceeding 250 m^3/s. The 'dry' months, from May to October, show clearly lower discharges, all being less than approximately 100 m^3/s and showing a minimum of 33 m^3/s in August. In other words, there is an obvious seasonal flow variation. This seasonal variation is clearly less distinct in the artificial regime box plot. For the artificial regime, the maximum median discharge occurs in February (150 m^3/s), while the minimum median discharge is 59 m^3/s (September), which is almost twice the minimum value of the natural flow regime.

- The **interquartile range (IQR)** is a measure of statistical dispersion. This value is calculated as the difference between the 75^{th} and 25^{th} percentiles. In fact, the IQR is the range of the middle 50 % of the recorded data. High IQR values indicate a large dispersion of the regularly occurring discharges. In other words, the IQR can be used for evaluating the range of regularly occurring discharges, which is of major ecological importance. There is a large distinction between the natural and the artificial flow regime. For example, the IQR value for the 'wet' months February and March accounts to 470 m^3/s for the natural situation, and 140 m^3/s for the artificial situation, respectively. This means that the construction of both dams impacts on the short-term flow variability. In particular, small floods historically used to occur often, but the regulation of the river has eliminated these smaller floods. The contrary of this finding occurs during winter months. In August, the IQR for the artificial regime is approximately 80 m^3/s, which is twice the IQR for the natural regime (approximately 40 m^3/s). This increased flow variability during 'dry' months results in specific environmental problems (e.g. the black fly problem, cfr. section 5.3.2).

- The 75^{th} **percentile** can be interpreted as a measure of the discharge corresponding to smaller floods which often occur. The 75^{th} percentile is of special importance during summer, as historically small floods were common. The 75^{th} percentile of the natural regime outstrip the values of the artificial regime, demonstrating the decrease of the magnitude of these floods by a factor 2 to 3.

- The **length of the whiskers** specifies the maximum discharge which has not been considered an outlier. In other words, this length quantifies the discharges associated with bigger floods, which do not deflect excessively from the other data points. In accordance to what has been concluded above, the length of the whiskers for the natural regime during summer outstrips the values of the artificial regime.

Figure 5.3 visualises the human impact on the seasonal flow distribution. The average of the lower 85 % of the mean monthly discharge data points is represented on the vertical axis. The 85 % requirement has been defined somewhat arbitrary in order to eliminate the large floods from this graph, as these would distort the average. One can find that the natural seasonal variation is smoothed to a nearly constant discharge curve, due to human impact. During the driest months, the discharges associated with the artificial regime outstrip the natural values. Although statistically less significant, the data records from 2001 to 2007 (i.e. after the completion of phase 1 of the LHWP) are plotted on the same graph, indicating more or less the same trend as the 1978-1994 data series. The data used in figure 5.3 can also be used to calculate the contribution of the wet, respectively the dry season to the total yearly flow volume. The period from November to April is included in the wet season, the dry season covers May to October. For the natural flow regime, the wet season contributes 81 % to the yearly flow, and the dry season contributes 19 %. By contrast with these values, the wet season of the artificial regime (1978-1994) contributes 60 %, while the dry season contributes 40 %. These numbers again evidence the lack of seasonal variation due to regulation of the river. From the same graph, one can easily calculate the total flow volume. This accounts to $5.8 \cdot 10^9$ m^3/a for the natural regime, and $2.9 \cdot 10^9$ m^3/a for the artificial regime (1978-1994), i.e. a reduction of 50 %.

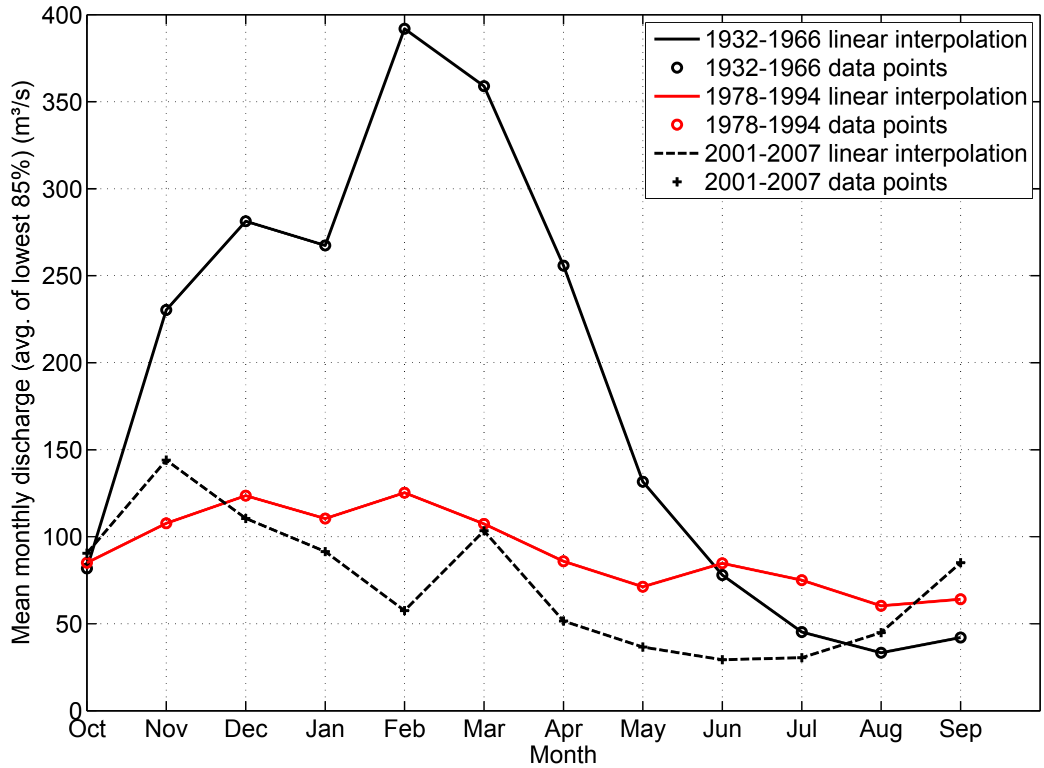


Figure 5.3: Average of the lower 85 % mean monthly discharges at Boegoeberg. Discharge (m^3/s) versus month.

Extreme flood events are of major importance in maintaining the condition of the river bed (cfr. section 5.2.3). Of course, these floods pose a challenge to the people inhabiting the river catchment as they cause severe flooding and economical damage. This explains the particular interest in the return period of these major floods. Figure 5.4 illustrates the occurrence of major floods from 1932 to 2007. A flood was considered a major flood if the mean monthly discharge for at least 1 month exceeded 2000 m^3/s. The calculated total flood volume only takes into account the consequent months with a mean discharge exceeding the 85^{th} percentile of that particular month. An exact return period cannot be defined from this limited data set, but one can expect the return period to be approximately 10 years. The last major flood occurred in 1988.

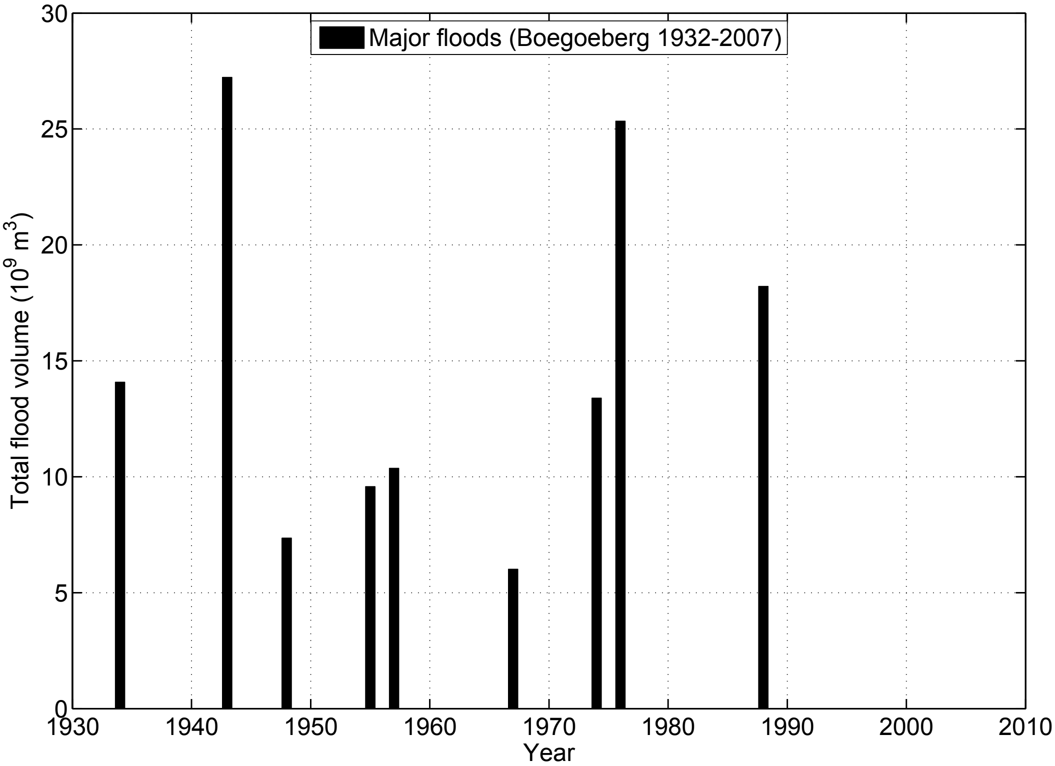


Figure 5.4: Major floods recorded at Boegoeberg (1932-2007). Volume (10^9 m^3) versus year.

The natural flow regime can be summarised as follows: strong floods occurred during the wet summer months, peaking in March, alternated with periods of very low flow during the dry winter months. In November, typically the first freshet of the wet season occurred. The regulation of the river results in the following impact on the hydrological regime [55]:

- Absence of seasonal natural flow patterns;

- Unseasonable winter releases (lack of very low flow periods);
- Absence of minor to medium maintenance floods (as these are captured by the dams);
- Reduction in water volume;
- Lack of short-term flow variability.

As illustrated in figure 5.3, the artificial curve and the natural curve intersect in June and during the dry season the artificial curve shows higher values than the natural curve. During summer, the opposite is happening. In a more extreme regime, these 2 curves would resemble 2 sinusoidal curves with a 180°phase shift. This explains why the difference between the natural and the artificial hydrogram is also referred to as the ‘reverse hydrogram’ phenomenon, i.e. flow volumes in a river which are the opposite to the natural situation [56].

The artificial hydrogram results from the human demands on Orange River water. These demands conflict with the environmental requirements. Indeed, the sum of the demands for hydropower generation, irrigation and urban purposes remains quite constant during the year, in constrast to the environmental demands. In fact, irrigation demands show a seasonal trend as these are higher during summer, but this variability is outweighed by the unseasonal hydropower and urban demands. During summer, the higher flow is captured by the dams in order to ensure the provision of water during winter.

5.2 Impact on water temperature, water quality and suspended solids

Besides the flow volumes and their distribution (i.e. the quantity of water), the transport of sediment, nutrients, pollutants and the temperature of the water (i.e. the quality of water) are of significant importance for the viability of the biota in the riverine ecosystem. These water-related features are also changed by the highly regulated river management. Therefore a description of the impact on water temperature, water quality and suspended solids is indispensable in order to allow a proper description of the impact on the biota.

5.2.1 Water temperature

Most deep temperate and subtropical lakes develop thermal stratification every summer [57]. Thermal stratification can be described as the physical separation of water masses of different densities, due to temperature differentials via warming of surface water [58]. This phenomenon is exacerbated by the fact that the residence times of the water in the impoundment are long [59]. The top layer, termed the epilimnion, has a constant temperature due to mixing and circulation and is usually warm. Below this layer, there is a zone of rapidly decreasing temperature referred to as the metalimnion or the thermocline. The lowest layer consists of cold, high-density water termed the hypolimnion [56] [59] . Figure 5.5 shows these 3 layers and the vertical temperature distribution of a hypothetical dam reservoir. The stratification is mainly affected by external forces as heat input (surface warming and inflow), wind and internal variables such as lake morphology and the light extinction coefficient of the water [57].

During winter, as the air temperatures decline and the surface water cools down, the thermal stratification becomes unstable and mixing of the different layers occurs. In summer, when the upper water layer is heated, the epilimnion becomes distinct and thermal stratification occurs.

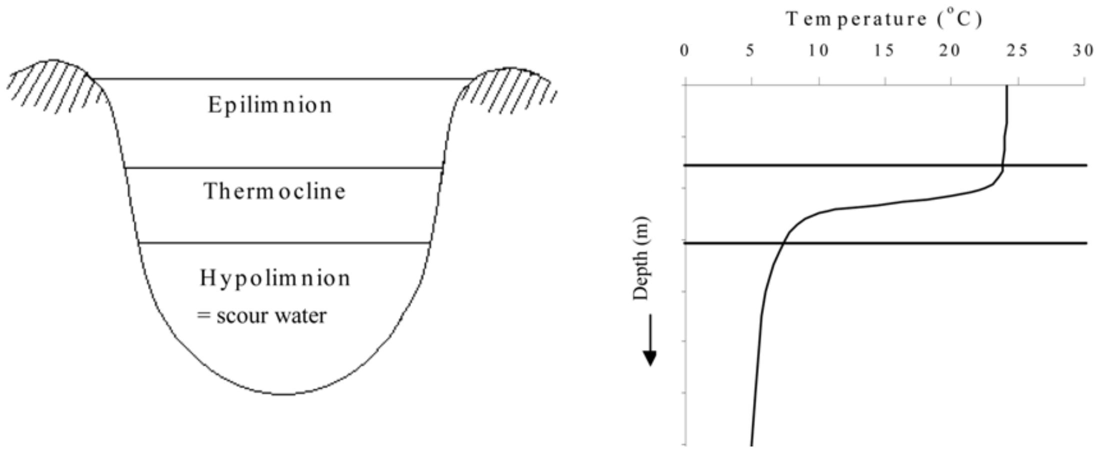


Figure 5.5: Temperature profile of a thermally stratified lake [59].

As the water intakes for hydropower generation drain water from the hypolimnion, the water discharged into the river section downstream of the dam will be colder than the water in the unregulated river during summer, and the opposite will occur (to a lesser degree) during winter. This results in unnatural water temperatures near the dams. In the Orange River the temperature regime is likely to be modified for some 130 to 180 km downstream of Vanderkloof Dam [55]. Pitchford and Visser [60] measured temperatures for 3 years directly downstream of the site of the Gariep Dam before and after completion. They found that water temperature after impoundment was 5 °C warmer in winter, and 7 °C colder in summer. As a consequence, the temperature range was reduced from 19.6 °C (pre-impoundment) to 12.8 °C (post-impoundment). In fact, seasonal effects were delayed by the thermal inertia of the reservoir water mass [56]. Research [61] after the vertical temperature distribution of the Vanderkloof Dam reservoir revealed that the water at the bottom is always cold (10-14 °C), whereas surface temperatures varied from less than 14 °C when mixed, to 20-22 °C when stratified. Thermal stratification of Lake Vanderkloof begins in October/November, and lasts until May [62].

The regulated water volumes passing through the river also impact on the water temperature of the whole river section downstream of Vanderkloof Dam. Increased flows lead to a larger flow depth, and hence an increased heat capacity per unit surface area, thus attenuating atmospheric heating to a larger extent. The opposite occurs during summer [63].

A changed temperature regime has profound impacts on the riverine ecosystem and can create conditions totally unsuitable for certain organisms. Except for birds and mammals, all organisms associated with fresh water are poikilothermic, i.e. they are unable to control their body temperatures, which are therefore the same as the ambient water temperature. These organisms are therefore very susceptible to changes in water temperature, as a temperature increase results in an increase of the organism's metabolic rate [64] [65]. Temperature changes naturally act as 'cues' for the timing of migration, spawning or emergence. For each organism there is a temperature at which optimal growth, reproduction and general fitness occur, as well as a range in which normal activities can continue [65].

5.2.2 Water quality

Lakes and reservoirs act as natural sinks for nutrients, metals, salts and organic matter. Significant concentrations of these pollutants can accumulate in bottom sediments over a period of years. Biological and chemical processes occur between the contaminants, the bottom sediments and overlying waters. These processes result in a great demand for oxygen. The stratification phenomenon isolates the bottom waters from external sources of oxygen replenishment, thus leading to low concentrations of dissolved oxygen (DO) in the hypolimnion after prolonged periods of stratification. In fact, the water in the lower layer is usually anoxic as it contains little or no dissolved oxygen [56]. As hydropower releases drain water from the hypolimnion, water quality impairment in the hypolimnion is undesirable and can negatively impact aquatic life downstream of the reservoir. Of course, the impaired water quality also impacts on the aquatic life in the reservoir itself [66].

Irrigated agriculture is one of the major economic activities in the Orange River basin, resulting in significant water abstractions from the river. Part of the abstracted water flows back to the river through surface and subsurface drainage (seepage). This kind of return flows are worldwide considered the major diffuse (i.e. 'non-point') contributors to the pollution of surface water and groundwater bodies. On the other hand, irrigated agriculture would not be able to survive if salts and other fertilizer constituents would accumulate in the crop's root zone [67].

Surface drainage consists of the overflow water and the surface run-off. The overflow water is the excess irrigation water which is directly diverted to the river, without flowing over the irrigated soil. Its quality is similar to that of the river water. Surface run-off water is the portion of the applied irrigation water that runs off over the soil and discharges from the lower end of the field directly into the drain system. Because of its limited contact and exposure to the soil surface, its quality degradation is generally minor. Subsurface drainage water is the portion of the infiltrating water that flows through the soil and is collected by the under drainage system or directly by the river or the groundwater. Because of its more intensive contact with the soil, its quality degradation is substantial [67].

The most important water quality constituents of the return flow water are salts, primary nutrients, agrochemicals and trace elements. The primary source of dissolved mineral salts is the chemical weathering of rocks, minerals and soils. The main solutes contributing to salinity are the cations calcium (Ca), sodium (Na) and magnesium (Mg), and the anions chloride (Cl), sulfate (SO_4) and bicarbonate (HCO_3). These salts also originate in fertilizers and other agricultural chemicals, and of course, in the irrigation water itself. Growing plants extract water through evapotranspiration and leave behind most of the dissolved salts, increasing its concentration in the soil water ('evapoconcentration effect'). The salt load of the return flow is also increased by leaching natural salts arising from weathered minerals occurring in the soil profile ('weathering effect'). Fertilizers typically consist of 3 primary macronutrients, i.e. nitrogen (N), phosphorus (P) and potassium (K). The overabundance of plant nutrients, usually nitrogen and phosphorus, can lead to eutrophication (i.e. nutrient enrichment of surface water) with consequent impact on the aquatic ecosystem (e.g. excessive algal growth). The decay of algae causes a decline in dissolved oxygen (hypoxia). Pesticide contamination in return flows is of concern in some agricultural areas, although it is typically less significant than the salinity or nutrient enrichment problem. High concentrations of trace elements in soils and waters pose a threat to agriculture, wildlife, drinking water and human health. The sources of trace element contamination may be divided into natural (i.e. geologic materials) and agricultural-induced sources (i.e. fertilizers, irrigation waters, soil and water amendments, animal manures, sewage effluent and sludge, and pesticides). Trace elements such as As, Cd, Hg, Pb, B, Cr and Se are especially harmful to aquatic species because of biomagnification (i.e. the increase of concentration of a substance that occurs in a food chain) [67]. In the particular case of the Orange River, one can state that cultivation is in general too close to the river banks. Excessive irrigation occurs, resulting in return flows carrying pesticides and fertilizers directly into the river [55].

In a natural riverine ecosystem, many water quality problems would be mitigated by natural assimilative processes. However, the extensive river regulation has led to a decrease of flow volumes, which would otherwise naturally disperse the contaminants and aerate the water. The deterioration of the riverine ecosystem functioning due to human impacts has reduced the assimilative capacity of the river. This explains why releases from upstream reservoirs and return flows can easily impair downstream water quality throughout the basin [66].

5.2.3 Suspended solids

One of the most characteristic features of the Lower Orange River, before it was impounded, was its high turbidity [68]. The consequent limited light penetration in the water, made this a cold and unproductive system [61]. However, the deposition of fertile sediments on the river banks due to the historical flooding provides chances for agriculture [62].

The construction of dams on the Orange resulted in a change of the natural sediment dynamics, as dam reservoirs act as sediment traps. The concentrations of suspended solids of water released from Vanderkloof Dam decreased by 68 % compared to the historical concentration [61]. Obviously, this sedimentation process caused a significant decrease of the storage capacity of both Gariep and Vanderkloof Dam.

Increased agricultural activity and overgrazing on the river banks made the fertile alluvial soil prone to erosion, with consequent sedimentation in the river, as the river's capacity to transport sediment is diminished by the more steady flow regime. Due to the present regulated nature of the river, less maintenance floods occur which would naturally wash these sediments away. As a result, river pools will decline in depth and number and small islands can be formed, which are consequently stabilised by the growth of pioneer vegetation, such as reeds. It is obvious that the change in sediment dynamics leads to the destruction of several microhabitats associated with pools and rapids. Aquatic plants, insects and fish all have specific requirements related to the composition of the stream bed for them to live and reproduce [67].

5.3 Impact on the riverine biota

5.3.1 Vegetation and algae

Changes in the natural flow regime of the river are of key importance for the distribution of both indigenous and alien vegetation. The resulting artificial regime can advantage certain species, resulting in the apparent dominance of these plants.

The river reed, *Phragmites australis*, is the dominant semi-aquatic plant along the Orange River [69]. The encroachment of this reed is a recent phenomenon, as photographs taken as recently as 1976 show an almost complete absence of this species [55]. These *Phragmites* reeds are pioneer plants, able to quickly colonise disturbed areas and sandbanks. Indeed, the recent extensive growth of these reeds can be linked to the mechanical disturbance of riverbanks. Flow reductions and a more constant flow regime have contributed towards the spread of reeds along the river. The abundant use of fire by farmers is causing *Phragmites australis* to extend its distribution from the wetbank zone to the drybank zone, as indigenous trees and shrub covers are reduced, leading to the invasion of these pioneer reeds [70]. The island-rich river section between Boegoeberg and Augrabies Falls is characterised by extreme *Phragmites* settlement and encroachment in and along the shallower stretches of the river [65]. This is illustrated by figure 5.6, showing reed growth downstream of Neusberg Weir. The location of the low notch spillway on the left-hand side of Neusberg weir has forced the flow to the left bank of the original river bed, resulting in the colonisation of the central section of the river bed by *Phragmites* reeds.

The dense reed beds restrict the flow to the central section of the river bed, resulting in river channels becoming deeper and narrower. Consequently, islands (wetlands) can develop in the riverbed. Sand is accumulated by the reeds, resulting in the creation of more suitable habitat for these reeds. The excessive vegetation growth and consequent morphological changes of the river bed will block the passage of high flows through these river sections. The *Phragmites* problem can be described as an ecological time bomb as serious economic damage and loss of lives are expected during the next major flood. In addition, the reeds are a problem because they compete with agricultural crops, are a fire hazard and increase evapotranspiration [62].

The colonisation of reeds in turn affects the riverine ecosystem. Reeds trailing in the current significantly increase the surface area for black fly larval attachment (see section 6.1). The increase in fine organic material through burning and decomposition of these reeds are of great importance in the nourishment of these filter-feeding invertebrates. The expansion of *Phragmites* reeds can be considered an aggravating factor for the black fly problem. The rampant growth of this vegetation also has a significant impact on particle retention and nutrient uptake [55]. Furthermore, reeds provide important habitat for many species of fish, birds, mammals and invertebrates.

Farmers burn *Phragmites* reeds to stimulate young growth for grazing and as protection, because stock losses occur in the older dense reed beds where stock becomes trapped in debris accumulations [70]. Rehabilitation measures through burning of the reeds cause damage to the riparian vegetation. Furthermore, this practice consequently results in more densely rooted young reed beds. It was proposed that a flush of water would help to control the spread of *Phragmites* reeds in the Orange River. However, these reeds seem to be less vulnerable to a short-lasting increase in water level than a significant drop in water level. In the vicinity of Upington, a rise in river level of 3 to 5 m for 9 weeks in February/March 1996 had no significant impact on reed survival [62].

Low flow conditions in combination with nutrient enrichment of the water (see section 5.2.2) can cause algal blooms. Cases of algal blooms in Lake Vanderkloof are known in literature [61]. Excessive amounts of cyanobacterial (or blue-green) algae (*Microcystis sp.* and *Anabaena sp.*) developed in Lake Vanderkloof during late summer and autumn. Although low nutrient levels in this lake, both these algae are able to fix atmospheric nitrogen and adjust their buoyancy to remain in a narrow (1 m) photic zone. These excessive algal blooms resulted in poor water quality downstream of the dam and in the dam lake [62]. Cyanobacterial algal blooms (*Cylindrospermopsis*, *Anabaena* and *Oscillatoria*) have also been observed in the whole Lower Orange during autumn [70]. Cyanobacterial

Figure 5.6: Dense *Phragmites australis* reed beds below Neusberg Weir (located in the south-east corner of the photograph). Photograph: field trip September 2009.

algae reduce water quality in terms of human water use but also result in a reduction in diversity of the aquatic species assemblage at all trophic levels (i.e. all stages of the food chain). The most obvious sign of an advanced blue-green algal bloom is the formation of green 'scum', which leads to deoxygenation of underlying waters, subsequent fish kills and foul odours. Serious public health concerns associated with cyanobacteria arise from their ability to produce toxins, which are harmful both to man and aquatic life [67]. The phytoplankton assemblage in the Orange is extremely poor for a large river, reflecting the impact of eutrophication and cyanobacterial development in the upper reaches of the Orange River [70].

Due to the regulated nature of the river, algal blooms can also occur downstream of the dams. The decrease of turbidity due to river regulation results in an increase of light penetration in the water, favouring algal growth. Also, increased salt levels (with which flocculation and sedimentation of suspended solids is associated) can reduce turbidity. As benthic algae grow on bottom sediments, they are strongly dependent on light penetration in the water. Benthic algal blooms are known to occur commonly in the river reach from

Orania to (at least) Upington. Benthic algal growth seems to depend on turbidity rather than on seasonal influences [62].

Many floodplain developments have removed the natural floodplain vegetation, particularly in riparian areas near Upington, Kakamas and Onseepkans. Removal of this vegetation reduces the river's buffer against nutrients and sediment being washed of the surrounding farmlands. Mechanical damage to the riparian zone makes this zone more susceptible to colonisation of pioneer vegetation [70].

New projects along the Lower Orange, e.g. prospecting and mining, grape and other farming have resulted in informal settlements becoming established. People employed on a highly seasonal basis and unemployed people remain in these informal settlements, even when they are out of work. This results in high pressure on local resources, such as the overgrazing of river banks and floodplains by uncontrolled domestic stock. In the upper part of the Lower Orange, many trees and snags are removed for firewood [55]. These trees have subsequently been replaced by *Phragmites* reeds. However, further downstream, the abundance of large riparian trees and the scarcity of reeds are remarkable. In the Lower Orange, where rapids are scarce, woody snags provide an important substrate for filter-feeding invertebrates. In an area which is scarce of wood, it is important that riparian trees are protected because they play an important role in stabilising banks, providing a specific habitat and preventing colonisation by pest reeds [62].

5.3.2 Macroinvertebrates

Invertebrates are useful indicators of the ecological status of an area because of their ubiquity, rapid life-cycles and importance in food chains. In rivers, their presence reflects conditions upstream. It follows that invertebrates in the Orange River provide a useful tool for monitoring the ecological conditions in the river catchment [62].

No species are considered endemic to the Orange River, although the present-day distribution of the black fly *Simulium gariepense* is almost restricted to the Orange, and an undescribed species of sponge is presently known from the Orange River only. At least 3 species have (most probably) become extinct. The decline and extinction of species can be related to the presence of impoundments, and in particular to their impact on flow variability. Dam construction has also stabilised downstream river temperatures, which is known to reduce the diversity of benthic (i.e. living on the bottom) fauna [71]. However, this temperature effect will be restricted to the 130 to 180 km downstream of Vanderkloof Dam. Flow is therefore considered the major variable impacting on the invertebrate fauna. In general, one can pose that species richness in the Orange is low for a river of its size (compared to other rivers [62]). The low species richness may be partly related to the extreme conditions which characterise the Orange River. Prior to the construction of dams, the river often ceased to flow in winter and was reduced to isolated pools. Extreme floods resulted in high levels of suspended material. Fauna in this kind of rivers has evolved to cope with droughts and floods. Characteristics of some of these invertebrates are for example desiccation resistance of eggs, larvae and adult stages, the ability to survive in damp sands, rapid development times and specialised feeding [70]. It is obvious that fauna has evolved to deal with the natural flow regime which is nowadays drastically altered. The arid surrounding of the Lower Orange isolates the river biogeographically. Recolonisation potential from adjacent rivers and wetlands is therefore low. Consequently, the river is highly vulnerable, and this emphasises the need for protection [62].

Population size of some invertebrate species is of particular interest in order to prevent the spread of diseases, harmful to man and stock. Initially, studies revealed the increased risk of Schistosomiasis (or Bilharzia, i.e. a parasitic disease), as changes in water temperature due to the river impoundment may lead to the spread of certain *Bulinus* and *Biomphalaria* snail species which are intermediate hosts of human Schistosomiasis [60]. However, Bilharzia snails did not appear after the impoundment of the river [62]. Malaria occurs occasionally in the Lower Orange during years of high rainfall. This is because the malaria vector *Anopheles gambiae* breeds in temporary pools and is therefore unaffected by the river. Common species of molluscs *Mollusca* are host of liver fluke and conical fluke. *Culicoides imicola* is a (less common) midge which transmits the bluetongue virus and African horse-sickness. Also the yellow fever mosquito *Aedes aegypti* is present along the river course. Species of black fly *Simulium* cause poultry pest at times of low flow. The famous black fly *Simulium chutteri* is considered a major pest of livestock (see section 6.2) [62].

Due to flow regulation in the Orange River, pest densities of black flies *Simulium chutteri* occur more frequently (annually or even bi-annually) than before regulation. Black flies cause economical damage and the present high densities are experienced quite annoying as their bites cause severe allergic reactions, which often lead to secondary infections. As the black fly issue is considered one of the major ecological problems, the black fly problem and its remedy will be discussed in more detail in chapter 6.

5.3.3 Fish

The indigenous fish species in the Orange River system have evolved in such a way that they can survive the large floods that take place as well as the extended dry periods. Floods are essential to stimulate spawning (during summer). Rapids are essential food production areas and nursery areas within the river system. A flow of water through these habitats is essential at least during the spring, summer and autumn months when primary and secondary production has to sustain the developing juvenile fish [72].

The river section from Augrabies Falls to the Orange River Mouth is of particular importance for the fish communities in the Orange River. Although this reach is situated in the driest part of the country, the freshwater fish species diversity is the highest of the whole Orange River system. No less than 12 of the Orange River system's total of 14 naturally occurring indigenous freshwater species are distributed in this river stretch [70]. So as to illustrate the ecological importance of this specific river reach, table 5.1 represents a list of the naturally occurring fish species in this river reach, and their current status. Endemic (i.e. worldwide only occurring in the Orange catchment) species, vulnerable species and Red List (i.e. IUCN Red List of threatened species) species are indicated. Endemic species populations are especially vulnerable to a catastrophe in the river system (e.g. agricultural pollution) [73].

The same environmental issues as mentioned in other sections also account for the viability of fish populations. The artificial flow regime, the greenish colour of the water due to algal growth and the *Phragmites* reeds expansion are major concerns with respect to the health of fish communities [70]. However, some fish species benefit from reed settlement, such as those seeking shelter and/or refuge from predators, notably River Sardine, Straightfin Barb, Southern Mouthbrooder and Banded Tilapia. Fish species being negatively affected by the *Phragmites* colonisation are the open water and stream preferring ones, viz Threespot Barb, Namaqua Barb, Largemouth and Smallmouth Yellowfish, Orange River Mudfish and Rock Catfish. Dams and weirs form a physical barrier to fish migration. In general, fish start migrating during November in an upstream direction. The fish exhibit ripe gonads once the water temperature has reached 20 °C, during late January or February [72]. The present Neusberg diversion and gauging weir (1993) is the first weir in South Africa to incorporate a properly designed, model tested and monitored fish ladder. An additional environmental issue due to impoundment is the abrupt dam water releases: the endangered Rock Catfish does not occur in the vicinity of the dams as it does not tolerate the flow pulses created

Table 5.1: Checklist of the indigenous freshwater fish species occurring from Augrabies Falls to the Orange River Mouth [69]. E=endemic, V=vulnerable, R=red list species.

Species		**Status**		
Scientific name	**Common name**	**E**	**V**	**R**
Anguilla mossambica	Longfin Eel			
Mesobola brevianalis	River Sardine			
Barbus trimaculatus	Threespot Barb		√	
B. hospes	Namaqua Barb	√		√
B. paludinosus	Straightfin Barb		√	
Labeobarbus kimberleyensis	Largemouth Yellowfish	√		√
L. aeneus	Smallmouth Yellowfish	√		
L. capensis	Orange River Mudfish	√		
Austroglanis sclateri	Rock Catfish	√		√
Clarias gariepinus	Sharptooth Catfish			
Pseudocrenilabrus philander	Southern Mouthbrooder			
Tilapia sparrmanii	Banded Tilapia			

by large scale electricity generation [72].

The effect of the black fly control programme (see section 6.3 and 6.4) on other riverine organisms should be considered. A drastic drop in water levels for black fly control could strand fish eggs and larvae, thus interfering with fish recruitment. Some fish species feed on black flies and therefore flow regime control at the wrong time of the year could reduce the natural predator-prey balance. Flow manipulation programmes applied in late winter have the least ecological disturbing effect on the river. Late winter is the period of the year when periodic cessation of water flow used to occur naturally [73].

Both the Orange-Vaal Smallmouth Yellowfish *(Labeobarbus aeneus)* and the Orange-Vaal Largemouth Yellowfish *(Labeobarbus kimberleyensis)* are the major target fish for angling (mostly catch and release). For the Vaal River it has been estimated that the annual turnover of fly-fishing and the associated tourism industry amounts to R 1.2 billion (2007). Moreover, many poor families depend on this source of food [74].

L. aeneus is common throughout its natural range, the Orange-Vaal River system, as well as in impoundments in the system. Despite the large habitat alterations within the

Orange-Vaal River system, in both habitat and flow regime, this species thrives. Naturally, it was endemic to the Orange-Vaal system, but due to inter-basin water transfer schemes and introductions for angling purposes, this species also occurs outside its natural range. Although it has demonstrated high levels of biological flexibility, it is affected by certain anthropogenic influences, particularly water abstraction and pollution. Impoundment of the river restricts both the upstream and downstream migration of fish. Large schools of yellowfish are observed migrating in an upstream direction towards the dams during summer months. When water is released from the impoundments, the fish cross traps set in rocky bays below the dam wall and when the water recedes, the fish are left stranded in the traps. Illegal netting (near informal settlements) is also an issue that needs to be constantly monitored and managed, as this practice can decimate yellowfish especially during their annual spawning migrations. The effect of fly anglers wading through spawning areas can also be considered as a threat. Poor water quality is a major issue in the Vaal River. Even water quality problems at sub-lethal limits can stress the fish which increases their susceptibility to disease, reproductive failure, reduced feeding and a decline in overall fitness. Alien fish species (originating from human introduction) all compete with or actually prey on yellowfish. Possibly a bigger problem owing to alien fish interacting with yellowfish has been the introduction of both endo- and ectoparasites. There may also be synergistic effects between contaminants and parasites. Parasitism may be a secondary effect as a result of pollution decreasing fish immunity and increasing susceptibility [74].

L. kimberleyensis is a large predator attaining 22 kg, which makes it much sought after by anglers (figure 5.7). *L. kimberleyensis* is nowadays much scarcer than the related *L. aeneus*. For a number of reasons related to man and his influence on nature, this species has become a high priority conservation species. The environmental problems applying to the viability of *L. aeneus* populations also account for *L. kimberleyensis*. Moreover, *L. kimberleyensis* is susceptible to additional threats. The habitat preferences of *L. kimberleyensis* are more demanding (i.e. deep-water habitat requirements), thus *L. kimberleyensis* is more affected by the artificial flow regime than *L. aeneus*. Contrary to *L. aeneus*, *L. kimberleyensis* does not inhabit smaller tributaries. This means that the impact of polluted waters in the main channels is very serious, as *L. kimberleyensis* populations cannot be recolonised from tributary populations. *L. kimberleyensis* only becomes sexually mature at eight years or later, which makes it more vulnerable to angling pressure [74].

Figure 5.7: Orange-Vaal Largemouth Yellowfish (*L. kimberleyensis*) [75].

5.4 Conclusions

The human impact on the flow regime and the riverine ecology is described earlier in this chapter. However, two environmental problems due to impoundment have not been mentioned, as these do not occur along the Lower Orange. The first issue concerns the impact on the ecosystem directly upstream of the dam. Here, a flowing-water (lotic) ecosystem is converted into a standing-water (lentic) ecosystem, and wetland as well as dry land ecosystems are flooded and have become part of the reservoir [76]. The second issue originates from the inter-basin transfers. Inter-basin transfers can cause the transfer of water quality problems from the donor catchment to the recipient catchment. As water is transferred from one basin to another, so are the various life forms inhabiting the water. This can result in the introduction of new species into the recipient catchment, and the transport of disease vectors. Last but not least, the recipient river also loses her natural flow pattern.

Table 5.2 presents an overview of the ecological status of the Lower Orange. In the same table, the 20-year prediction of the ecological status is shown [70]. In table 5.3, the characters used in table 5.2 are described. The prediction is based on the assumption that no fundamental operational management measures are taken in order to mitigate the present environmental problems. The overall ecological status evolution is negative. River systems function as an integrated whole, and changes made in one part of a system will inevitably lead to changes in another part, and so it is unsurprising that the disciplines predict similar trends. It is obvious that an integrated river management is imperative in order to prevent an ecological disaster in the near future. However, one should keep in mind that even the most successful environmental flow programme will only partially compensate the effects of dam construction and water abstraction. Taking into account all boundary conditions to the environmental problem, the recommended ecological category would most likely be a C category [55].

Table 5.2: Present ecological state (PES) and 20-year prediction for the Lower Orange [70].

Discipline	**PES**	**20-year prediction**	**Trajectory**
Water quality	B/C	C/D	Negative
Geomorphology	C	D	Negative
Algae	D	E/F	Negative
Vegetation	D	E	Negative
Macroinvertebrates	D	D/E	Negative
Fish	D	D/E	Negative
Overall	**D**	**D/E**	**Negative**

In order to translate the ecological requirements into a concrete operational management programme, the concept of the instream flow requirement has been introduced. The instream (or environmental) flow requirement IFR (or EFR) is intended to be a flow which reconciles the changes in the abiotic and biotic ecosystem components, so that the ecosystem is maintained in a negotiated ecological condition [78]. This condition is decided by society and is normally a compromise between economic, social and ecological values of the water for various users [55]. These flow requirements can be used as a boundary condition for the hydraulic model so as to determine an appropriate dam water release pattern.

Some general guidelines for the determination of a more environmentally sound flow pattern

Table 5.3: Key to the ecological status character code [77].

Ecological status	Description
A	Unmodified, natural
B	Largely natural with few modifications
C	Moderately modified
D	Largely modified
E	Highly degraded
F	Extremely degraded

can be suggested in advance. Of course, the extent of implementation of the guidelines also depends on economic and social interests. These guidelines have been listed below [56]:

- **Flow release variability**

  The release of water should be varied in a way that mimics, to the best degree possible, the natural flow of the river. In particular, one should assure both short-term variability (over days and weeks) as long-term variability (seasons). Every attempt should be made to have a mix of drought conditions as well as periodic flooding;

- **Release patterns**

  Water should be released from the dam in a way that is sympathetic to the natural flow of the river. For example, if the flow to the downstream has to be reduced, this should be done gradually over several days, as would be the case in a natural river. It is obvious that the sudden hydropower releases are violating this basic rule. The duration of the decrease or increase in flow should ideally mimic the natural situation and can be determined by close observation of the natural hydrograph. Commonly, increasing flows occur rapidly as would happen after a storm event. Decreases in flow occur fairly rapidly soon after the peak, but then the rate of decrease generally slows over days, weeks or months.

Not all environmental problems can be blamed on the artificial flow regime. The government should outline a policy so as to prevent environmental damage to the river and its fertile alluvial deposits caused by its consumers. Important issues include restrictions on return flows and other agricultural practices and the control of informal settlements.

Chapter 6

Black fly pests and control programmes

6.1 Introduction

A black fly is an insect of the *Simuliidae* family, belonging to the *Diptera* order. The black flies are small, dark flies with a humped back (see figure 6.1 and 6.2). The bite of these insects is very painful. Black flies slash the skin and lap up the pooled blood, in contrast to a mosquito, which sucks up the blood through a proboscis (i.e. a snout that is used as a kind of tube) [79]. There are a lot of different species of black flies, spread all over the world. Most species belong to the *Simulium* genus, such as those found in southern Africa.

Figure 6.1: Black fly or *Diptera Simuliidae* [80].

Black flies are mostly found in the proximity of flowing water. The eggs are laid in running

Figure 6.2: Black fly or *Diptera Simuliidae* [81].

water. Larvae use tiny hooks to attach themselves to a substrate, mostly rocks and vegetation. In section 5.3.1, the related problem of extensive reed growth and black fly pests was already broached. These reeds do duty as a perfect environment for black fly larvae. Black flies seem to be favoured by the changed ecosystem (altered flow conditions, reed growth, etc.) in contrast with their natural predators, who seem to suffer from this situation. In fact, black flies are able to survive the winter season as they rely on higher lipid, protein and carbohydrate reserves [82]. The black fly larvae depend highly on their lotic (i.e. a flowing-water ecosystem) habitats to feed them as these invertebrates are rather immobile and take all necessary nutritious substances by filtering the flowing water. Thereafter, they will pupate under water. The adult, flying black flies will emerge in a bubble of air [79]. The larvae and pupae life stages are shown in figure 6.3.

Originally, black flies (*Diptera: Simuliidae*) were not considered a pest in South Africa. After the building of dams, canals, irrigation schemes and hydroelectric plants, black flies have developed a pest status along many rivers [83]. The reason for that are the ideal conditions for immature black flies that were created by those impoundments [83] [84]

Figure 6.3: Larvae and pupae black fly life stage [86].

[85]. The black fly problem is attributed mainly to high winter flows. Black flies increase in number in rapids downstream of such structures as the impoundments promote the development of suspended organic material (originating from e.g. deteriorated reeds or increased algal growth) combined with a more constant seasonal flow of water [87] [88]. In general, many rivers are changed from ephemeral (i.e. rivers cease flowing during winter months) to perennial (i.e. permanently flowing) rivers due to the construction of these impoundments. This creates ideal and continuous breeding conditions for these insects [89] [90]. In southern Africa, 39 black fly species are known to occur [91] [92]. The two most frequently occurring ones are the mammalian pests *Simulium chutteri* and *Simulium damnosum*.

Along many South African rivers, especially the Orange River, black flies have become common and significant pests. Outbreaks of pest black flies have been one of the most serious problems affecting agriculture and tourism along the Lower Orange River.

In the Republic of South Africa (RSA), the Agricultural Research Council - Onderstepoort Veterinary Institute (ARC-OVI) was involved in the development and implementation of black fly control programmes [93]. The ARC-OVI is taking charge of all research studies concerning the black fly problem. Since the end of the 1960's, they set up strategy plans and control programmes to impose restraints on these pests.

6.2 Medical, veterinary and economic importance of black flies

Black flies feed on nectar and sugar, which is used as a fuel for flight [94] [95] [96] [97]. In addition, adult female black flies also require a blood meal for ovarian development [91] [98] [99] [100] [101] [102]. Because of their blood-feeding activity they are considered ideal disease vectors and are probably best known for transmitting the filarial nematode *Onchocerca volvulus* to humans [99] [102] [103] [104] [105]. The resulting disease known as onchocerciasis or 'river blindness' has left more than 20 million people infected and millions of them blind in west Africa and south America [105] [106] [107] [108]. Onchocerciasis is caused by a filaria worm (see figure 6.4), which gets into the human through a black fly bite. Once the worm is in the skin, it births thousands of microfilariae (i.e. baby worms) which move to the eye and the skin. When the microfilariae die, their decomposing bodies produce toxins that cause extreme itchiness and lesions. After enough time, this toxicity causes blindness (see figure 6.5) and extreme skin disfigurations such as nodules (see figure 6.6) [109].

Figure 6.4: Filaria worms that cause Onchocerciasis [109].

Figure 6.5: Onchocerciasis: an infected eye [109].

Figure 6.6: Onchocerciasis: skin disfiguration [112].

Furthermore, in humans, the bites of some black fly species can cause allergic reactions known as 'black fly fever' or simuliotoxicosis [91] [102]. This condition is characterised by swelling, itching, haemorrhage (i.e. bleeding or the abnormal flow of blood) and oedema (i.e. fluid retention in the body) which, in severe cases, requires medical attention [110] [111].

In animals, black flies have been implicated in the spread of many diseases. It has also been shown that allergic reactions to black fly bites, similar to that described in humans, can lead to the death of cattle [111]. In South Africa, simuliids have been implicated in the spread of two pathogens to animals namely *Chlamydophila sp.*, that causes blindness in sheep and abortion in cattle, and the Rift Valley Fever virus [113]. Black fly readily attack exposed body parts of livestock such as eyes, ears and teats [114]. The resulting wounds are prone to secondary infections which sometimes can lead to death of animals [91].

Black fly annoyance also leads to economic losses through reduced efficiency of agricultural and industrial workers, interference in recreation and reduced real estate values [111]. The economic impact on the touristic sector may also not be diminished. Even though many research studies on the black fly epidemics were conducted in the RSA, only a few concern the economic impact of the pest. In [115], a detailed study on the physical destruction of the teats of some cows and a reduced milk production are reported as some of the main impacts. According to [115], the milk production can be reduced with 30 to 50 % as a result of black fly attack. In poultry, egg production can fall to 85 % of its original volume. Also the lambing percentages are diminished. As a result of secondary infections that develop because of black fly wounds, cows can lose their udders and sheep lose their ears [116]. The Northern Cape Agriculture Union estimated in 1996 that black flies can cause a potential annual loss of more than R 88 million to the stock industry along the Orange River if no actions were taken [91]. This figure is based on a 25 % reduction in lamb production and excludes any other, secondary costs such as land depreciation and tax losses to the state.

Today, *S. chutteri* is considered to be the most important black fly pest species in the RSA. This species occurs along many rivers, but is abundant and causes the largest economic problems along the Lower Orange River [91]. Endemic to southern Africa, this species can have larval densities exceeding 500 000 per m^2 under favourable conditions [92]. *Simulium chutteri* has several generations per annum [62]. These black flies occur a whole year long, but an increase in biting activity is normally experienced in spring and early summer (August tot November) and autumn (April to May) [117] [118]. This suggests that this species is adapted to moderate weather conditions [93].

6.3 History of black fly control in South Africa

Since the 1960's, the ARC-OVI analyses and tests different methods to decrease the pest impacts. The first attempts to control black flies in South Africa started already in 1965. The different phases in the planned control programmes are described below.

6.3.1 Phase 1: DDT applications

Prior to 1940, only periodic black fly outbreaks were experienced. After the construction of many impoundments (e.g. Boegoeberg Dam and many weirs), black fly numbers have been increasing constantly [83]. This leads to considerably more frequent and severe black fly outbreaks. After a severe outbreak during 1963 in the Warrenton District, the first studies were undertaken on the ecological requirements of the locally occurring black fly species [84] [119]. These very first black fly studies were conducted in 1965 followed by the first attempts to control the pest. At first, the insecticide dichlorodiphenyltrichloroethane (DDT) was used. In the 1960's, this chemical was described as 'the perfect weapon for the perfect target' [120].

A result of the DDT applications was the growth of benthic algae on rocks. The algal mats had the benefit that they did not allow new generations of black fly larvae to attach to affected rocks [83]. Although high larval mortalities were obtained, rapid reinfestation was recorded following the disappearance of the algal mats [84]. Because of the environmental damage caused by DDT, this control programme was already suspended after two years. Research later on, showed that DDT is an extremely poisonous agricultural insecticide [121]. In fact, the algal bloom was a result of the eradication of most invertebrates. This is caused by the low target specificity of DDT [122].

6.3.2 Phase 2: Water flow manipulation

After the adjournment of the DDT applications in the 1970's, black fly pests were not yet disappeared. On the contrary, after the completion of the Vanderkloof and Gariep Dams on the Orange, *S. chutteri* was allowed to develop to pest proportions in this river system [83] [117]. In a new attempt to control these problems, the ARC-OVI presented a new solution. In a second phase, a water flow manipulation process was used. According to this method, the water levels of rivers were artificially (by controlling sluice gates of dams and weirs) fluctuated to expose and desiccate the pupae as well as forcing the larvae to move to undesirable sites were they are prone to starvation and predation [123].

Several trials on the Orange River were successful. Cut-offs in water flow must be implemented twice a year, during May and August, to be effective [93]. Some river sections where regular water flow fluctuations were implemented lost their pest status. Despite the success of this approach, it was only applicable for a few kilometres downstream of a weir or dam [93].

6.3.3 Phase 3: Integrated water flow manipulation

A third method was proposed during the same period (late 1970's and early 1980's). This procedure involved an integrated approach were data on the life-cycle, population dynamics and microhabitat preferences of the most abundant *Simulium* species and their natural aquatic invertebrate predators were used to determine the best time to carry out a series of river-flow cessations [113] [124]. Water flow regulation was then applied to halt the build-up of populations and maintain *S. chutteri* at levels at which they could be controlled by natural predators [93].

It should be clear that this approach can be regarded as the most cost efficient and ecologically the least disruptive of all available methods. However, this method is limited by the availability of impoundments upstream of *Simulium* breeding sites and is therefore impractical [125]. Furthermore, the need for irrigation water, as well as the release of water from the Vanderkloof and Gariep Dams, for the generation of hydroelectricity, made the use of strategically-timed water flow manipulation impractical along the Orange River [83].

6.3.4 Phase 4: Bti and temephos applications

During the 1980's, the first attempts to control black flies with biological and chemical agents took place. Instead of the application of DDT, these agents may not be harmful to the environment. The most frequently used biological larvicide is Bti, which is an acronym for *Bacillus thuringiensis Berliner var. Israelensis de Barjac (serotype H-14)*. The organophosphate temephos, a chemical larvicide, can be used as alternative.

Bti is a naturally occurring bacterium that produces protein crystals with larvicidal activity against filter-feeding *Diptera* such as mosquitoes and black flies [93]. The active substance (delta-endotoxin) is released in the stomach of the larvae and destroys the stomach cells. The alkaline fluid can enter the blood and results in a general paralysis and death. Bti works best in clear water where there is no dilution due to silt particles or algae. In polluted rivers with a high sewage level and high chlorine concentration, its toxicity is considerably reduced [126]. This biological larvicide is used and considered to be effective in many parts of the world. Also in South Africa, high larval black fly mortalities were reported [122].

Subsequent trials in the Orange River confirmed the efficacy of Bti against black flies and its low toxicity to non-target organisms [125].

The alternative to Bti is temephos, specially formulated for black fly control in a specific suspension concentration. This chemical larvicide has proven to be very effective and environmentally acceptable in west African rivers during the onchocerciasis (i.e. river blindness) control programme [93]. Instead of Bti, is temephos best used in rivers that have silt particles in suspension. At high flow rates, many rivers become silt-laden, so this characteristic is quite interesting.

Both Bti and temephos proved to be effective against *S. chutteri* larvae and led to the establishment of an annual black fly control programme along the Orange River [62] [127]. One should take into account that the river conditions suitable for these larvicides also differ, as they have a different mode of action. Bti is normally restricted to rivers with relatively low flow rates less than 100 m^3/s. Application is usually by helicopter to allow dispersion. Temephos can still be applied if flow rates exceed 300 m^3/s. In these circumstances, temephos is effective for up to 50 km downstream of the application point. At this flow rate, the larvicide is applied from a bridge or a boat [62] [118] [128]. Various studies on the impact of these two larvicides on non-target organisms showed that they are safe for use in the Orange River.

6.4 Current policy on black fly pests

Nowadays the National Department of Agriculture (DA) implements the Orange River Black fly Control Programme (ORBCP). To control the pest, between 2 and 19 temephos and Bti applications per annum are needed [90] [91]. To inhibit selection of resistant individuals, especially to temephos, it is recommended to use these two larvicides alternately [93]. Although, in practice it is always necessary to check the current flow conditions. One should take into account that both variants are not always applicable under each condition.

Despite the fact that an effective black fly control programme as the ORBCP is set up for the Lower Orange River, major outbreaks do still occur [89] [91]. Two factors are causing these unwanted outbreaks: human error and a lack of information on several black fly population dynamic factors. This lack of information makes planning of control actions difficult and inaccurate [131]. The ACR-OVI conducted several studies under contract to the Water Research Commission (WRC) to address some of the aspects believed to influence adult black fly survival [93]. The results of these studies can be used to understand the typical seasonal variation in the annoyance levels of black flies. In this way, outbreaks can be predicted more accurately and the control programmes can be adjusted accordingly [93].

Some recent studies showed that black flies along the Orange River are developing resistance to temephos [132]. The challenge is to develop a strategy to overcome this resistance problem and/or testing new larvicides. It should be clear that continuous research to adjust and develop control programmes is essential. Future research should aim to integrate chemical and biological control with other methods of control. The research should also provide a framework for minimising the number of treatments and therefore the total costs, both financial and environmental [127].

6.5 Conclusion

Black flies have reached a pest status in the RSA as they are harmful to both human and animal. Due to damming on the Orange River and the resulting high winter flows (see chapter 5), an ideal habitat for black flies species was created by man. What is more, the natural predators of black flies are suffering under the altered situation. Therefore, the population size of black flies is increasing very quickly.

To stop this problem, the DA implemented the ORBCP. Several methods have yet been tested to solve the black fly problem. Control programmes on the basis of poisonous chemicals, such as DDT, were abandoned because of their ecological impact. An approach of (integrated) water flow manipulation didn't make it neither, because the outcome was too limited. The currently adopted solution exists of the application of biological (i.e. Bti) or chemical (i.e. temephos) agents. It is important to mention that these substances have no significant impact on the environment. The merit of this control programme is already been proved. Nevertheless, further research on this matter is necessary to optimise the South African policy of black fly control. It is the aim to combine the biological and chemical control agents with flow manipulation procedures in order to reduce the application of these agents to an absolute minimum.

Chapter 7

Environmental aspects pertaining to the river mouth

7.1 Introduction to the Orange River mouth

The Orange River mouth (ORM) is one of few perennial wetlands along southern Africa's arid Atlantic coastline. It is the sixth most important southern African coastal wetland in terms of the number and diversity of birds supported [133]. In recognition of this exceptional ecological significance, the ORM was designated a Wetland of International Importance in terms of the Ramsar Convention on wetlands in 1991. The Convention on Wetlands of International Importance, called the Ramsar Convention, is an intergovernmental treaty that provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources [134]. When the Republic of Namibia (NA) designated its portion of the ORM a Ramsar site in 1995, it created the potential for this wetland to become the first jointly managed transboundary Ramsar site in southern Africa [55].

During the past 3-4 decades the ORM has been subjected to significant anthropogenic influences, which appear to have influenced the number and diversity of waterbirds using this wetland. As a result of this decline in bird numbers, combined with the final collapse of the salt marsh component of the wetland, the ORM has been placed on the Ramsar Convention's Montreux Record in 1995. The Montreux record is a register of Ramsar sites where changes in ecological character have occurred as a result of human interference. This record intends to prioritise sites for national and international conservation attention [55] [135]. The Republic of South Africa and the Republic of Namibia are now obliged, as a signatory of the Ramsar Convention, to ensure that the ecological character of the site is restored [136].

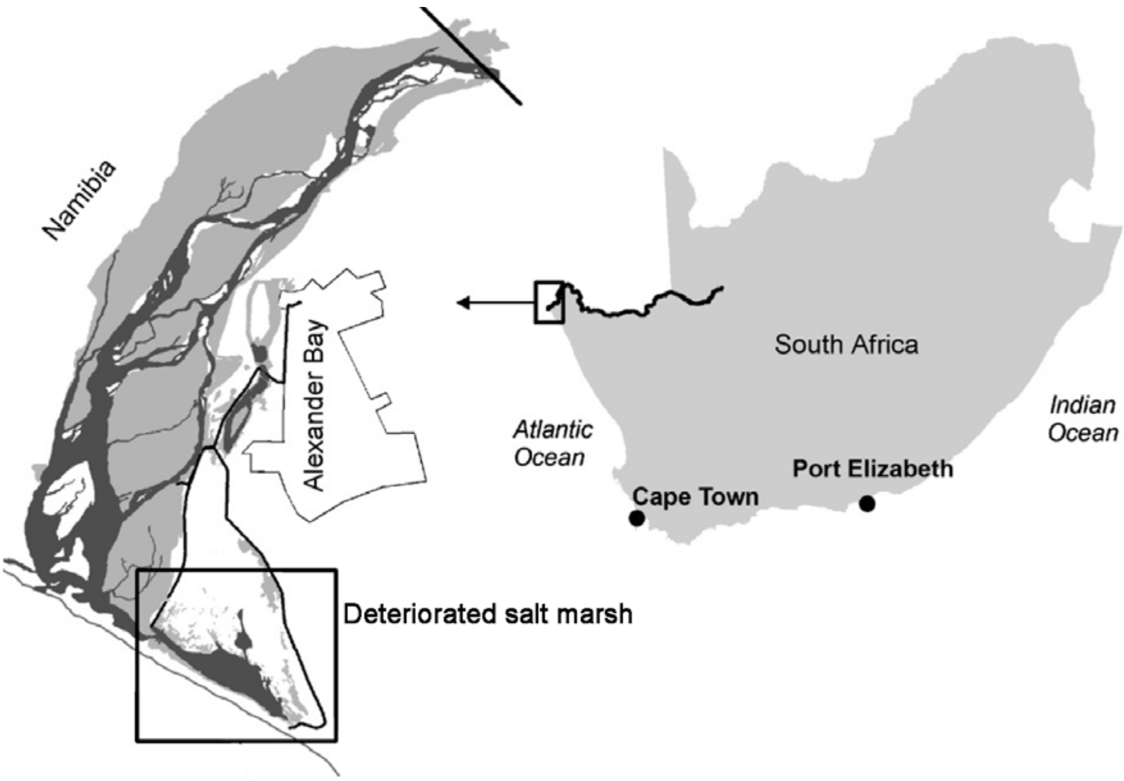


Figure 7.1: Overview map of the Orange River mouth [136].

Figure 7.1 shows an overview map of the Orange River mouth. The ORM is situated between the mining towns of Alexander Bay (Republic of South Africa) and Oranjemund (Republic of Namibia). The river mouth system extends from the shoreline as far as the Ernest Oppenheimer Bridge, approximately 9.5 km upstream. Tidal variations of a few centimetres are observed at spring tide at this bridge [137]. The ORM is not a true estuary as it is dominated by fresh water and has few estuarine characteristics. It is best defined as a delta-type river mouth [138]. The 2000 ha Ramsar site consists of a distributed and braided channel system, a small tidal basin, extensive salt marshes, freshwater lagoons and marshes, sand banks, and reed beds [134].

The state of the river mouth (open or closed) determines the extent of the marine influence in the river mouth, and is thus of major ecological importance. The state of the mouth depends on the balance between factors that tend to block the mouth, viz sediment deposited by the river and long-shore currents (i.e. an ocean current that moves parallel to the shore), and factors that flush it open, viz outward flow of river water and inward flow of sea water during high tides. Recent studies have highlighted the effect of direct wave action [139]. Higher waves cause more turbulence and therefore bring more sediment in suspension than lower waves. This sand is transported on the incoming tide into the estuary mouth and settles out when the wave action subsides and the current velocities decrease [140].Under natural conditions, the blocking factors would dominate when river flow is low and the mouth would close. Water then backs up flooding the low lying areas, particularly the salt marsh on the southern bank. This continues until the sand spit is breached and a new mouth forms [135]. Due to the current artificial flow regime, the natural dynamics of the mouth are severely disturbed. The unseasonal water release pattern lacking very low flow periods inhibits the mouth from closing. The result is that the dynamics of the mouth are now largely artificially controlled, and closure of the mouth seldom occurs. The rare occasions the mouth had closed it was artificially breached by the Alexkor and Namdeb mining companies so as to avert flooding of low lying properties [135].

7.2 The salt marsh and its rehabilitation

Part of the Orange River mouth can be classified as salt marsh. The salt marshes under concern are located on the south bank of the river. A detailed map of the deteriorated salt marsh indicated on figure 7.1 is represented in figure 7.2. The salt marsh provides a specific habitat for many waterbirds, so its rehabilitation is indispensable in order to remove the ORM from the Montreux record.

The loss of approximately 300 ha of salt marsh was caused by numerous anthropogenic impacts. These include leaking of diamond-mining process plant water, mine dump dust that blankets the vegetation, construction of flood protection works, construction of a beach access road (east of the river mouth), the elimination of tidal exchange into the wetland due to a causeway constructed at the river mouth (to provide easy access to central part of the beach [140]), diversion of flood channels away from the wetland, grazing of cattle on the floodplain and the use of fertilizers [136] [141].

Analyses of past aerial photographs suggests that the dieback of the salt marsh could be partly attributed to the 1988 flood [136]. Flood water then breached the causeway (indicated on figure 7.2) and flooded the salt marsh. Subsequently, the presence of the

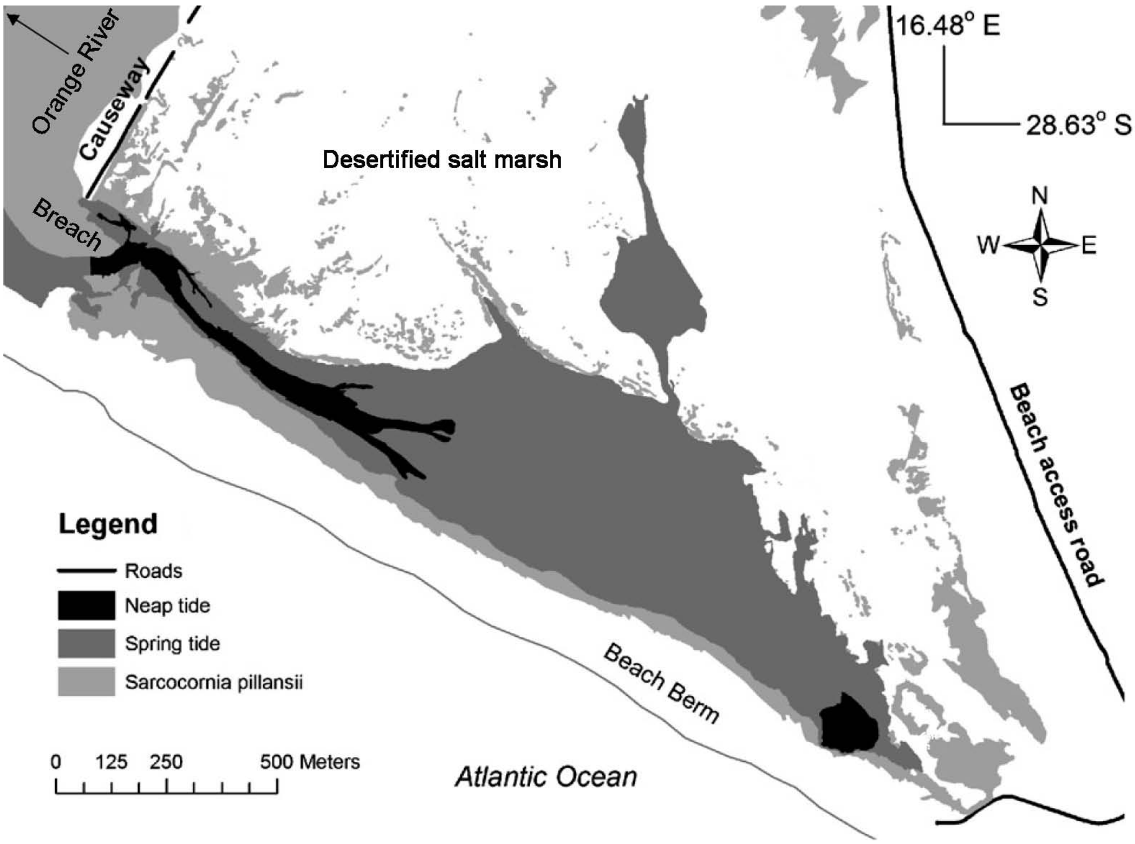


Figure 7.2: Detail of the deteriorated salt marsh indicated on figure 7.1 [136].

causeway (3 m MSL, this is 1.5 m above the adjacent salt marsh [142]) prevented the flood water from draining into the river, and large sections of the salt marsh were covered by low salinity water [143]. So as to cope with this problem, the beach berm (indicated on figure 7.2) was artificially breached in the southeastern corner. Although this intervention resulted in the drainage of the salt marsh component, it also provided a chance for fresh seawater to enter the salt marsh for about one month. Of course, this increased the salinity of the water standing on the floodplain [143]. The standing water killed off the salt marsh vegetation that survived the scouring effect of the flood and subsequent evaporation of the seawater increased the salinity of the salt marsh sediment and groundwater [136].

Historically, large-scale destruction of the salt marsh floodplain occurred during major flood events. However, rehabilitation of the salt marsh was a natural process that restored the salt marsh into its original state in a period of years. Complete recovery of the salt marsh component between 1976 and 1986 (following the 1976 flood) indicates that natural

Figure 7.3: Deteriorated (desertified) salt marsh, with *Sarcocornia pillansii* vegetation on the foreground. Photograph: field trip September 2009.

recolonisation of the salt marsh is possible within a 10-year period. In contrast, the only recolonisation of this area since the major 1988 flood was a 2 ha area after a breach was made in the causeway (indicated on figure 7.2) [136]. Until now, the majority of the original salt marsh area (500 ha east of the causeway) is still deteriorated to a desertified area (figure 7.3) [136].

The naturally dominant vegetation at the salt marsh site is *Sarcocornia pillansii* (figure 7.3), which is a typical supratidal and floodplain species [136]. The rehabilitation of this salt marsh vegetation will depend on its ability to reproduce. The sediment characteristics will determine whether the deposited seeds and emerging seedlings will be able to survive [136].

The high salinity levels of both groundwater and surface sediment (> 50 psu[1]) can be pointed out the major culprit of this problem [144]. Laboratory experiments indicate that *S. pillansii* germinates best in freshwater conditions. 40 % germination was achieved

[1] psu=practical salinity unit

at 0 psu, in contrast to 5 % germination at 35 psu [136]. The current hypersaline salt marsh conditions are above the tolerance range of *S. pillansii*. A decrease of salt marsh salinity levels can be established through regularly flooding. *S. pillansii* uses water as the main means for the transportation of seeds, which also illustrates the importance of flood events [145]. The remaining viable *S. pillansii* fields have the potential to produce 40 billion seeds, which would be sufficient to revegetate the desertified salt marsh [136].

Seed germination, seedling growth and adult survival is dependant on favourable sediment and groundwater characteristics [136]. This can be achieved by linking the marsh back to the main river channel, i.e. removing sections of the causeway or the whole of it [144]. Back-flooding of the floodplain used to occur under natural conditions and is required to flush the salts from the surface soils, for the transportation of seed to favourable areas and for the creation of microhabitats [136] [144]. Floodplain salt marsh is intolerant of standing water so proper drainage of the floodplain should be ensured before back-flooding is attempted [144]. Naturally, two mechanisms for inundating the floodplains with fresh or brackish water used to occur. The first mechanism for flooding the salt marshes is the regular mouth closure and the related back-flooding. Previous studies indicate that mouth closure occurred for less than 10 % of the time, i.e. approximately once in four years for a brief period (dry period) at flows of ca 10 m^3/s [140]. The second mechanism includes the combined effect of high river inflows/floods and tidal variation. At a water level between 0.5 and 1 m MSL, about 27 % of the salt marshes is inundated. At a water level of 1.5 m MSL, 70 % of the marshes is inundated. The mean high water spring is about 1.1 m MSL. The 40 cm increase in water level required for inundating the majority of the salt marshes is easily achieved through damming up of the river outflow during a spring high tide [140]. However, as illustrated in chapter 5, river regulation results in a severe decline in minor flood events. This means that one cannot rely on this mechanism for the rehabilitation of the salt marsh floodplain. As a consequence, the mechanism of mouth closure is the only feasible mechanism for regularly flooding the salt marshes. At the moment, unseasonal water releases and artificial mouth breaching inhibit the river mouth to close according to the natural dynamics.

The current rehabilitation project on the salt marsh (see figure 7.4) aims to remove the ORM from the Montreux Record. It is obvious that a restoration of the river mouth to its natural state cannot be expected. The following options were considered in the restoration process [140]:

- The connection of the lower salt marsh with the main channel, by breaching the

Figure 7.4: ORM wetland rehabilitation in progress. Photograph: field trip September 2009.

utmost southern tip of the causeway (completed). Recovery of salt marsh vegetation in the proximity of the tidal channel is already observed [136];

- Removal of local obstructions within the salt marsh to enhance inflow;
- Additional openings in the causeway and/or complete removal of the causeway;
- Reduction in river flow during winter so as to allow the mouth to close and thereby permit back-flooding during the flow increase in spring. It is obvious that the reduction of water releases from Vanderkloof Dam would have severe social and economic consequences for the Lower Orange. The construction of a new dam in the proximity of the river mouth will allow the establishment of a flow regime that partially mimics the natural dynamics, without affecting the water supply for many farmers and families;
- Mechanical closure of the river mouth. In addition to this, the river mouth can be artificially breached at strategic positions. The location of the mouth has a major influence on the salinity of the water reaching the salt marsh near the mouth. A river

mouth near the salt marsh component results in considerable amounts of seawater entering the area at spring tides. The needs of the salt marsh should be evaluated before breaching.

Unfortunately, the authors of this report have no further information on the progress state of the rehabilitation project. Considering the importance of flow patterns on the ORM health, it is clear that more research must be conducted on this topic.

Future expansion of economic activities and population growth in the Gauteng area, in the Eastern Cape region and in the Orange-Senqu-Fish catchment can result in a higher stress imposed on the ORM. A further increase of the water demands, both for inter-basin water transfers and for water use along the Orange, is expected. An increase in hydraulic modelling accuracy and operational management efficiency could result in less flow reaching the river mouth during the whole year, as operational losses are minimised. This emphasizes the need for the implication of environmental flow requirements in operational management procedures. Otherwise, future reductions in river flow could cause frequent and prolonged mouth closures, occurring more often and for longer periods than would naturally be the case. Mouth closure during wet season months will create conditions opposite to the natural conditions in the ORM. At low flows (possibly below 10 m^3/s) the mouth will close. The water level will initially increase, but could then remain constant or even drop again, based on the balance between the flows and the losses, mainly through seepage and evaporation. Under these circumstances, tidal flows through the mouth will not occur and seawater will not enter the estuary. Although this scenario may be conceived as distant future or merely a worst-case scenario, it is obvious that this scenario will result in a total collapse of the local ecosystem, and should be avoided at any cost [140].

7.3 Birds and Ramsar status

The Orange River mouth provides a suitable habitat for many bird species for foraging, breeding, resting and roosting. The ecological importance of the ORM is illustrated by table 7.1. This table shows the ecological status of some commonly occurring species at the river mouth. It illustrates the importance of the numbers of these species present at the ORM in terms of national and international population health, and emphasizes the need for conservation of this important wetland habitat. In addition to these species, many

Table 7.1: Waterbirds regularly recorded at the Orange River mouth which are listed on the South African Red List (2000 status [146]) or the Namibian Red List (1998 status [147]) or the international IUCN Red List of threatened species (2009 status [148]) [135]. NT=near-threatened, VU=vulnerable, EN=endangered (EN is worse than VU, and VU is worse than NT).

Species		Status		
Scientific name	**Common name**	**RSA**	**NA**	**International**
Pelecanus onocrotalus	Great White Pelican	NT	EN	-
Phalacrocorax capensis	Cape Cormorant	NT	-	NT
Threskiornis aethiopicus	Sacred Ibis	-	VU	-
Plegadis falcinellus	Glossy Ibis	-	VU	-
Bostrychia hagedash	Hadada Ibis	-	VU	-
Phoenicopterus ruber	Greater Flamingo	NT	EN	-
Phoenicopterus minor	Lesser Flamingo	NT	EN	NT
Haliaetus vocifer	African Fish Eagle	-	EN	-
Circus ranivorus	African Marsh Harrier	VU	VU	-
Charadrius pallidus	Chestnut-banded Plover	NT	VU	NT
Larus hartlaubii	Hartlaub's Gull	-	VU	-
Sterna caspia	Caspian Tern	NT	VU	-
Sterna bergii	Great Crested Tern	-	VU	-
Sterna balaenarum	Damara Tern	EN	EN	NT

'vulgar' (i.e. not endangered) species also occur at the ORM. Some vagrant species have occasionally been recorded at the river mouth [135].

Since 1980, survey data on birds in the ORM is collected. The number of waterbirds recorded at the ORM has varied considerably since 1980 when the first comprehensive survey was conducted. The highest number of waterbirds was recorded in 1980 and 1985, yielding more than 20 000 birds. Subsequent surveys, beginning in the early 90's, never recorded such high numbers. Comparison between the 1980-1985 and the 1996-2001 data average reveals a 74 % decline in the number of waterbirds. Despite this drop in the numbers of birds present, species richness of waterbirds remained relatively constant from 1980 to 2001: an average of 52 species was recorded. A total of 87 different waterbird species was recorded during 20 surveys from 1980 to 2001 [135].

The decline in waterbird numbers is mainly accounted for by the virtual absence of Cape Cormorants (*Phalacrocorax capensis*) and Common Terns (*Sterna hirundo*). During the early 80's, the ORM was still considered an important breeding site for thousands of Cape Cormorants. Several other waterbird species that were particularly numerous during the early 80's have not subsequently attained their original numbers [135].

It is obvious that the altered flow regime has direct and indirect impacts on the waterbird habitats at the ORM. In particular, the salt marsh habitat is severely deteriorated due to the lack of regularly occurring flooding of the marsh. Anthropogenic factors which have directly impacted on the presence of birds at the ORM include recreational activities (fishing, off-road vehicles on the beach) at or in the vicinity of sensitive breeding and roosting sites, disturbance by recreational aircraft, disturbance by cattle, feral cats and dogs and the hunting of ducks and geese within the Ramsar site [135]. Various measures can be implemented to improve the situation for waterbirds at the ORM. More natural flow release patterns at Vanderkloof Dam (or at a new dam) will restore the estuarine dynamics and improve habitat quality. Rehabilitation measures for the salt marsh component and an appropriate policy in order to minimise on-site anthropogenic impacts will most probably also result in an increase of the waterbird numbers. Where feasible, artificial roosting and breeding sites for certain bird species can be created [135].

In 1991 the Orange River mouth was designated a Ramsar wetland area. A wetland is identified as being of international importance if it meets at least one of nine criteria. Since 2005, a wetland is considered Internationally Important if [134]:

1. it contains a representative, rare, or unique example of a natural, or near-natural

Figure 7.5: The authors assessing the ecological status of the Orange River mouth, standing at the look-out tower on the beach at Alexander Bay. Photograph: field trip September 2009.

wetland type found within the appropriate biogeographic region;

2. it supports vulnerable, endangered or critically endangered species or threatened ecological communities;

3. it supports populations of plant and/or animal species important for maintaining the biological diversity of a particular biogeographic region;

4. it supports plant and/or animal species at a critical stage in their life cycles, or provides refuge during adverse conditions;

5. it regularly supports 20 000 or more waterbirds;

6. it regularly supports 1 % of the individuals in a population of one species or subspecies of waterbird;

7. it supports a significant proportion of indigenous fish subspecies, species or families, life-history stages, species interactions and/or populations that are representative of

wetland benefits and/or values and thereby contributes to global biological diversity;

8. it is an important source of food for fish, spawning ground, nursery and/or migration path on which fish stocks, either within the wetland or elsewhere, depend;
9. it regularly supports 1 % of the individuals in a population of one species or subspecies of wetland-dependent non-avian animal species.

Although deteriorated since it was acknowledged as a Ramsar wetland, the ORM still complies with 5 of these criteria [135] [149]:

- The succulent Karoo biome, including the southern African west coast, is characterised by a lack of large perennial wetlands. The ORM is one of the largest perennial and coastal wetlands in an arid climatic region **(criterion 1)** [135];
- The ORM supports 14 regularly occurring (table 7.1) and an additional 7 occasionally occurring bird species listed on the South African [146], Namibian [147] and international [148] Red List. The ORM supports two freshwater fish species appearing in the IUCN Red List (viz Orange-Vaal Largemouth Yellowfish and Namaqua Barb [150]). Several other freshwater species, endemic to the Orange River system, occur at the ORM, including the Orange-Vaal Smallmouth Yellowfish and Orange River Mudfish. The marine White Steenbras (*Lithognathus lithognatus*), which is listed in the IUCN Red List, also occurs at the ORM **(criterion 2)** [135];
- The ORM supports several animal species that would otherwise not have been present in this arid region. These include many waterbird species and mammals, such as the Straw-coloured Fruit Bat (*Eidolon helvum*) and the Cape Clawless Otter (*Aonyx capensis*) **(criterion 3)** [135];
- The ORM is an important staging area for several Palaearctic migrants and intra-African migrant and nomadic waterbird species. It is also a breeding area for many waterbird species and a roosting site for marine-feeding terns and cormorants **(criterion 4)** [135];
- The ORM supports more than 1 % of the southern African population of 15 species and more than 1 % of the global population of seven waterbird species **(criterion 6)** [135].

In 1991, when the ORM was acknowledged as a Ramsar wetland, it also complied with criterion 5. At the moment, the site no longer regularly supports in excess of 20 000 waterbirds, and thus presently does not meet criterion 5 [135].

7.4 Conclusion

The Orange River mouth (ORM) is of major ecological importance. It was designated a Ramsar site in 1991. However, due to bad management practices and anthropogenic impacts, its condition is severely deteriorated. In particular, the salt marsh component is in a tremendously bad condition, which attributes to the decrease in bird numbers and the consequent addition of the ORM to the Montreux Record. As a signatory of the Ramsar Convention, the Republic of South Africa and the Republic of Namibia are obliged to rehabilitate the river mouth. Several rehabilitation measures have been proposed in this chapter. Currently, a rehabilitation project is ongoing at the ORM. Future monitoring of the site will indicate whether these rehabilitation measures have been successful.

Chapter 8

Hydraulic modelling of the Lower Orange River

8.1 Introduction

In the first part of this Master thesis, the Integrated Water Resources Management (IWRM) of the Lower Orange River (LOR), including the socio-economic and ecological issues, was extensively described. The following chapters deal with the hydraulic modelling of the LOR. As it was already described in the preceding chapters, a hydraulic model can contribute to and is necessary for a well-considered way of water management. Moreover, the hydraulic model can be used to determine the releases (i.e. point in time, duration and amount of discharge) at Vanderkloof Dam precisely to meet the requirements of the different users of the system. As well irrigation, urban and environmental water demands need to be taken into account to prescribe an appropriate operational procedure of the dam. It may not be neglected that the water takes its time to flow from the dam to the abstraction point. The time shift between release and abstraction can be considerable as it sometimes takes up to several weeks.

This chapter tries to give a general overview of all the modelling work that has been done in the framework of this Master thesis. At first, all the gathered data that were used are briefly explained. Secondly, a brief introduction to the different water users of the system follows. Subsequently, the following chapters that are dealing with hydraulic modelling (i.e. chapters 9, 10, 11 and 12) are presented in this introductory chapter. An overall conclusion concerning the hydraulic modelling of the LOR is given in chapter 13.

During this report, most flow series are referred to as kind of code. These codes are written as 'flowseries'_'year'. This should be helpful when checking the information (data, models, outputs, etc.) on the DVD attached to this report (see chapter 16).

8.2 Data

A lot of data are needed to build a river model. As this Master thesis considers the hydraulic modelling of the Orange River, only hydraulic and topographical data were used. Nevertheless, the authors of this thesis have collected more data than only the information which is necessary to build a hydraulic model. Data that can be used in further studies (see chapter 14), such as biological and chemical data of the river, is also gathered. All raw and processed data is archived on the DVD (see chapter 16) which is attached to this report. However, only the used data will now be presented.

All hydraulic data that was collected, are summed up in table 8.1. Moreover, the source of each data list is mentioned in the last column. All topographical data, as well as their sources, are summarised in table 8.2.

Table 8.1: Outline of the collected hydraulic data

Hydraulic data	**Description**	**Source**
Flow charts	Overview of dams, weirs, canals, transfer systems, ...	[3]
Discharges	Hourly discharges (m^3/s) for several weirs	[151]
Water levels	Both hourly and daily water levels (m) for several weirs	[151]
Precipitation	Daily precipitation (mm) for several weather stations in the catchment	[152]
Evaporation	Daily evaporation (mm) for several stations in the catchment	[153]
Manning	Manning's roughness coefficients for all reaches under concern	[154]
Monthly demands	Monthly abstractions used in 'Model v2.0'	[3]

Table 8.2: Outline of the collected topographical data

Topographical data	Description	Source
Cross sections	Measured altitudes along cross sections (perpendicular to the river)	[155]
Longitudinal profile	Measured altitudes along the riverbed (along the river)	[155]
Weir ratings	Rating curves (relations between discharge Q and water level h) for all weirs	[151]

8.3 Water requirements

The water requirements of the LOR catchment can be divided into different water uses, namely:

- Irrigation;
- Urban (including industrial, mining and stock watering);
- Environmental;
- Losses (including evaporation, transmission and operational losses).

Another water 'user' that is not listed above is Eskom, who is running the hydropower generation stations at Gariep and Vanderkloof Dam. The Department of Water Affairs (DWA) is responsible for the management of the water releases as they give permission to Eskom to perform the releases. Moreover, the DWA decides how much water may be released from the dams each month [156].

The different water demands that were considered for the building of the hydraulic model are based on monthly figures [3]. These water requirements were estimated for different regions along the LOR. What's more, these requirements also provide a basis for the water allocations. This is obviously necessary to build an accurate model that can be used for the overall water management and the dam operation in particular.

8.3.1 Irrigation and urban water requirements

Downstream of Vanderkloof Dam, the LOR is flowing through the Province of the Northern Cape. Besides some mining activities in the areas around Alexander Bay, most income originates from agriculture in this part of South Africa. Therefore, irrigation is by far the most important user of the water resources of the LOR.

The irrigation and urban water demands are currently being supplied on a monthly basis (i.e. the amount of authorised water abstraction is defined on a monthly basis). These water demand figures are implemented in the hydraulic Model (see chapter 11). Moreover, these data are annually updated when feedback is provided from the DWA Regional Offices in Kimberley and Bloemfontein [157].

After the fields have been irrigated, a part of the abstracted water flows back to the river. These return flows are highly depending on the applied irrigation techniques (see section 4.4.1). The fact that these return flows are highly unpredictable (both in size and time) creates an additional modelling problem. As long as no more accurate information and data are available, these return flows are included in the monthly figures for irrigation.

8.3.2 Environmental water requirements

The Environmental Water Requirements (EWR) are the water amounts that are requisite for evapotranspiration. Evapotranspiration can be explained as the transpiration occuring from the vegetation growing in the riparian zone along the riverbanks and on the numerous small islands and sandbanks. It's important to notice that EWR (i.e. the amount of water 'used' by the river) and IFR or EFR (i.e. the amount of water needed by the river in order to maintain the health status of the different ecosystems (see section 5.4)) are two different notions.

It may be expected that some of the EWR can be supplied by irrigation return flows from the lower part of the system, as well as by the infrequent inflows from the tributaries downstream of Vanderkloof Dam. Operational losses (see further) can also contribute to the water flow at the Orange River mouth [157].

The riverine and estuarine environmental water requirements were determined for the Orange River, downstream of Vanderkloof Dam [3]. These data are available as monthly figures and are implemented in the model as well (see chapter 11).

8.3.3 Losses

River losses from the river system can be described as any loss that is a result of evaporation or seepage from dams, the river channel and irrigation canals receiving water from the LOR. River losses represent one of the major 'demands' from the LOR, second only to irrigation demands in volume. Evaporation losses from the main channel downstream of Vanderkloof Dam can reach values of 615 million m^3/a. This corresponds to an average annual flow in the LOR of approximately 80 m^3/s [157]. In case of high flows, the evaporation losses can reach to about 1000 m^3/s [158].

In addition to the evaporation losses, other sources of losses do also occur: transmission losses and operational losses. Transmission losses have to do with losses from the different canals that receive water from the LOR. The net transmission losses, evaporation included, for the canals in the region of Upington and Kakamas comes to 4 to 6 %, where the losses of the Ramah Canal can even run up to 27 %. On the other hand, operational losses include the effect of inaccurate releases, the difference between the planned and actual abstractions as well as the uncertainties involved in predicting return flows from the different irrigation schemes. Operational losses due to inaccurate releases are considered as wastages as the additional water amounts can no longer be used by man. The total operational losses are estimated as 270 million m^3/a [157].

8.4 The hydraulic model - part 1

In chapter 9, a theoretical background of hydraulic modelling is given and the de Saint-Venant equations are briefly explained. The numerical model STRIVE and its software environment FEMME are also discussed. In this chapter, the entire modelling process will be passed through for the first reach of the LOR (i.e. the reach between Dooren Kuilen and Marksdrift). It will be explained in more detail which data were used as well as how they were processed. Different problems were encountered during the development of the model. The way of tackling these is discussed in great detail. Furthermore, attention is given to the implementation of some new functions into the existing STRIVE model. The hydraulic model that is built up in chapter 9 is referred to as 'Model v1.0'.

8.5 Model evaluation - part 1

In a next step (see chapter 10), the model is tested and evaluated. The Manning's roughness coefficient is used as a calibration parameter. On the basis of calibration runs of some characteristic flow series, a fixed value for the Manning's roughness coefficient is chosen. Once the model is calibrated, some validation runs are necessary to check whether the choice of the roughness coefficient can be justified.

8.6 The hydraulic model - part 2

The results of 'Model v1.0' (see chapter 9) are quite satisfactory for the first reach (i.e. Dooren Kuilen - Marksdrift). Moreover, the analysis which was stated in chapter 9 seems to be well-thought-out and generally applicable. Unfortunately, the recorded flow data (i.e. discharges) of almost all LOR gauging stations prove to be inaccurate. Therefore, a revised hydraulic model (i.e. 'Model v2.0') is presented in chapter 11. This new model should be applicable for all reaches, irrespective of the accuracy of the gauged data.

8.7 Model evaluation - part 2

This new hydraulic model 'Model v2.0' also needs to be calibrated. Again, the Manning's roughness coefficient serves as calibration parameter. It is abundantly clear that the results of this model are less reliable than those of 'Model v1.0', as the calculations start from more inaccurate gauging data. Nevertheless, the 'Model v2.0' will be more practical as it is valid to use for any reach. The results of the evaluation of the model are presented in chapter 12.

Chapter 9

The hydraulic model - part 1

9.1 Theoretical background

9.1.1 Governing equations

One-dimensional unsteady surface water flow is expressed by the de Saint-Venant equations. These equations are the one-dimensional expression of the Navier-Stokes equations. These last equations describe fluid flow in three dimensions and form the base of hydrodynamic modelling. The de Saint-Venant equations can be derived from the Navier-Stokes equations, based upon the following series of assumptions [159] [160]:

- The flow is one-dimensional, i.e. the velocity is uniform over the cross section and the water level across the section is horizontal;
- The streamline curvature is small and vertical accelerations are negligible hence the pressure is hydrostatic;
- The effects of boundary friction and turbulence can be accounted for through resistance laws analogous to those used for steady state flow;
- The average channel bed slope is small so that the cosine of the angle it makes with the horizontal may be replaced by unity.

The de Saint-Venant equations consist of the continuity equation and the momentum equation. Here, the differential form is used which assumes that the dependent flow variables (discharge, water level, water depth, etc.) are continuous and differentiable functions [160].

The continuity equation describes the storage of water in the different cells of the model. It expresses the principle of mass conservation, i.e. the net rate of flow into the cell volume is equal to the rate of change of storage inside the volume. There are three terms: (a) convective flow, (b) storage and (c) lateral inflow and outflow. The same notation is used for the subscripts of the terms of equation (9.2). The continuity equation is written according to 2 different notations [160].

In *Q(x,t)* and *z(x,t)*

$$\frac{\partial Q}{\partial x} + \frac{B\partial z}{\partial t} = q \tag{9.1}$$

In *Q(x,t)* and *h(x,t)*

$$\frac{\partial Q}{\partial x}_{(a)} + \frac{B\partial h}{\partial t}_{(b)} = q_{(c)} \tag{9.2}$$

The momentum equation describes the transport of the water between the neighbouring cells (principle of momentum conservation). In other words, the net rate of momentum entering the cell volume plus the sum of all external forces (pressure, gravity, friction) acting on the volume is equal to the rate of accumulation of momentum. The equation (9.4) has following terms: (a) local acceleration term (change in momentum, due to change in velocity over time), (b) convective acceleration term (change in momentum, due to change in velocity along the channel), (c) gravity force term (proportional to the bed slope S_o), (d) friction force term (proportional to the friction slope S_f), (e) pressure force term (proportional to change in water depth along the channel) and (f) lateral inflow. The momentum equation is written according to 2 different notations [160].

In *Q(x,t)* and *z(x,t)*

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}(\frac{Q^2}{A}) + gA(S_f + \frac{\partial z}{\partial x}) = q\frac{Q}{A} \tag{9.3}$$

In Q(x,t) and h(x,t)

$$\underbrace{\frac{\partial Q}{\partial t}}_{(a)} + \underbrace{\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)}_{(b)} - gA(\underbrace{S_o}_{(c)} - \underbrace{S_f}_{(d)} - \underbrace{\frac{\partial h}{\partial x}}_{(e)}) = \underbrace{q\frac{Q}{A}}_{(f)} \tag{9.4}$$

The above equations illustrate the different variables which are of particular interest for hydraulic modelling: discharge Q (m^3/s), water level z (m), water depth h (m), channel bottom slope S_o (m/m), friction slope S_f (m/m), lateral in- or outflow q ($m^3/s{\cdot}m$), wetted area A (m^2) and the channel width at free surface B (m). The longitudinal position in the channel is denoted as x (m), time is denoted as t (s) and the gravitational acceleration is denoted as g (m/s^2).

9.1.2 Numerical solution

The de Saint-Venant equations are a set of non-linear partial differential equations. An analytical solution of this system is not possible, but the use of numerical models allows a numerical solution. In the scope of this research, discretisation is performed by the scheme of Preissmann (finite difference method) where the equations are linearised using a Taylor expansion. A numerical solution of the resulting system of linear equations is found by using the Double Sweep algorithm [160]. Figure 9.1 depicts the scheme.

For more details on the Preissmann scheme and the Double Sweep algorithm the reader is referred to [160].

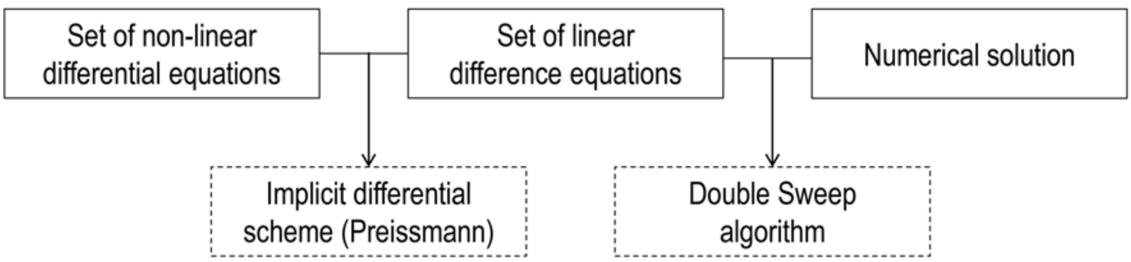


Figure 9.1: Numerical solution of the de Saint-Venant equations.

9.2 The software environment

9.2.1 Introduction

The numerical solution of the de Saint-Venant equations is performed by an appropriate computer model. We present the STream-RIVer-Ecosystem package (STRIVE) that enables the construction of integrated river ecosystems. The term 'integrated' indicates that this package incorporates the interaction of several riverine ecosystem processes. The STRIVE model has been developed by the Hydraulics Laboratory (Ghent University) and the Ecosystem management research group (University of Antwerp), using the existing FEMME software environment. This Master thesis deals with the development of a hydraulic model for the Orange River, as this model will serve as a basis for the further development of a water quality model for the Orange River.

9.2.2 The FEMME environment

'FEMME' or 'a Flexible Environment for Mathematically Modelling the Environment' is developed by NIOO (Netherlands Institute of Ecology) [161] [162]. 'FEMME' is a modelling environment for the development and application of ecological time dependent processes by use of numerical integration in time of differential equations. The environment is written in Fortran. 'FEMME' has a library of numerical calculations and model manipulations (such as integration functions, forcing functions, linking to observed data, calibration possibilities, etc.). These technical possibilities allow the user to focus on the scientific part of the model and detailed research of the model without the confrontation with real program linked problems [160].

'FEMME' is focused on ecosystem modelling, is open source and exists of a modular hierarchical structure (implementation of different models next to each other). Within the framework of an FWO-project (Research Foundation - Flanders), a hydrodynamic surface water model has been developed, in order to couple ecology and surface water in each time step. For the study of the interaction of ecological processes and flow in the river, a realistic modelling of the surface water flow is necessary. The resulting STream-RIVer-Ecosystem package (STRIVE) provides the accurate modelling of surface flow characteristics and the interaction with different ecological processes [160].

9.3 STream-RIVer-Ecosystem package (STRIVE)

The STRIVE package has been developed using the 'FEMME' environment. This package aims at the integrated modelling of river ecosystems. The term 'integrated' indicates that this package incorporates the interaction of several river ecosystem processes. This allows the mathematical description of cascade effects and feedbacks, influencing the transport and retention time of water, nutrients, sediment, etc.

The meaning of a cascade effect can be illustrated by the following example. Vegetation growth in rivers leads to an increase of the Manning roughness coefficient, which means that the presence of vegetation actually retards the water flow. This results in a heterogeneous flow pattern, characterised by smaller flow velocities near the macrophyte patches, and larger velocities in the zones which are not obstructed by vegetation. The decrease of flow velocity near the macrophyte patches results in an increase of organic particles being deposited on the river bed. This increase of organic substances leads to a shift of mineralisation processes. This means that other decomposition processes will become more important, as the transport of oxygen to the river bed is insufficient for providing all the oxygen needed for the aerobic decomposition. Consequently, the share of denitrification processes will increase. This is an example of a cascade effect. Due to the decomposition of organic substance, nutrients are being released, stimulating vegetation growth. This macrophyte growth will again increase the river bed roughness, resulting in a higher deposition of organic particles, etc. This is an example of a feedback effect [163].

A 1D hydrodynamic model for unsteady free surface flow based on the de Saint-Venant equations has been implemented, yielding accurate modelling of surface flow characteristics, which subsequently has been coupled to several processes (such as macrophyte growth, sediment transport and suspended solids) to achieve the required interaction between the subsystems of the ecosystem [160].

For more details on the basic structure of the STRIVE package the reader is referred to [160]. A description of the most important files of the STRIVE model is presented below. The naming convention for the most significant parameters appearing in the model is also expound. One will refer to these specific parameter names in the continuation of this report.

9.3.1 Parameter files

The parameter files *.par* fix the value of the parameters declared in the model. Although each parameter has a standard initialisation value, the parameter values mentioned in the parameter files will overwrite the initial values. Two parameter files have been implemented in the basic version of the STRIVE model. *Orange_geometry.par* (see table 9.1) describes the geometry of the system, while *RunSetting.par* (see table 9.2) determines the boundary condition types, the Manning coefficient and the lateral inflow discharge. Another parameter file has been composed during this study, in order to allow the quantification of flow losses. *Orange_latinflow.par* specifies the input values for the loss functions evaluated by the hydraulic model. The content of *Orange_latinflow.par* is discussed in section 9.5.2.

Table 9.1: *Orange_geometry.par*: naming convention and description

Parameter name	**Description**
StreamLength	Total length of the modelled reach
ZbottomUpstream	Bottom height of the most upstream node
ZbottomDownstream	Bottom height of the most downstream node
ZwaterlevelUpstream	Initial water level at the most upstream node
ZwaterlevelDownstream	Initial water level at the most downstream node
QZpar1	First parameter (a) in the weir rating function $Q = a(z - z_0)^b$
QZpar2	Second parameter (z_0) in the weir rating function $Q = a(z - z_0)^b$
QZpar3	Third parameter (b) in the weir rating function $Q = a(z - z_0)^b$

9.3.2 Forcing files

Variables can be declared as forcing variables, via which forcing data can be linked to the user defined model. These forcing files *.frc* specify the value of the forcing variables for each time step. The hydraulic model under concern makes use of 4 different forcing files, described in table 9.3.

Three forcing files have been developed within the framework of this study. The DailyFlow, HourlyMonth and DailyRain forcing files provide input values for the evaluation of lateral inflow functions. These inflow functions are discussed in more detail in section 9.5.

Table 9.2: *RunSetting.par*: naming convention and description

Parameter name	**Options**	**Description**
UpstreamBoundaryType		Type of upstream boundary condition
	Qup	Upstream discharge
	Zup	Upstream water level
QUpstreamBoundaryType		Type of upstream discharge function
	constant	Constant discharge
	forcing	Forcing a time-dependent discharge series
DownstreamBoundaryType		Type of downstream boundary condition
	Qdown	Downstream discharge
	Zdown	Downstream water level
	QZdown	Downstream rating function
ManningConstant		Manning's roughness coefficient
qlatUpstream		Lateral inflow at the most upstream node
qlatDownstream		Lateral inflow at the most downstream node

9.3.3 Initialisation files

The initialisation files *.ini* determine the initial condition value of the specified variables. Initialisation files are used for initialising variables declared as ordinary variables, not for forcing variables or parameters. In this model, use was made of the *reach'number'.ini* file (table 9.4) describing the geometry of the reach under concern. This method allows the user to specify the geometry of a river section as a function of the distance from the most upstream node. In other words, a variable geometry can easily be implemented.

Table 9.3: Forcing files: variables and function

File name	Variable	Function
HourlyFlow_'flowseries'_'year'	fQupstream	Upstream discharge as a boundary condition
DailyFlow_'flowseries'_'year'	fQdaily	Upstream daily averaged discharge used for lateral inflow evaluation
HourlyMonth_'flowseries'_'year'	fMonth	Current month number as a function of time used for lateral inflow evaluation
DailyRain_'flowseries'_'year'	fRaindaily	Daily rainfall used for lateral inflow evaluation

Table 9.4: *reach'number'.ini*: naming convention and description

Variable	Description
WidthBottom	Bottom width of the trapezoidal cross section
Tal	Angle of the left slope of the trapezoidal section
Tar	Angle of the right slope of the trapezoidal section
Zbot	Bottom level of the trapezoid cross section
Zwaterlevel	Initialisation water level

9.4 Reach 1: Dooren Kuilen - Marksdrift

The first reach is enclosed by Dooren Kuilen Weir and Marksdrift Weir. Dooren Kuilen is situated 1 kilometre downstream of Vanderkloof Dam. This means that the flow data recorded at Dooren Kuilen approximates the discharges released at Vanderkloof Dam. In the following sections, the hydraulic model will be discussed in detail for this reach. Some characteristics of this reach are presented in table 9.5.

In order to have more or less the same box length (i.e. the length of a box over which the de Saint-Venant equations are evaluated) for all reaches of the Lower Orange River, a length of approximately 100 m is chosen. This results in a total of 1700 boxes and 1701 nodes in the numerical model.

Table 9.5: Details on reach 1: Dooren Kuilen to Marksdrift

StreamLength	173 722 m
ZbottomUpstream	1096.2 m
ZbottomDownstream	978.5 m
Number of cross sections	8
Number of boxes	1700
Box length	102 m

9.4.1 Rating curve of the downstream weir

A rating table for Marksdrift Weir is on-line available [151]. In order to be able to use this weir as a downstream boundary condition, one should manage to fit a curve through the rating table data points.

The formula relating weir discharge to the water level z can be written in the general form $Q = QZpar1 \cdot (z - QZpar2)^{QZpar3}$. *QZpar1* and *QZpar3* can be determined through curve fitting (figure 9.2), *QZpar2* represents the level of the weir crest. As it didn't seem possible to retrieve the exact value of *QZpar2*, this parameter has been determined through an engineering guess. The exact weir height is of minor importance, because the weir height only influences the river flow locally. The value of the squared correlation coefficient R^2 reflects the proportion of the variance that can be predicted by the fitted curve. The values of *QZpar1*,*QZpar2*, *QZpar3* and R^2 are represented in table 9.6.

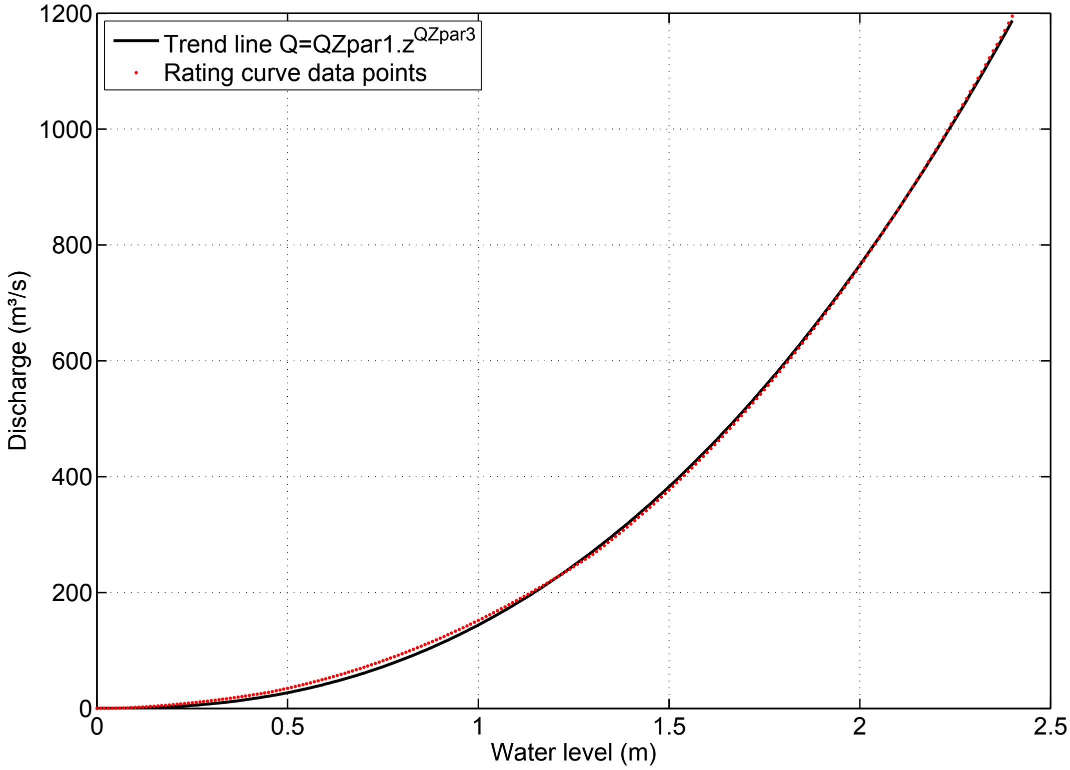


Figure 9.2: Fitting of a rating curve for Marksdrift Weir using TableCurve. Discharge (m^3/s) versus water level (m).

9.4.2 Geometry

As stated above, the *reach'number'.ini* file defines the variable geometry of the cross sections along the river. Each cross section has been characterised by three parameters: *WidthBottom*, *Tal* and *Tar*. These parameters fix the dimensions of a trapezium fitted through the measured cross sectional data points.

Table 9.6: Marksdrift Weir: rating curve

Parameter	**Value**
QZpar1	144.02974
QZpar2	980.724 m
QZpar3	2.4097704
R^2	0.9997

Attempts to develop a standard method for determining the dimensions of these trapezia didn't prove to be successful. One can allow automated processing of the cross sections by choosing a criterion for the fitting of the trapezia, such as equal wetted perimeters corresponding with a specified water level. However, due to the highly irregular data points of the measured cross sections, the calculated wetted perimeters seemed to outstrip the values one should estimate just by quickly drawing a trapezium through the measured cross sectional data points. This means that the calculated wetted perimeters didn't prove to be a reliable criterion.

A more complex method could include the numerical integration of the wetted area corresponding to the water level at each time step. This wetted area can subsequently be translated into the dimensions of a trapezium. However, one has decided to adopt a more practical and transparent way of processing the cross sections in the framework of this study.

The accepted method for fitting the trapezia relies on the good sense of who is processing the data. The method of working is just as simple as drawing a best-fitting trapezium through the cross sectional data points. This is the only way to guarantee trapezia approximating the measured cross sections. This method of working implies a constant gradient of the slopes of each cross section (because a trapezium is fitted), which seems to be feasible within a realistic water level range.

The bottom level *Zbot* of each cross section has been specified in the *reach'number'.ini* file. The longitudinal profile of the first reach is illustrated on figure 9.4.

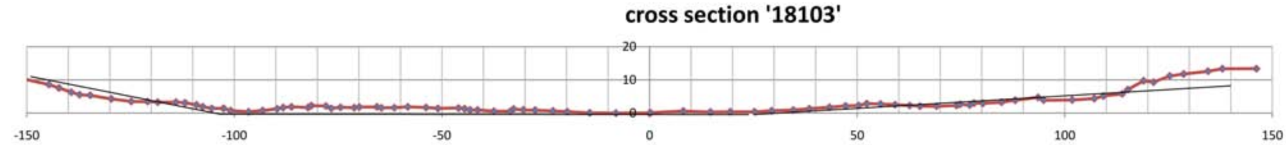


Figure 9.3: Drawing a trapezoidal cross section at chainage 18103 m (downstream of Vanderkloof Dam). Bottom level (m) versus horizontal distance (m).

9.4.3 Lateral inflow evaluation

Problem statement

Figure 9.5 shows flow series 2_2006, starting the 26th of February 2006 and ending the 6th of March 2006. This flow series shows the beginning of a flood, ending in June 2006. This flood is characterised by increasing discharges, which remain almost constant after the maximum discharge has been reached. This very moment is the beginning of a steady state flow series.

By comparing the downstream simulation curve with the downstream recorded discharge curve, one can notice a discharge surplus amounting to approximately 75 m^3/s. A similar finding accounts for flow series 1_2009 (figure 9.6), starting the 24th of February 2009 and ending the 21st of March 2009. As this phenomenon can only be concluded for periods of high flow, the recorded high discharges seem to go together with mechanisms of groundwater and floodplain interaction.

In order to evaluate the flow surplus and flow losses properly, a profound understanding and interpretation of the data is indispensable. For this reason, several plots were made, comparing the downstream recorded discharges with the upstream recorded discharges. The flow surplus or flow losses is referred to as 'lateral inflow' in the continuation of this text. By plotting the upstream daily average discharge, the average daily rainfall and the recorded lateral inflow, one can discover certain correlations between these 3 parameters. This insight will prove to be very useful, in order to develop a mathematical function for predicting the lateral inflow. First, the parameters influencing the lateral inflow have been described. A few examples illustrate the importance of these parameters. After finishing this qualitative analyses, one can try to formulate a function by considering the different influence factors.

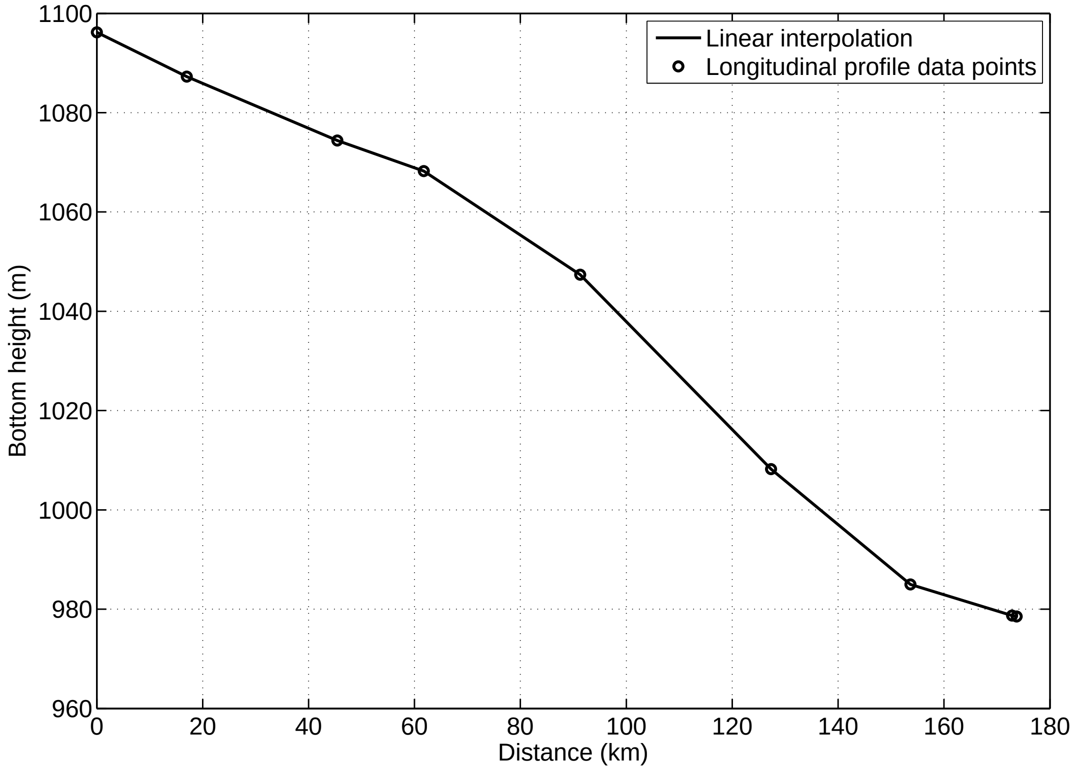


Figure 9.4: Longitudinal profile and linear interpolation (reach 1). Bottom height (m) versus distance (km).

The **daily average discharge** represents the upstream discharge, averaged over a twenty-four hours' period. The most upstream node of this reach is situated 1 km downstream of Vanderkloof Dam. This implies that the upstream recorded flow curve has steep slopes and sharp turns, due to the abrupt dam water releases for purposes of hydroelectric power generation, twice a day. Although these discharge peaks can account to almost 400 m^3/s, the influence of these peaks on the lateral inflow is negligible (i.e. in spite of the huge discharges, power generation may not be detected as a flood event), as these abrupt changes in recorded discharge do not indicate the average flow. In order to evaluate the lateral inflow properly, one should consider the daily average discharge, as this curve demonstrates the occurrence of floods and droughts.

The **average daily rainfall** curve comprises the rainfall data of 8 rain stations, being

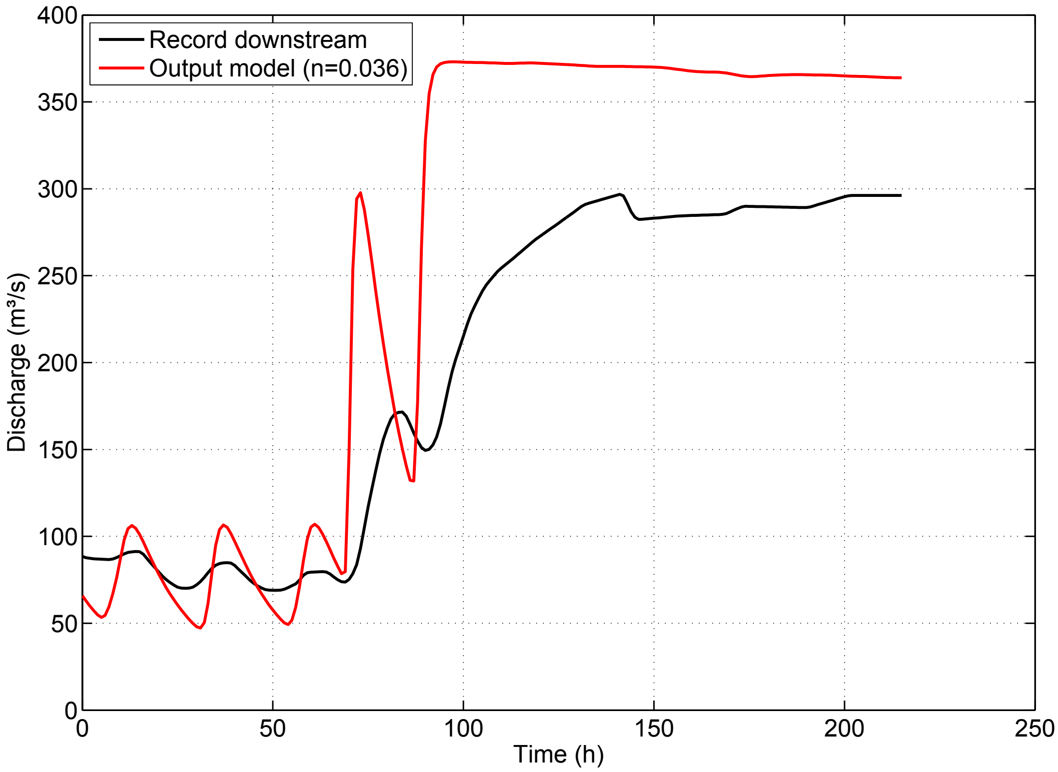


Figure 9.5: Simulated flow versus recorded flow at Marksdrift (26/02/2006 - 06/03/2006 (series 2_2006)). Discharge (m^3/s) versus time (h).

situated in the catchment of the reach under concern. The daily rainfall data of each station has been taken into account, resulting in a series of average rainfall data. Each value of this series is the average of the measured rainfall of the 8 stations during that specific day.

The **recorded lateral inflow** has been calculated by comparing both the upstream and downstream recorded discharges. In order to calculate the flow surplus or losses, one should take the transfer time of the water into account. Although this time delay depends on flow conditions, the average transfer time from Dooren Kuilen to Marksdrift amounts to 40 h. By subtracting the recorded daily downstream discharge from the upstream discharge 40 h before, one can get the lateral inflow as a function of time. A flow loss is represented by a positive value (this means that the downstream discharge is smaller than the upstream discharge 40 h before), a flow surplus is characterised by a negative value.

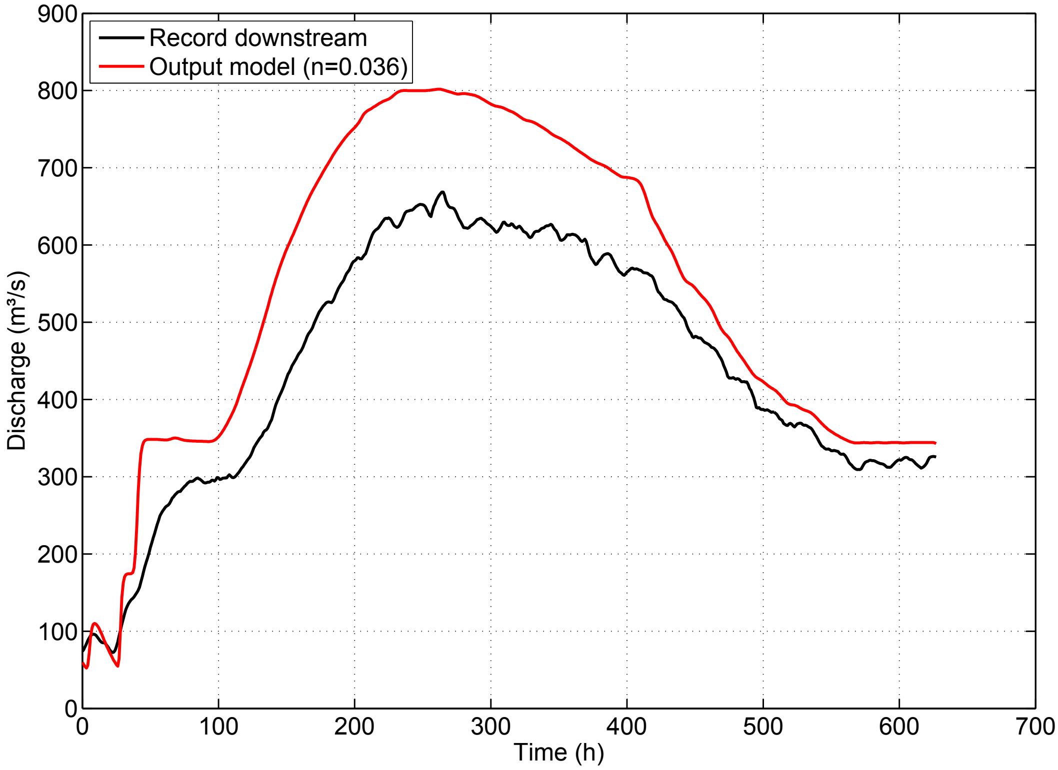


Figure 9.6: Simulated flow versus recorded flow at Marksdrift (24/02/2009 - 21/03/2009 (series 1_2009)). Discharge (m^3/s) versus time (h).

Examples

Figure 9.7 shows a flow series, recorded during February and March 2006. The upper curve represents the daily average of the recorded upstream discharge (at Dooren Kuilen), while the second curve represents the daily average of the recorded downstream discharge (at Marksdrift). The third depicted curve represents the recorded lateral inflow. It is obvious that the increased discharge results in a simultaneous increase of the lateral outflow. Several reasons can be attributed to this finding. The higher water level during flood periods results in the flooding of the countryside next to the river. The presence of floodplains results in a net loss of water during high flow periods. The water stored in these floodplains dissipates particularly by evaporation, groundwater interaction and as a return flow to the river. The flood event in figure 9.7 results in an increase of the flow losses of more than 60 m^3/s. So as to accurately model the Orange River flow, a prediction of the flow losses based on the actual flow conditions is essential.

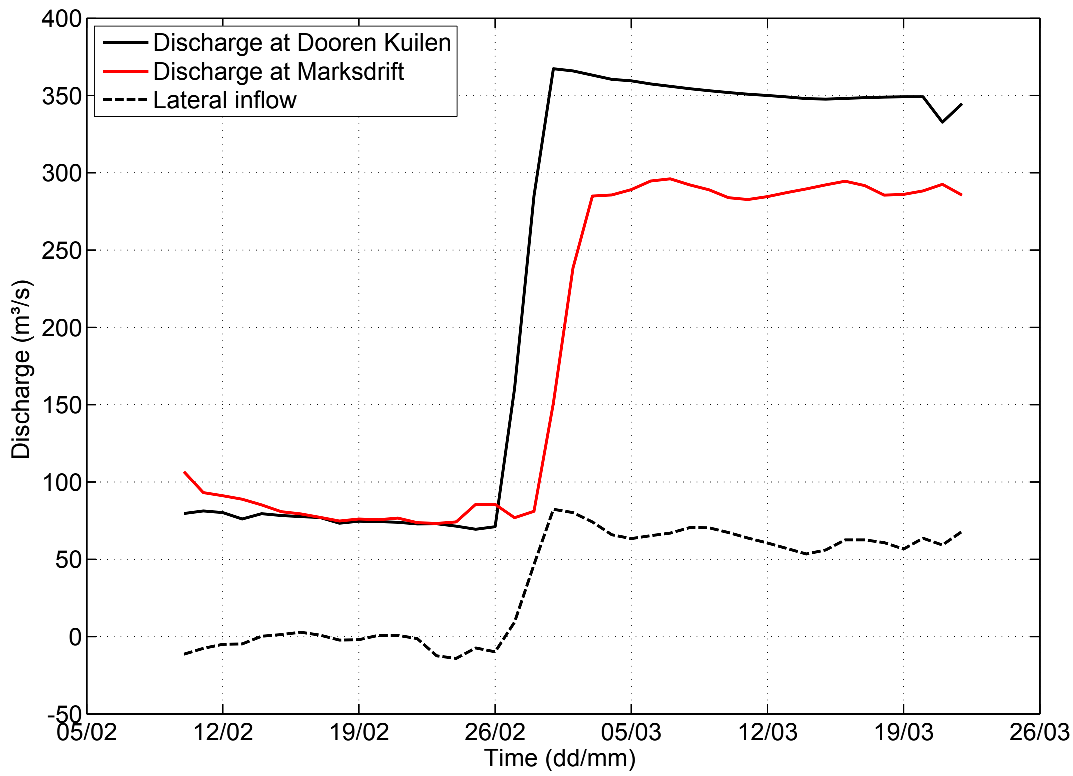


Figure 9.7: Flow losses induced by a flood (February and March 2006 (series 2_2006)). Discharge (m^3/s) versus time (dd/mm).

The correlation between rainfall and lateral inflow can be illustrated by figure 9.8. The flow series under concern has been recorded during October 2004. The upper curve represents the daily average of the recorded upstream discharges (at Dooren Kuilen). The red line shows the average daily rainfall (i.e. the average rainfall data of the stations situated in the reach subcatchment). The third curve depicted is the lateral inflow time series. During the evaluated time series, the upstream discharge remains quasi constant. This means that changing lateral inflow values cannot be caused by a change of flow regime. However, heavy rainfall has been recorded from 18/10 until 20/10. This rainfall results in a quick run-off. It is clear that the sudden decrease of lateral outflow as shown in figure 9.8 has been caused by the simultaneous heavy rainfall. Before and after the rainfall period, the lateral inflow value remains almost constant. One can conclude that the occurrence of heavy rainfall periods should be taken into account, as the resulting lateral inflow cannot be neglected.

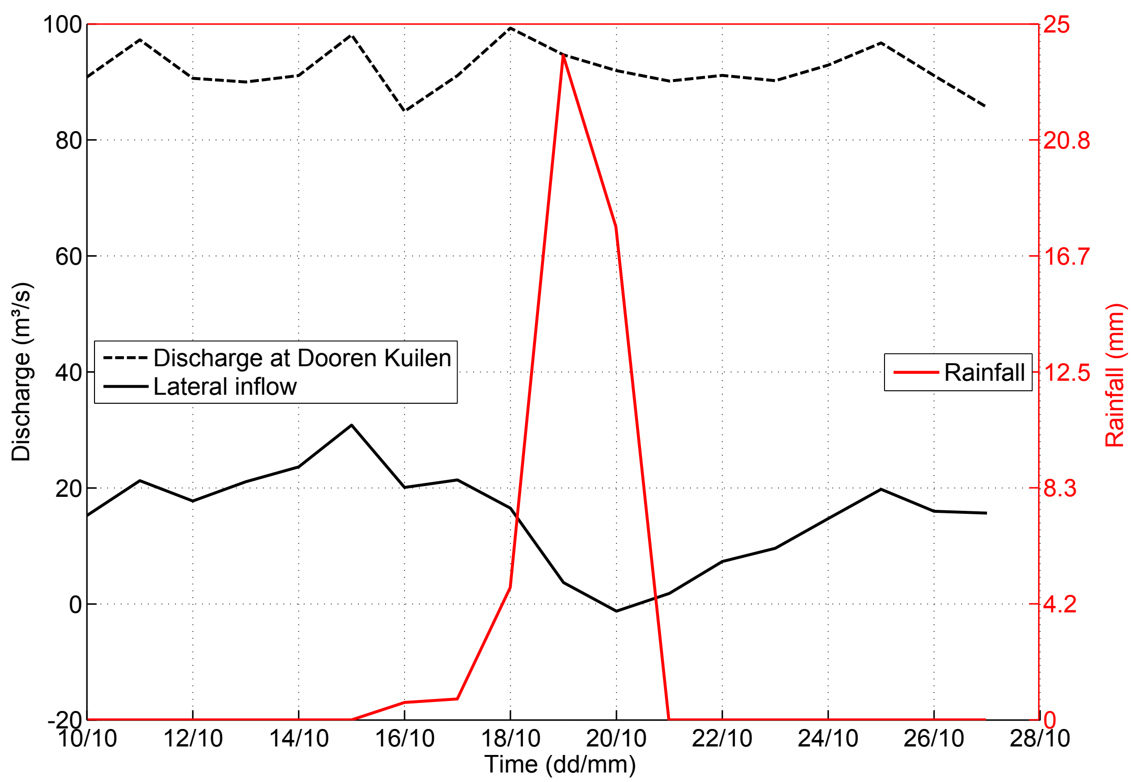


Figure 9.8: Lateral inflow induced by heavy rainfall (October 2004). Discharge (m^3/s) and average rainfall (mm) versus time (dd/mm).

9.4.4 Lateral inflow function

As concluded above, it is clear that both floods and rainfall influence the lateral inflow. However, during non-rain and non-flood periods, a certain trend with regard to lateral inflow can be detected. This trend value can be interpreted as a base loss/surplus. In case of rain or flood events, the appropriate surplus value should be added to this base value.

Base (monthly) lateral inflow

Even in non-rain and non-flood periods, lateral inflow discharges have been recorded. The flow losses can be accounted to the large water demands, mainly for irrigation purposes, as described in section 8.3. Furthermore, losses can also be a result of evapotranspiration or seepage into the ground. These demands depend on the crop growth rate and the current temperatures. On the other hand, water surpluses can be recorded due to return flows and groundwater drainage. This reasoning suggests that the base level of lateral inflow should be characterised by a seasonal variation. This is illustrated in figure 9.9. The river flow, rainfall and lateral inflow have been depicted for the last 4 months of 2005. The daily average discharge at Dooren Kuilen is smaller than 120 m^3/s, so this flow series can be described as a non-flood event. This means that the losses due to water storage can be neglected. The period under concern can also be described as a rather dry period, since heavy rainfall events are scarce. One can conclude that the depicted lateral inflow must be accounted to the seasonal variation as mentioned above. In fact, developing a lateral inflow function merely based on a seasonal variation, will prove to be inaccurate. For this reason, a monthly average (instead of a seasonal one) of the lateral inflow values during non-rain and non-flood periods has been defined. This monthly average is referred to as the base lateral inflow. In figure 9.9, the different base flow discharges have been depicted, represented by a horizontal line.

Figure 9.10 shows the lateral inflow series for 2005, being a non-flood year. For reasons of clarity, the discharge and rainfall curves have not been depicted. However, one should keep in mind that both the discharge curve as the rainfall curve influence the lateral inflow. When analysing the lateral inflow curve, one can notice certain deflections from the horizontal base inflows. These deflections are due to rainfall and deviations from the assumed 40 h water transfer time. Another reason for this is the finding that even for the daily average discharge series, the upstream peaks are more abrupt than the downstream peaks, resulting in the peaks of the calculated lateral inflow curve. However, it is clear that

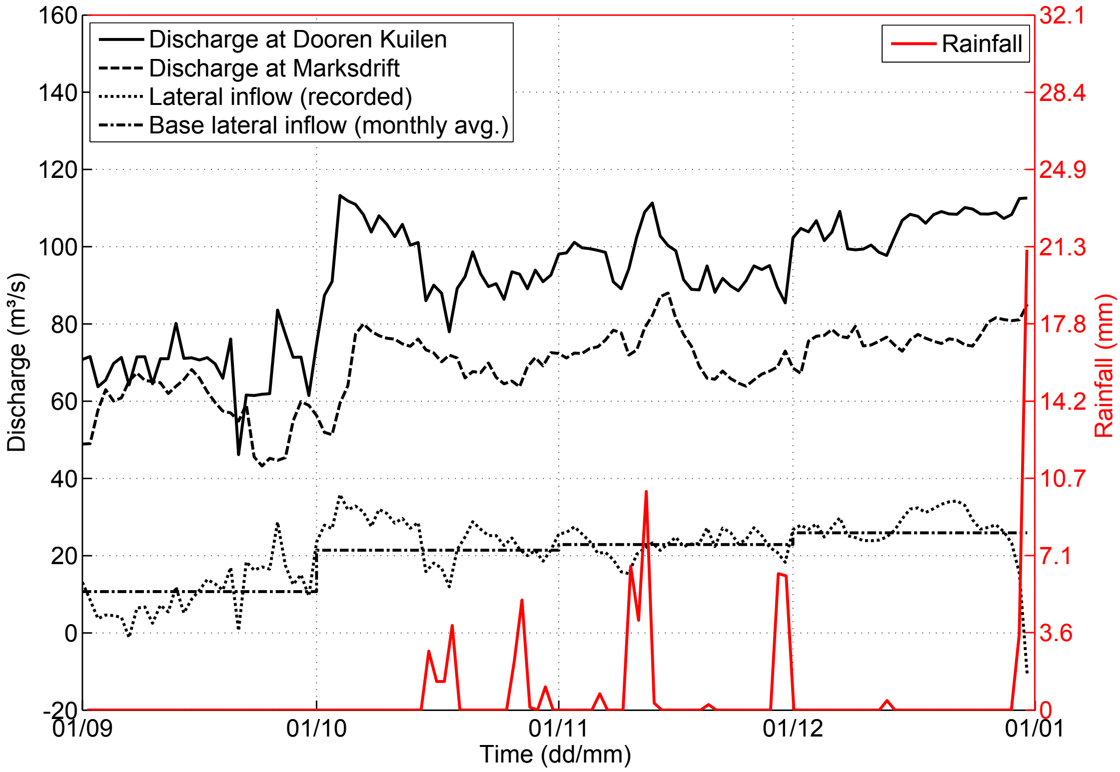


Figure 9.9: Base (monthly avg.) lateral inflow versus recorded lateral inflow (September-December 2005). Discharge (m^3/s) and average rainfall (mm) versus time (dd/mm).

the lateral inflow as illustrated in figure 9.10 follows a yearly trend, as characterised by the horizontal base inflow lines. Comparison of the base lateral inflow and evaporation data showed a clear relationship between these. Both variables follow more or less the same seasonal trend.

In table 9.7, the base inflow values have been represented. For example for January, this value is implemented into the STRIVE model by the parameter 'january_dry'. The monthly averages are calculated on the basis of data for the period 2003-2009.

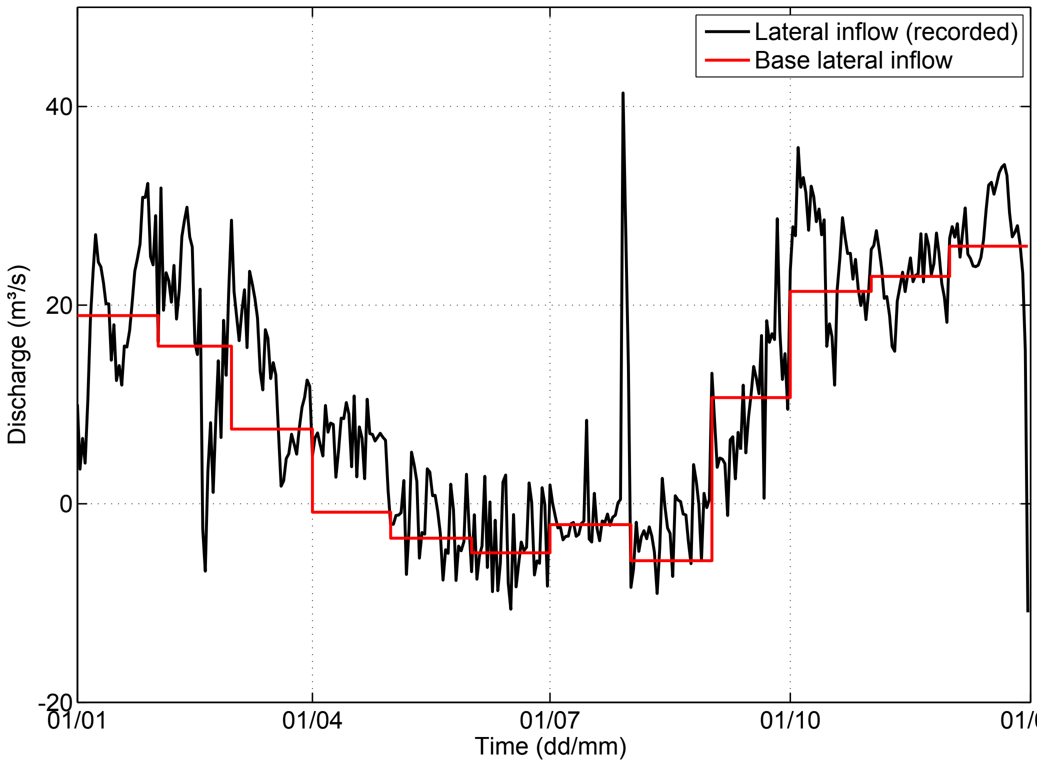


Figure 9.10: Base (monthly avg.) lateral inflow versus recorded lateral inflow (2005). Discharge (m^3/s) versus time (dd/mm).

Table 9.7: Base (monthly avg.) lateral inflow

Month	**Discharge (m^3/s)**
January	18.937
February	15.871
March	7.511
April	-0.851
May	-3.469
June	-4.939
July	-2.107
August	-5.744
September	10.689
October	21.387
November	22.900
December	25.935

Rainfall

As illustrated in 9.4.3, rainfall events result in a flow surplus. In fact, one can quantify the influence of a certain amount of rain, by drawing the deflection of the recorded lateral inflow curve as a function of the average daily rainfall during that day. In general, the deflections of the lateral inflow curve due to rainfall events can only be noticed during the same day when the rainfall event occurs. From this point of view, figure 9.8 is somewhat exceptional as the deflection of the lateral inflow curve remains significant more than 4 days after the rainfall event has ended. Of course, this is a logical conclusion as the water needs some time to flow to the river. However, when analysing all the data from 2003 until 2009, one can conclude that the deflections of the lateral inflow curve are mainly significant only for the days when rainfall events occur. This finding justifies the following assumption: deflections of the lateral inflow curve are only taken into account for those days when the average daily rainfall differs from zero. Figure 9.11 represents the deflection of the lateral inflow curve as a function of the average daily rainfall. By analysing rainfall data over a 7-year period (2003-2009), this data set has been acquired by manually linking the significant lateral inflow deflections to the corresponding average rainfall value. As one can see, there is a significant scattering of the data points. 5 rain classes have been defined (arbitrarily), illustrated in table 9.8. The flow surplus value corresponding to each rain class has been calculated as the average of the data points located between the x-axis limits of each rain class. These rain classes have been implemented in the STRIVE model. For each day, the model reads in the average rainfall data. After evaluating the appropriate rain class, the model assigns the corresponding flow surplus value.

Flood events

As stated above, a sudden rise of the daily average discharge due to a flood results in flow losses. On the other hand, at the end of a flood period when the discharges are decreasing, often a flow surplus has been recorded. By analysing the flow and lateral inflow data, one can observe certain trends amongst the increase or decrease of the daily average discharge at Dooren Kuilen (Δ Q) and the observed lateral inflow data. During this analysis a set of data has been collected (for the period 2003-2009), relating the Δ Q value to the deflection of the lateral inflow curve. This has been established manually by only taking into account the significant lateral inflow deflections. The causal connection between lateral inflow deflection and discharge gradient was used as a criterion. These data points have been depicted in figure 9.12. In the same graph, a 1^{st} order trend line has been drawn. Higher order trend lines did not seem feasible and cannot be accepted. The surplus lateral inflow is described by the equation $0.349 \cdot \Delta$ Q, offering a correlation $R^2 = 0.86$ with the observed data.

Table 9.8: Lateral inflow as a function of rain class

Rain class	**Lower limit [$\leq$] (mm)**	**Upper limit [$<$] (mm)**	**Inflow (m^3/s)**
Rain class 1	0.001	5	-4.212
Rain class 2	5	10	-8.220
Rain class 3	10	15	-12.5
Rain class 4	15	20	-15.909
Rain class 5	20		-29

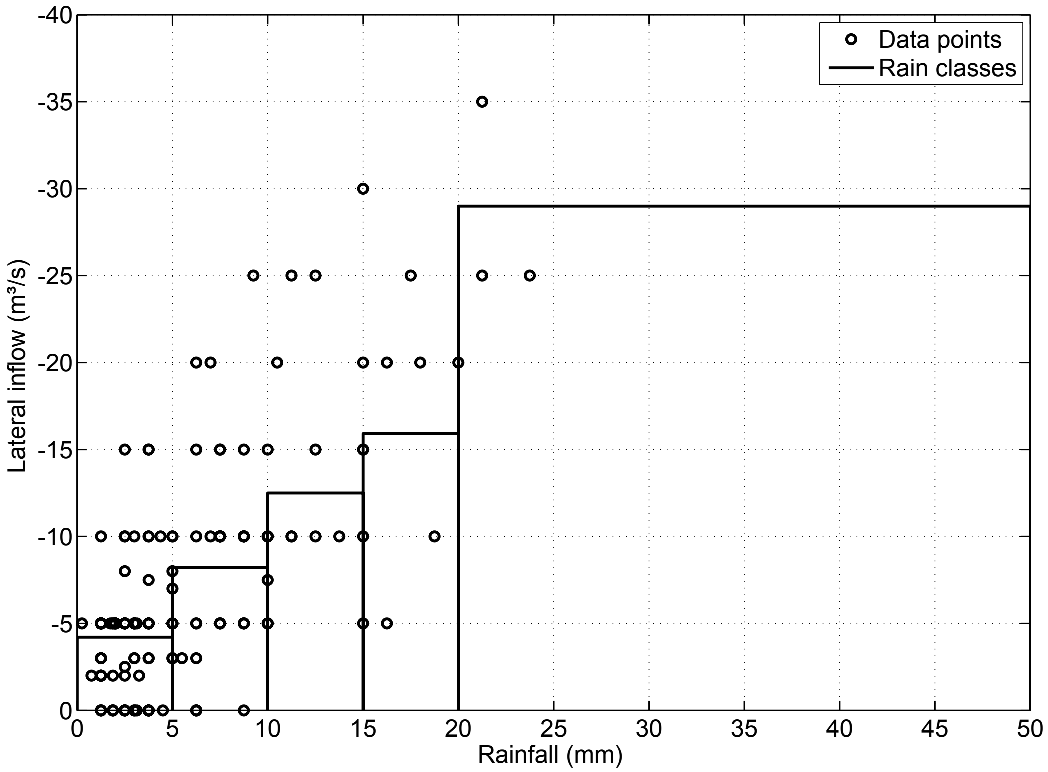


Figure 9.11: Deflection of the lateral inflow curve (m^3/s) as a function of the average daily rainfall (mm).

9.5 Implementing the lateral inflow function into the existing STRIVE model

9.5.1 Forcing files

Three forcing files have been added to the existing model. *HourlyMonth_'flowseries'_'year'.frc* determines the value of the forcing variable fMonth as a function of time. This input is being evaluated in order to calculate the base lateral inflow value, which depends on the current month. *DailyFlow_'flowseries'_'year'.frc* specifies the daily average flow fQdaily at the most upstream node (Dooren Kuilen). This forcing variable is used in order to evaluate the de-

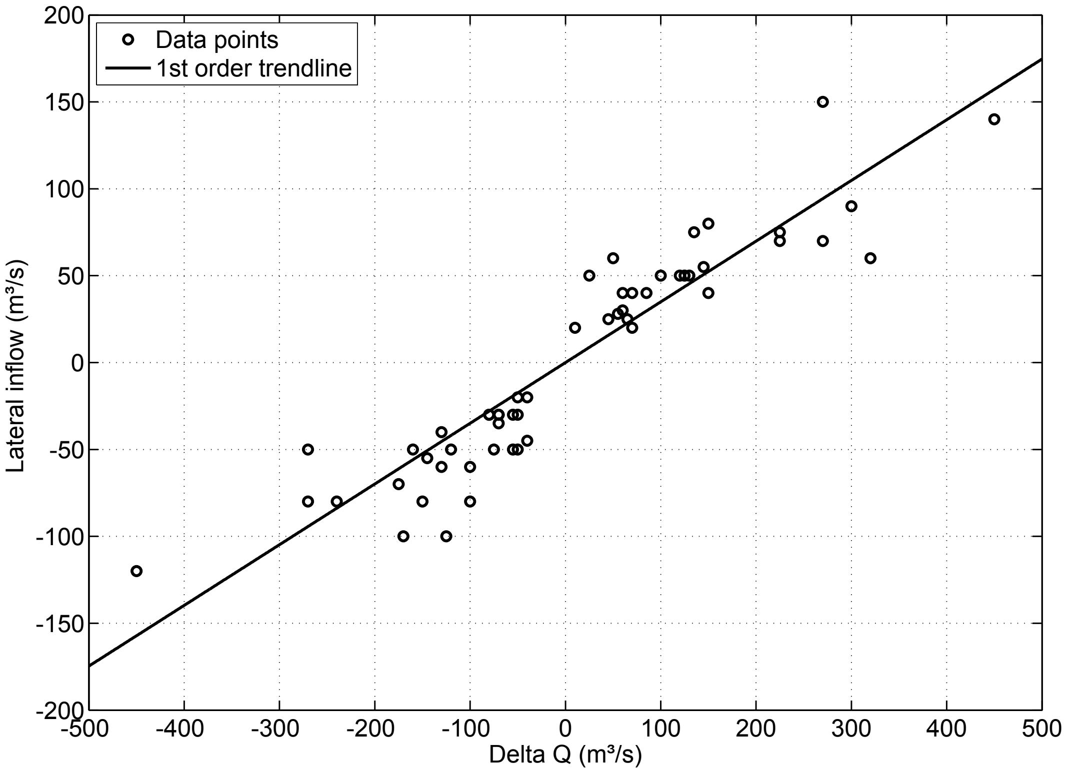


Figure 9.12: Deflection of the lateral inflow curve (m^3/s) as a function of the discharge gradient (m^3/s).

flections of the lateral inflow curve in case of flood events. *DailyRain_'flowseries'_'year'.frc* specifies the forcing variable fRaindaily, which is time dependent. By reading in this data, the hydraulic model can evaluate whether a flow surplus value due to rainfall events needs to be taken into account.

An extract of the three forcing files mentioned above is presented below (see tables 9.10, 9.11 and 9.12). For reasons of completeness, an extract of the existing *HourlyFlow_'flow-series'_'year'.frc* forcing file has also been presented (see tabel 9.9). The forcing files under concern contain data for the 2_2006 flow series, recorded during February and March 2006.

The fQdaily values have been calculated according to the following method: for each day, the average of the fQupstream values has been calculated. This average value has been assigned to the time step at 12.00 a.m. for the current day. This means that at 12.00 a.m., the model already knows the average flow for the current day. In other words, the model can 'predict' the flow regime for one day. By evaluating this value, the model can predict whether a flood will occur. Although this method of working seems unusual, it can be justified. Indeed, when a flood wave encounters Vanderkloof Dam, it has already passed several upstream gauging stations. In general, flood waves originate in the Lesotho mountains. So one can certainly assume that when a flood wave is approaching Vanderkloof Dam, it has already been detected more than 1 day before. The fQdaily values are only being used to detect the start and the end of a flood.

Table 9.9: Extract from *HourlyFlow_'flowseries'_'year'.frc*

@Variable	**@Time** (s)	**@Value** (m^3/s)
fQupstream	0	16.564
fQupstream	3600	8.956
fQupstream	7200	5.267
fQupstream	10800	3.237

Table 9.10: Extract from *Hourly-Month_'flowseries'_'year'.frc*

@Variable	**@Time** (s)	**@Value**
fMonth	0	2
fMonth	3600	2
fMonth	7200	2
fMonth	10800	2

Table 9.11: Extract from *DailyFlow_'flowseries'_'year'.frc*

@Variable	**@Time** (s)	**@Value** (m^3/s)
fQdaily	0	731.692
fQdaily	86399	731.692
fQdaily	86400	718.406
fQdaily	172799	718.406

Table 9.12: Extract from *DailyRain_'flowseries'_'year'.frc*

@Variable	**@Time** (s)	**@Value** (mm)
fRaindaily	0	158.125
fRaindaily	86400	0.25
fRaindaily	172800	4.25
fRaindaily	259200	0.25

9.5.2 Parameter files

In order to be able to evaluate the lateral inflow function, the model reads in certain parameter values. These parameter values are fixed values, they do not depend on the flow series and they are time-independent. Each reach has its own set of parameter values, depending on the specific lateral inflow parameters. Table 9.13 summarises the different parameters as defined in *Orange_latinflow.par*. The specific use of each parameter is clarified in the description of the lateral inflow function in section 9.5.4.

Table 9.13: *Orange_latinflow.par*: naming convention and content

Parameter name	**Description**
'month'_dry	Base lateral inflow as a function of the current month
limit'number'	Lower limit of the rain class under concern
rainclass'number'	Lateral inflow value for the specified rain class
delQ_1_limit	Limiting value for the discharge gradient in case of the start of a flood event (interval: 1 day)
delQ_2_limit	Limiting value for the discharge gradient in case of the start of a flood event (interval: 2 days)
flood_startlimit	Lower discharge limit for starting the flood function in case the flood already started before the first 2 days
flood_stoplimit	Upper discharge limit for ending the flood function in case the discharge is lower than this value for 10 days
baseflow_ini	Initialisation value for the *baseflow* variable
Qdaily_t1_ini	Initialisation value for the *Qdaily_t1* variable
Qdaily_t2_ini	Initialisation value for the *Qdaily_t2* variable

9.5.3 Variables

The variables described in table 9.14 have been declared as ordinary variables, which means that they only occur within the model, so they do not require any input. These variables are used in the Fortran code of the TransWater module, describing the hydraulics. The specific use of each variable is clarified in the description of the lateral inflow function in section 9.5.4.

9.5.4 The lateral inflow function as programmed in Fortran

A schematic overview of the lateral inflow evaluation by the model is represented in figure 9.13. This scheme should allow the reader to understand the logical sequences of lateral inflow evaluation, without examining the complete Fortran code.

Table 9.14: Variables added to the TransWater module

Variable name	**Description**
monthnumber	Reads the forcing parameter fMonth for the current time step
monthlyloss	Base lateral inflow for the current time step
floodloss	Surplus lateral inflow for the current time step, in case of a flood
rainsurplus	Appropriate rain class value for the current time step
baseflow	Ground level of flow before the start of a flood
delQ	$Discharge(I) - baseflow$ for the current time step
Qdaily_t1	fQdaily value of the previous day
Qdaily_t2	fQdaily value of two days before
delQ_1	$fQdaily - Qdaily\_t1$
delQ_2	$fQdaily - Qdaily\_t2$
floodstart	Logical variable, set to 1 when a flood starts
floodstop_counter	Counts the number of days with discharge less than the *flood_stoplimit*
maxQ	Maximum discharge observed during the period when $floodstart = 1$

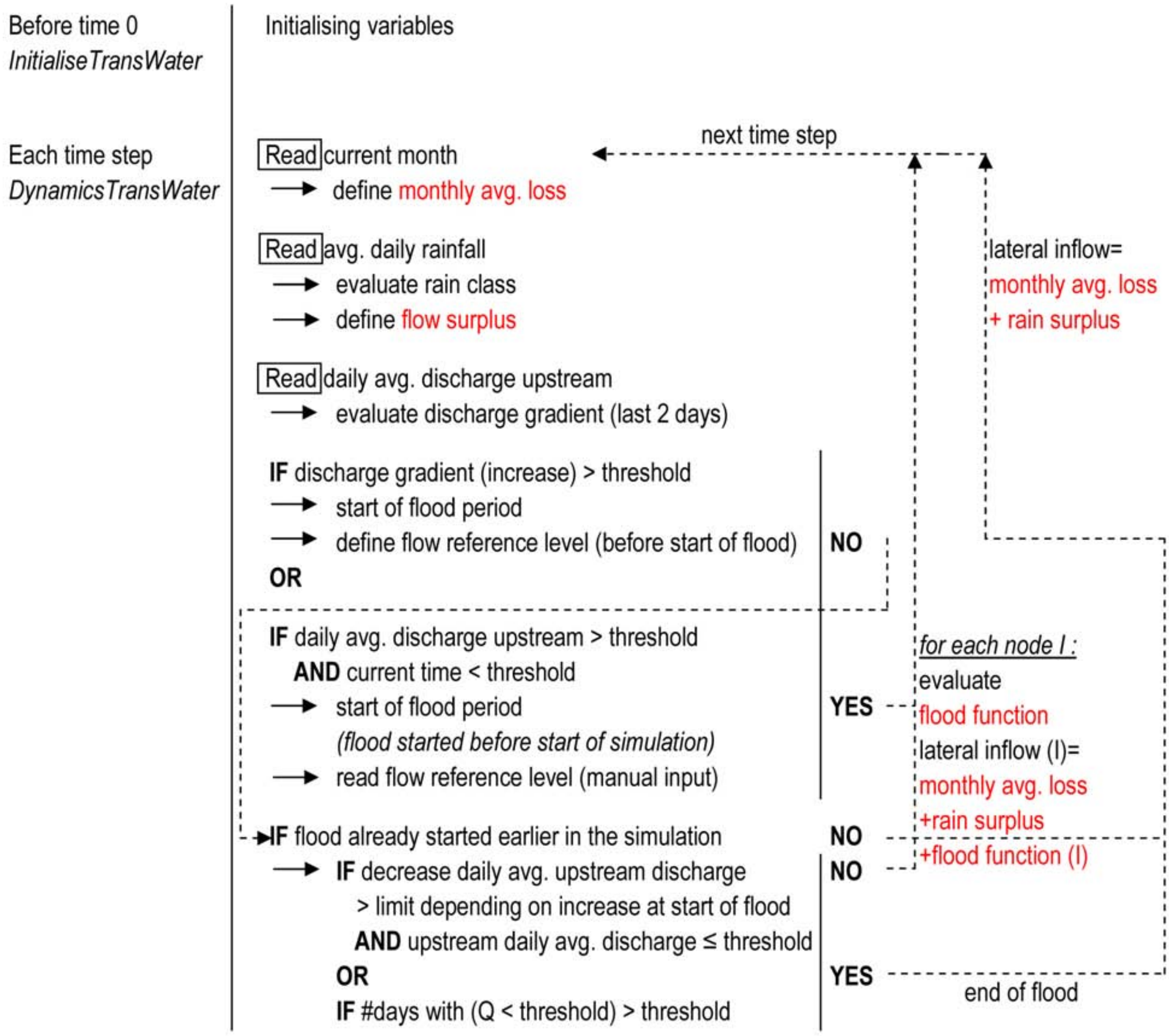


Figure 9.13: Schematic overview of the lateral inflow evaluation implemented into the TransWater code.

In the following frames, the structure and syntax of the developed function are described. The developed Fortran code is split up into several components, so as to allow a clear description and understanding of each part of the code.

floodstart=0
flood_stoplimit=0
maxQ=0
baseflow=0
floodloss=0
Qdaily_t1=Qdaily_t1_ini
Qdaily_t2=Qdaily_t2_ini

First, the variables need to be initialised. This has been established through adding the code as illustrated above to the InitialiseTransWater subroutine. The initialisation process is only performed before the evaluation of time step 0.

monthnumber=floor(fMonth)
IF (monthnumber .EQ. 1) monthlyloss=january_dry
IF (monthnumber .EQ. 2) monthlyloss=february_dry
IF (monthnumber .EQ. 3) monthlyloss=march_dry
IF (monthnumber .EQ. 4) monthlyloss=april_dry
IF (monthnumber .EQ. 5) monthlyloss=may_dry
IF (monthnumber .EQ. 6) monthlyloss=june_dry
IF (monthnumber .EQ. 7) monthlyloss=july_dry
IF (monthnumber .EQ. 8) monthlyloss=august_dry
IF (monthnumber .EQ. 9) monthlyloss=september_dry
IF (monthnumber .EQ. 10) monthlyloss=october_dry
IF (monthnumber .EQ. 11) monthlyloss=november_dry
IF (monthnumber .EQ. 12) monthlyloss=december_dry

For the evaluation of the base lateral inflow, for each time step the number of the current month is read from the fMonth forcing variable. Depending on the exact value of the *monthnumber* variable, a *monthlyloss* value is defined. This value determines the base lateral inflow, expressed as a discharge (m^3/s). The logical operator .EQ. should be interpreted as ‘equals’.

IF (fRaindaily .GE. limit1 .and. fRaindaily .LT. limit2) rainsurplus=rainclass1
IF (fRaindaily .GE. limit2 .and. fRaindaily .LT. limit3) rainsurplus=rainclass2
IF (fRaindaily .GE. limit3 .and. fRaindaily .LT. limit4) rainsurplus=rainclass3
IF (fRaindaily .GE. limit4 .and. fRaindaily .LT. limit5) rainsurplus=rainclass4
IF (fRaindaily .GE. limit5) rainsurplus=rainclass5
IF (fRaindaily .LT. limit1) rainsurplus=0

The average daily rainfall is represented by the forcing variable fRaindaily for each time step. Depending on the applicable rain class, a *rainsurplus* value is defined. The *rainsurplus* variable is a discharge (m^3/s), and should be interpreted as the deflection of the lateral inflow curve due to the recorded rainfall. .GE. is a logical operator meaning 'greater than or equal', .LT. should be read as 'less than'.

```
delQ_1=fQdaily − Qdaily_t1
delQ_2=fQdaily − Qdaily_t2
IF (delQ_1 .GE. delQ_1_limit .OR. delQ_2 .GE. delQ_2_limit) THEN
IF(floodstart .EQ. 0 .AND. delQ_1 .GE. delQ_1_limit) baseflow=Qdaily_t1
IF(floodstart .EQ. 0 .AND. delQ_2 .GE. delQ_2_limit) baseflow=Qdaily_t2
floodstart=1
ENDIF
```

The variables *delQ_1* and *delQ_2* are being used to judge whether or not a flood is coming. In order to do this properly, the daily average discharge is being evaluated, as this is representative for the current flow regime. Indeed, the hourly flow series shows abrupt peaks, which are not representative for the average flow. For the analysed flow data from 2003 until 2009, each flood is characterised by a sudden increase of the daily average discharge curve (upstream). The hydraulic model should be able to detect the start of a flood as soon as possible. By thoroughly analysing the flow data, one can conclude that either a discharge gradient of 35 m^3/s in a period of 1 day, or a discharge gradient of 50 m^3/s in a period of 2 days should be met in case a flood event is starting. Both discharges are respectively referred to as *delQ_1_limit* and *delQ_2_limit*. In case one of both conditions is met, the current flow regime is recognised as a flood, and the *floodstart* variable is set to 1. Consequently, the value of the *floodstart* variable activates the functions for calculating the change in lateral inflow due to this flood event (cfr. infra). The *baseflow* variable refers to the average flow at the upstream node, just before the start of the flood. This flow level acts as reference level, in order to determine the increase in discharge due to the flood. If the 1-day-condition is met, *baseflow* is defined as the average flow of 1 day before. In case the 2-day-condition is met, the assigned discharge is the average discharge of 2 days before. In case both conditions are met, *baseflow* is defined as the discharge of 2 days before, which can be attributed to the order of declarations in the code. Choosing the discharge of 2 days before ensures that the defined *baseflow* is the most accurate: indeed, defining the *baseflow* variable as the *Qdaily_t1* value results in a higher thus less accurate *baseflow* value.

IF (fQdaily .GE. flood_startlimit .AND. XGetCurrentTime() .LE. 172800 .AND. floodstart .EQ. 0) THEN
floodstart=1
baseflow=baseflow_ini
ENDIF

The method for detecting flood periods has only been developed for the case of an abrupt discharge gradient. However, one could also select a flow series that starts during a flood period. This means that even at time step 0, a flood event is occurring. As the flood already started before the start date of the selected flow series, no discharge gradient is detected. However, the model should be able to detect the flood. This problem has been bypassed by the introduction of the *flood_startlimit* parameter. The value of this parameter has been set to 200 m^3/s for the first reach. If the daily average discharge at Dooren Kuilen is greater than or equal to this limiting value during the first 2 days, the *floodstart* variable is set to 1, as a flood period has been detected. As the start of the selected flow series does not include the start of the flood period, the model cannot retrieve the *baseflow* value. The *baseflow* value should be obtained from the flow data from the start of the flood period. This means that this value should be specified by the user, as the data from before the start of the flood event is not read by the hydraulic model. The *baseflow* value is defined by the *baseflow_ini* parameter. This parameter is used in order to calculate the *delQ* variable.

IF (fQdaily .LT. flood_stoplimit) THEN
floodstop_counter=$floodstop\_counter + ((XGetTimestep())/(24 * 3600))$
ELSE
floodstop_counter=0
ENDIF

The end of a flood period should also be detected, so as to close the flood inflow function. Of course, this can be realised through the detection of an abrupt discharge decrease. However, one should be sure that the flood function is terminated, even in case of a very slowly decreasing discharge. This problem can be solved by demanding to close the flood function if the discharge is less than a limiting value during a certain period. The upper limit for the daily average discharge is being specified by the *flood_stoplimit* parameter, which amounts to 150 m^3/s for the first reach. The number of consecutive days with an average discharge less than the *flood_stoplimit* parameter is count by the *floodstop_counter* variable. Each time the *flood_stoplimit* value is exceeded, the *floodstop_counter* is reset.

IF (floodstart .EQ.1) THEN
maxQ=MAX (fQdaily,maxQ)
IF (maxQ-Qdaily_t1 .GT. $0.5 * (maxQ - baseflow)$ *.AND. fQdaily .LT. flood_stoplimit)*
THEN
floodstart=0
floodstop_counter=0
maxQ=0
baseflow=0
floodloss=0
ENDIF
IF (floodstop_counter .GE. 10) THEN
floodstart=0
floodstop_counter=0
maxQ=0
baseflow=0
floodloss=0
ENDIF
ENDIF

In case a flood has been detected, the *floodstart* variable tells the model to open the appropriate flood functions. The *maxQ* variable records the maximum daily average discharge that has been recorded since the start of the flood. In case of an abrupt decrease of fQdaily, the end of the flood event should be detected. This can be realised by requiring that the total decrease of the discharge curve should be half of the total increase of the discharge since the start of the flood. An additional requirement has been formulated, as the fQdaily value should be less than 150 m^3/s. The detection of the end of a flood period implies that all the variables are set to the initial value 0.

As mentioned above, the *floodstop_counter* variable counts the number of consecutive days with an fQdaily discharge less than the specified *flood_stoplimit* parameter. When the *floodstop_counter* amounts to 10 days, the flood period is ended anyway. This IF-statement has been introduced, in order to prevent the model from failing to detect the end of the flood period.

```
DO I=1, NoI
IF (floodstart .EQ.1) THEN
delQ=Discharge(I)-baseflow
floodloss=0.34933136 * delQ
ELSE
floodloss=0
ENDIF
qlat(I) =(monthlyloss+rainsurplus+floodloss)/StreamLength
ENDDO
```

In case the *floodstart* variable is set to 1, the flood loss function is evaluated in each node. For each node, the model calculates the appropriate *delQ* value, depending on the discharge in node I. Discharge(I) varies for each time step. The number of nodes is referred to as NoI. Consequently, the linear function relating Δ Q to the deflection of the lateral inflow curve as shown in figure 9.12 is evaluated for node I. Finally, the lateral inflow per unit length *qlat(I)* is being defined. The unit of *qlat* is $m^3/s \cdot m$.

```
Qdaily_t2=Qdaily_t1
Qdaily_t1=fQdaily
```

After evaluating the *qlat* values, the lateral inflow code is being finalised by the redefinition of *Qdaily_t1* and *Qdaily_t2*, which are used in the next time step.

Chapter 10

Model evaluation - part 1

10.1 Introduction

Now that the model has been built, one can check its accuracy. First of all, the hydraulic model needs to be calibrated by determining the correct Manning's roughness coefficient. Once this has been done, some runs are required to validate the correctness of the estimated value. In this chapter the accuracy of 'Model v1.0' (see chapter 9) is checked only for the first reach, viz Dooren Kuilen-Marksdrift. The code of the concerned model is given in section 9.5, where the reasoning of it was explained in section 9.4.

To calibrate, a characteristic flow series should be evaluated by the model for several Manning's roughness coefficients. In fact, the same run (i.e. same upstream input and same initial and boundary conditions) have to be calculated a few times, by only changing the Manning's coefficient. By fine-tuning, one should find the most appropriate value for the Manning's coefficient. It is difficult to assume a certain interval of roughness coefficients in advance. Therefore, this interval is based upon the Manning's values that are mentioned in [154]. These values were implemented in the model of the Danish Hydraulic Institute (DHI), using MIKE 11. They made use of a Manning's roughness coefficient of 0.036 for the first reach. It should be clear that the final result of this 'Model v1.0' can easily differ from the given value as both models are different. The value of 0.036 will only serve as an indication to determine an appropriate interval.

As the differences between two calibration runs are often small, there is no sense in decreasing the calibration step to an absolute minimum. A calibration step of 0.004 was chosen (arbitrarily) as this results in small, but perceptible differences. Calibration runs are thus calculated for Manning's coefficients which are natural multiples of 0.004, more or less around the value of 0.036. To start, the interval is chosen from 0.032 to 0.048. If necessary, this range can easily be extended.

10.2 Calibration process

10.2.1 Introduction

In order to evaluate the model that was discussed before, some typical flow series must be examined. The computed output of the model can be compared with the recorded data downstream (i.e. at Marksdrift Weir for the first reach) for a restricted number of flow series. In this way, both accuracy and sensitivity of the model can be assessed. Moreover, these flow series can be applied to determine a 'correct' value of the roughness coefficient. Once the calibration process has been finished, this coefficient is set to a fixed value. The calibration process has been done by means of a qualitative analysis (instead of a quantitative one) of the different outputs.

The number of the so-called calibration flow series is set to three. As a river model intends to be a useful tool for predicting flood events in advance, at least some of these flow series must contain periods of flooding.

10.2.2 First calibration run (1_2009 - February until March 2009)

The first period that will be investigated contains a flood, situated in February and March 2009. Compared to other years, there was a major flood with very high discharges (up to nine times the ordinary values). First of all, it seems necessary to check whether the lateral inflow function (see section 9.4.4) is the key to obtain correct results. Therefore the model output is plotted and compared to the situation without any losses along the reach. These plots are represented in figure 10.1. As one can see on this graph, the loss function which was implemented is a clear improvement in comparison with the original situation without loss function.

In order to select a correct value for the Manning's roughness coefficient, a plot was made for different values going from 0.032 to 0.048. This plot is shown in figure 10.2 and 10.3. These plots are more detailed zooms of the above period to emphasise the differences according to different Manning values.

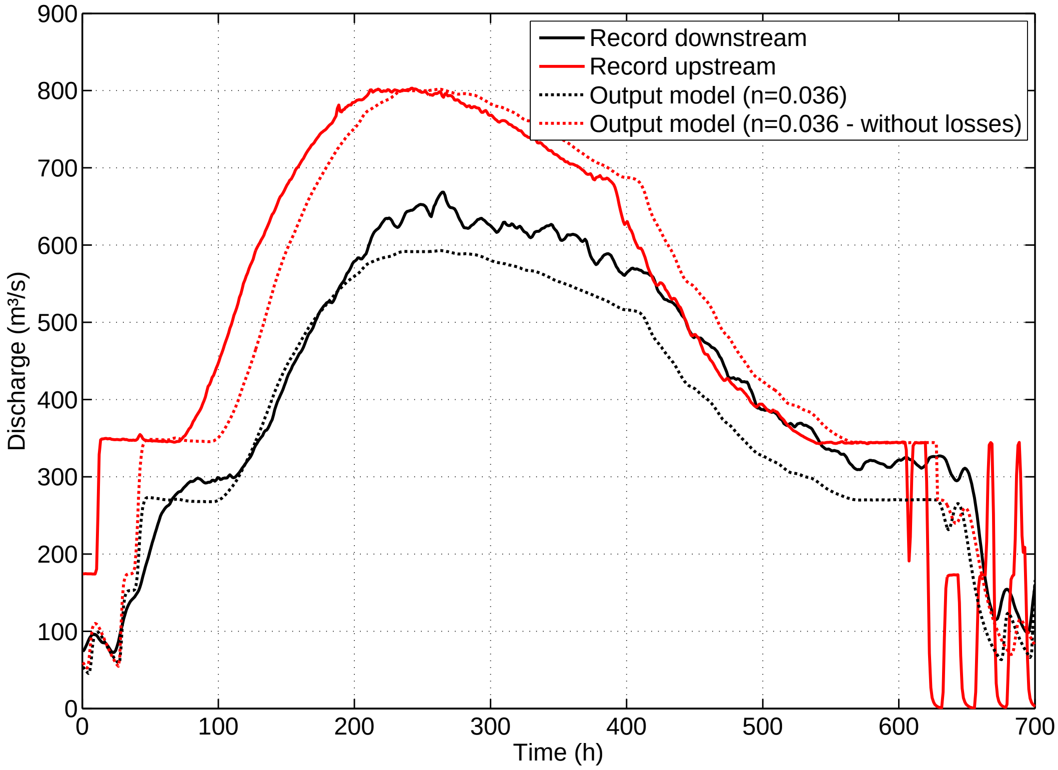


Figure 10.1: Evaluation of the loss function for a flood (21/02/2009 - 27/03/2009 (series 1_2009)). Discharge (m^3/s) versus time (h).

When the discharges can be considered as 'high' (i.e. higher than 150 m^3/s) a Manning's roughness coefficient of 0.048 seems to be the most correct of all the tested values. By contrast, a value of 0.048 is way to high for lower discharges. If it comes to that a value of 0.032 or 0.036 will fit better.

There are several factors that influence the Manning's roughness coefficient namely [164]:

- Surface roughness:

  Surface roughness is influenced by grain size and shape. Where the channel's bed is covered with fine sized grains, the flow resistance is less but if there are boulders and gravel, the resistance is increased;

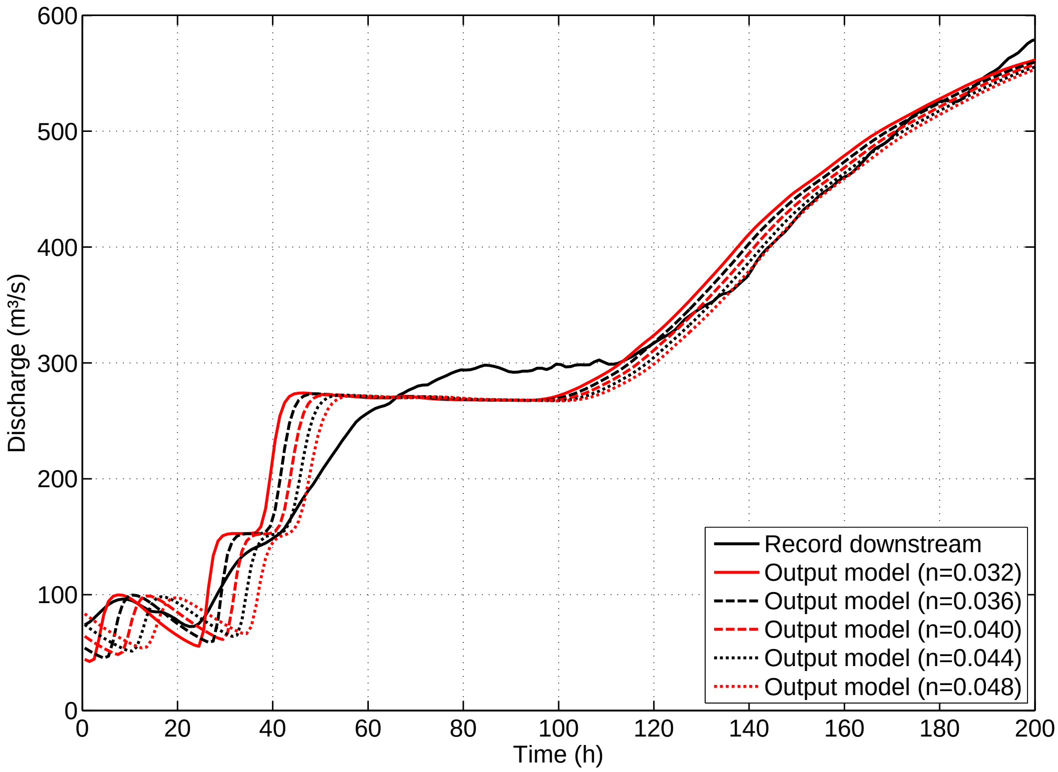


Figure 10.2: Influence of Manning's roughness coefficient (21/02/2009 - 27/03/2009 (series 1_2009)). Discharge (m^3/s) versus time (h).

- Vegetation:

  The influence of vegetation on the flow depends on the vegetation type, size and density;

- Channel irregularities:

  Variations in size and shape of the cross sections along the channel length will influence the roughness;

- Channel alignment:

  Sharp curvature with severe meandering will increase the roughness coefficient [165].

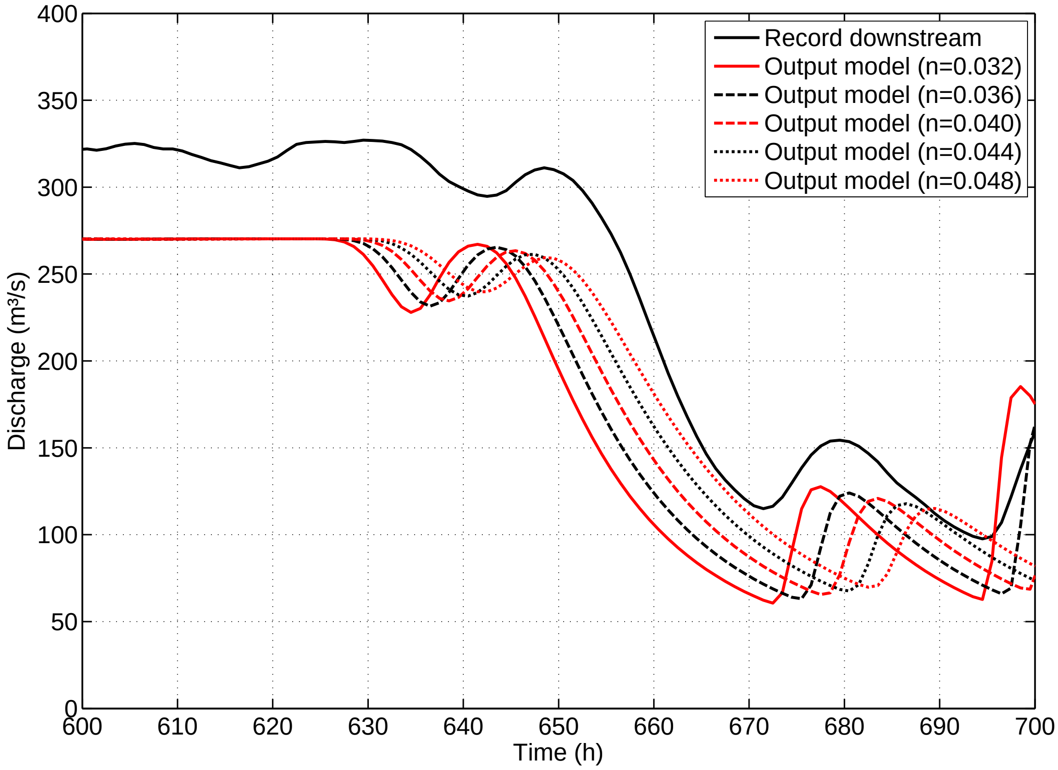


Figure 10.3: Influence of Manning's roughness coefficient (21/02/2009 - 27/03/2009 (series 1_2009)). Discharge (m^3/s) versus time (h).

An increased roughness in case of flooding can be explained as follows: the river will overflow its banks and the average roughness of the riverbed will increase as a result of it. Manning's roughness coefficients can reach values up to 0.150 in case of floodplains with dense vegetation [166].

10.2.3 Second calibration run (2_2006 - March 2006)

During March 2006 there was the start of another flood, which was much smaller than the flood described in section 10.2.2. Before the start of the flood, during the first hours of the considered flow series, the flow conditions can be characterised as a 'non-flood regime'. According to the roughness coefficients, similar findings as in section 10.2.2 can be concluded from the model results. Figure 10.4 shows once more that the implementation of the loss function (see section 9.4.4) yields to better results.

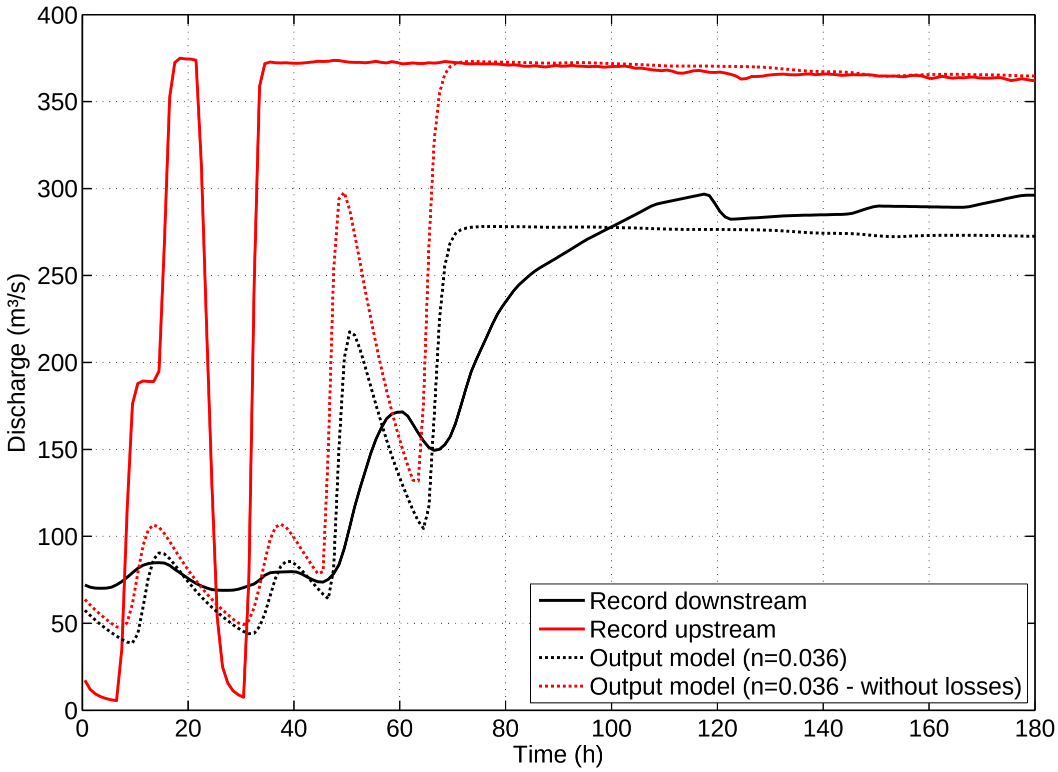


Figure 10.4: Evaluation of the loss function for a flood (26/02/2006 - 17/03/2006 (series 2_2006)). Discharge (m^3/s) versus time (h).

Again, the selection of a fixed Manning's roughness coefficient seems to be very difficult. There is a huge difference in roughness according to the current discharges (see figure 10.5). For the lower discharges one could prefer a value of 0.036, while a higher value is more reasonable in case of flooding.

10.2.4 Third calibration run (3_2006 - April 2006)

The artificial loss function (see section 9.4.4) seems to result in a good prediction of the downstream discharges. The flood of April 2006 will be a last test. The results are plotted

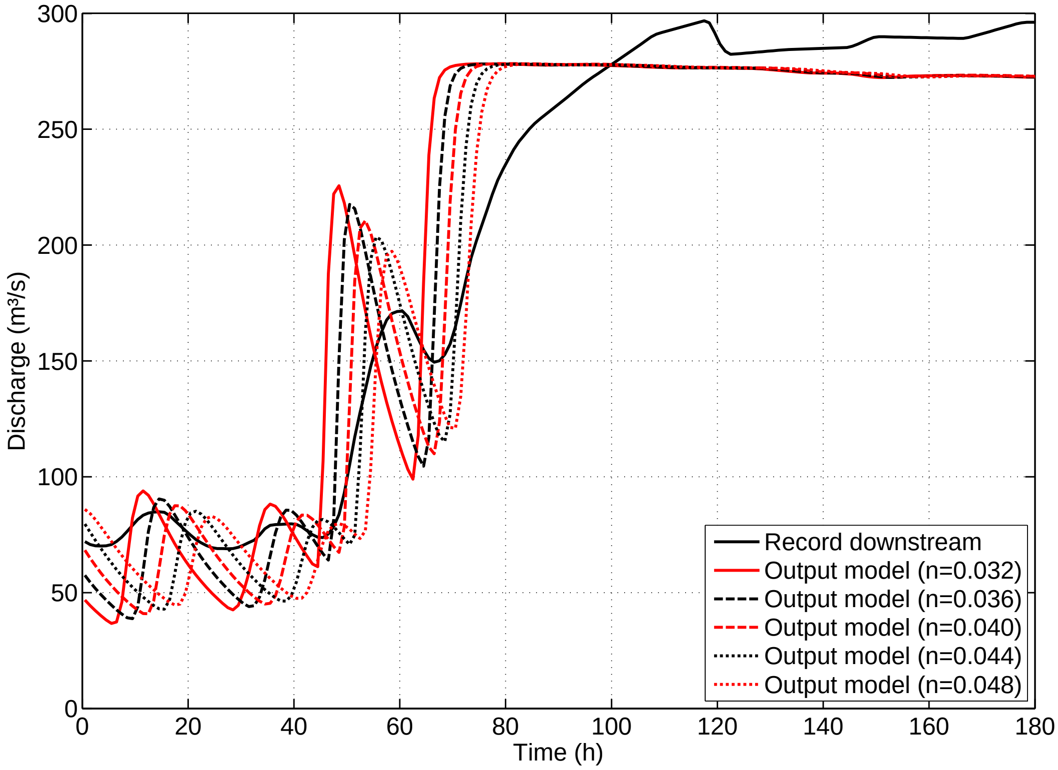


Figure 10.5: Influence of Manning's roughness coefficient (26/02/2006 - 17/03/2006 (series 2_2006)). Discharge (m^3/s) versus time (h).

below on figure 10.6. As can be seen on this plot, the correction is in this case nearly perfect. As can be expected due to the high discharges, a high value of the Manning's roughness coefficient results in the best approximation of the downstream record (see figure 10.7). At the beginning of this flow series, a flood is already started. Therefore, it is important to chose an appropriate value for the *baseflow_ini* parameter. Otherwise flood losses would not be included, resulting in a too high discharge downstream of this reach. In this a example a value of 100 m^3/s was chosen for *baseflow_ini*.

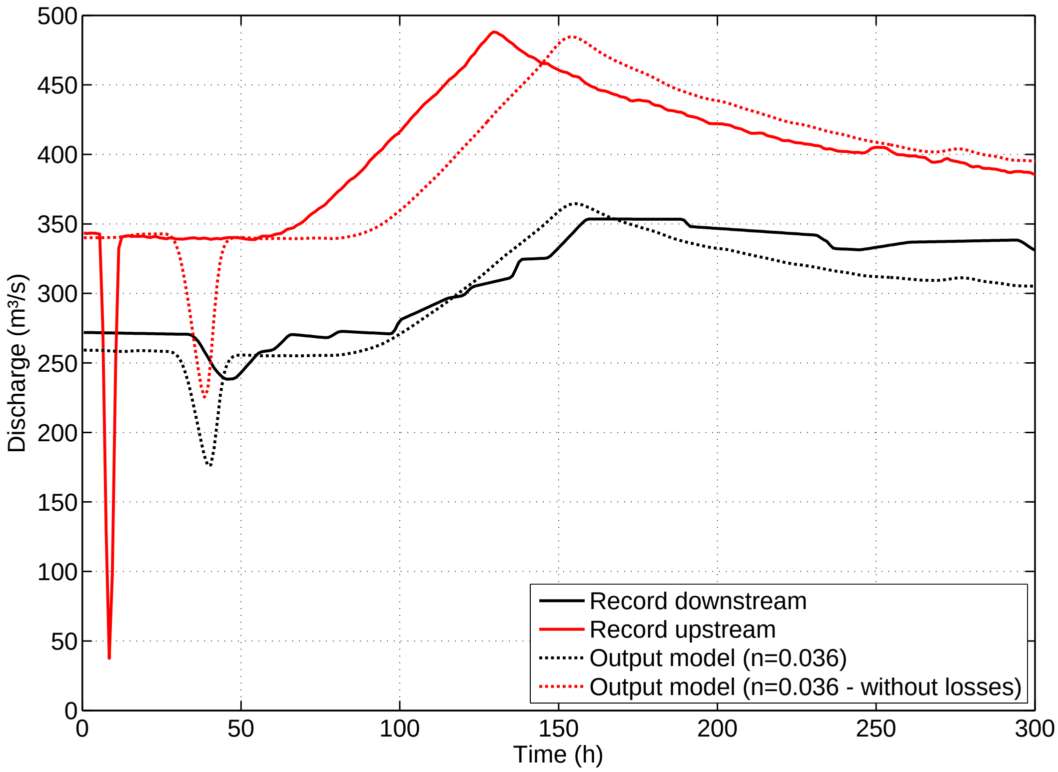


Figure 10.6: Evaluation of the loss function for a flood (28/03/2006 - 16/04/2006 (series 3_2006)). Discharge (m^3/s) versus time (h).

10.2.5 Conclusion

After analysing the different model outputs, it is obvious that the Manning's roughness coefficient cannot be declared as a constant. Further research is necessary to find a relation between roughness and other variables such as discharge and macrophyte growth. A seasonal trend in the riverbed roughness is also highly presumable [160]. Although this research could not be done during this study, it is highly recommended to improve the accuracy of the current 'Model v1.0' for the Orange River by the implementation of a variable Manning function.

In anticipation of such a reliable function which describes the roughness fluctuations, a fixed value has been chosen. As flooding is rather an occasional event, a rather low value for the

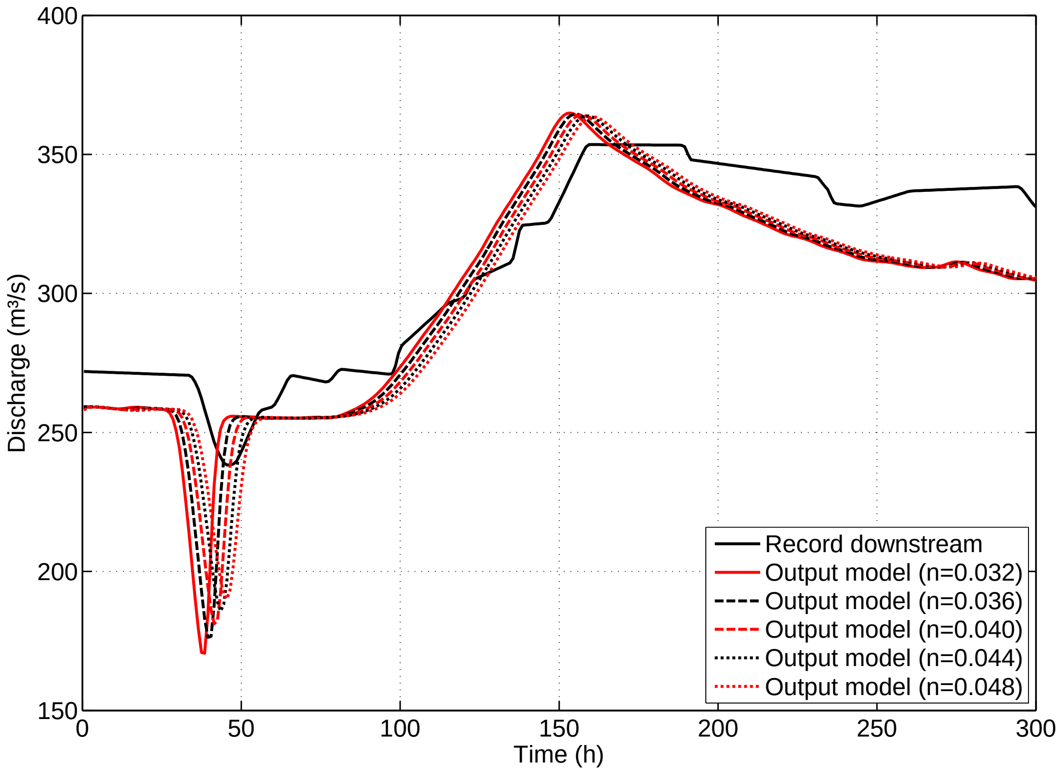


Figure 10.7: Influence of Manning's roughness coefficient (28/03/2006 - 16/04/2006 (series 3_2006)). Discharge (m^3/s) versus time (h).

Manning's roughness coefficient is preferred. Nevertheless, the modelling and prediction of flood events is also important. This would lead to higher values for the roughness coefficient. It seems to be preferable to adopt a middle course by choosing a value of 0.040. In this way, the model will lead to good results most of the time. Although, one should take into account that the roughness can fluctuate a lot, as was shown in the previous examples.

10.3 Validation process

Now that the calibration process is finished, only the validation process is left to check whether the assumption according to the Manning's roughness coefficient can be justified.

Therefore, two runs of different flow series have been calculated. The following series will be briefly discussed: 10_2006 (05/10/2006 until 20/10/2006) and 1_2007 (15/01/2007 until 24/01/2007).

10.3.1 First validation run (10_2006 - October 2006)

The first validation run contains typical flow series for reach 1, i.e. many abrupt changes in discharges upstream due to the dam releases at Vanderkloof Dam. As one can see on figure 10.8, the calculated discharges are actually too small in comparison with the recorded discharges. It may be said that in this particular case the losses were overestimated. Anyway, the time component seems to be well calculated. A time shift between the output curve and the recorded curve is hardly noticeable. Even though the losses are not well considered in this validation run, it may be said that the choice of the Manning's roughness coefficient seems to be acceptable.

10.3.2 Second validation run (1_2007 - January 2007)

The second run of the validation process was recorded at the end of a flood event. Because these flow series start in the middle of a flood, the *baseflow_ini* parameter needs to be determined in order to take the losses due to floods into account. The value of this parameter was set to 180 m^3/s in this particular case. Again, time shifts between the recorded and calculated series are hardly to recognise. So the roughness may be well estimated. Anyhow, the discharges are overestimated this time. In the beginning of the run, the differences are very small. In the last part of the series (i.e. after 150 h) the differences become bigger as the total losses are now underestimated.

10.3.3 Conclusion

The two validation runs gave good results concerning the value of the Manning's roughness coefficient. There are no time shifts worth mentioning. Nevertheless, the calculated discharges deviate from the recorded discharges. It may be concluded that a value of 0.040 for the roughness coefficient seems to be a good assumption, resulting in acceptable outputs.

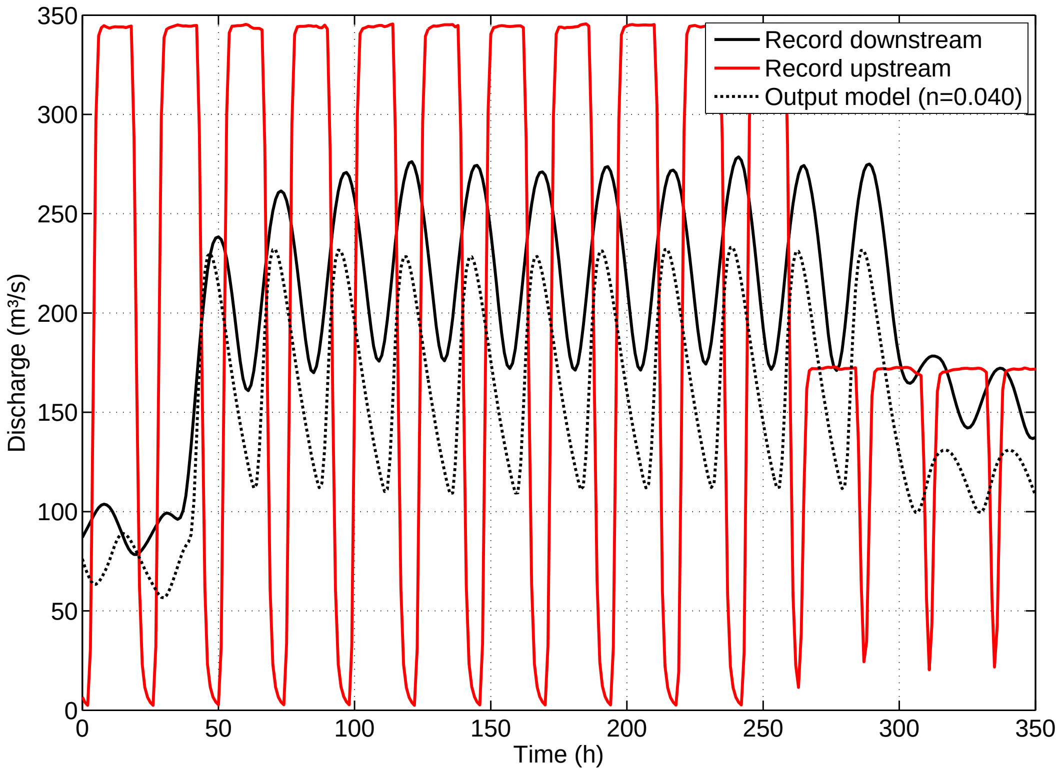


Figure 10.8: Result of the first validation run (05/10/2006 - 20/10/2006 (series 10_2006)). Discharge (m^3/s) versus time (h).

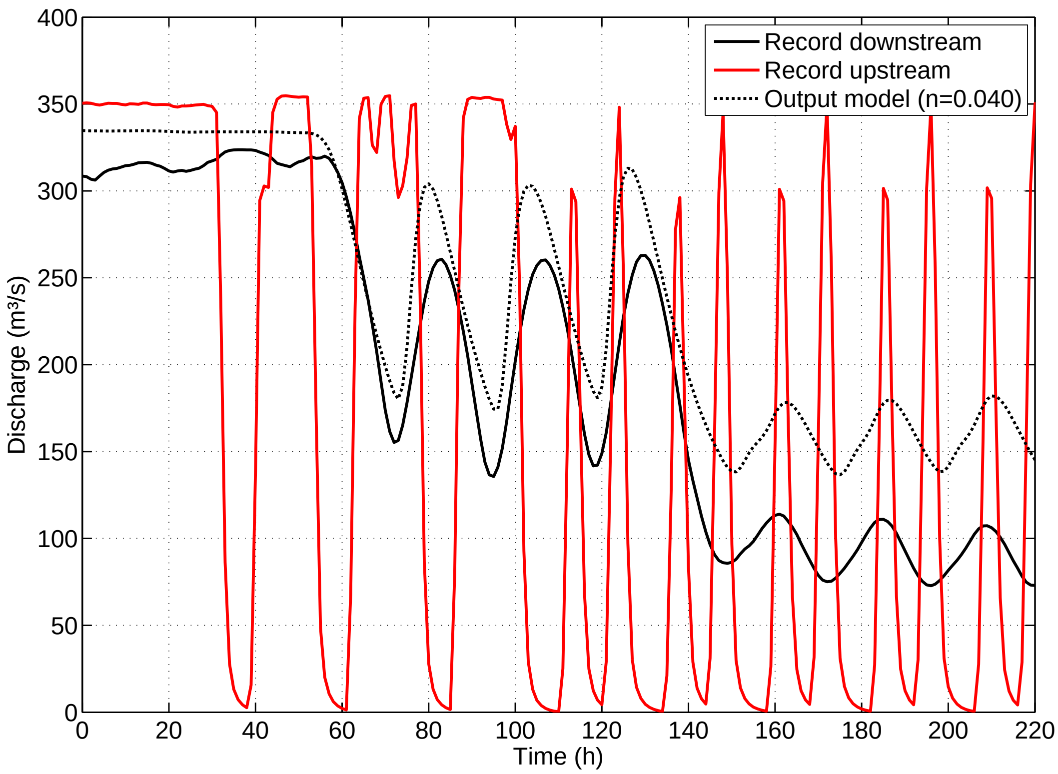


Figure 10.9: Result of the second validation run (15/01/2007 - 24/01/2007 (series 1_2007)). Discharge (m^3/s) versus time (h).

Chapter 11

The hydraulic model - part 2

11.1 Introduction

Evaluation of 'Model v1.0' (see chapters 9 and 10) proved that this model leads to quite accurate results. Building the hydraulic models for the other reaches of the Lower Orange River (LOR) should now be easy. By following the same operating procedure as described in chapter 9, satisfying results may be expected.

Nonetheless, some additional problems cropped up when checking the discharge data for the other river reaches in more detail. These gauging data seem to be unreliable as in most of the reaches, continuous huge lateral inflows (i.e. the downstream discharges are consequently higher than the upstream discharges) are observed without any possible explanation. In addition, these reaches are situated in the Northern Cape province, a semi-arid region where evaporation rates can easily come up to 2700 mm/a while precipitation is limited to 50 mm/a in some areas [158] [2]. Furthermore, a lot of abstractions for irrigation purposes occur along these river reaches.

As one can see, it is impossible that a continuous surplus of water is flowing into the river under these severe climatic conditions. An example of this unrealistic phenomenon is depicted in figure 11.1. For the considered period, no rainfall worth mentioning was recorded. Besides, reach 7 (i.e. Neusberg Weir - Vioolsdrift Weir) is situated in a semi-desert region.

In this chapter, one tries to adapt the current model, 'Model v1.0'. It was stated above that the gauging data seems to be unreliable. A few other problems will also arise during

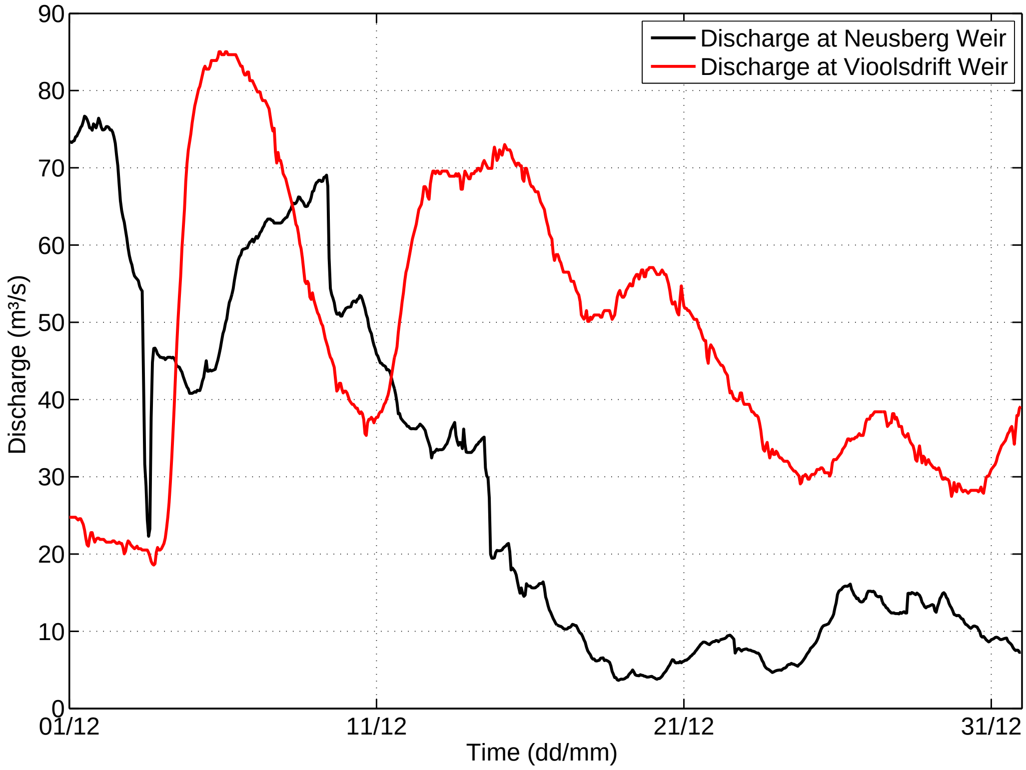


Figure 11.1: Unrealistic situation (continuous surplus of water at the downstream node (Neusberg)) for reach 7 for the month December 2008. Discharge (m^3/s) versus time (dd/mm).

this building process and they all need to be tackled according to a well thought-out plan. The purpose is to get round these difficulties in a manner that is scientifically acceptable. Once a solution is offered, a model can be built for all the reaches of the LOR. This model is referred to as 'Model v2.0'.

11.2 Difficulties to tackle during the modelling process

11.2.1 Physical difficulties

The LOR is a 1400 km long, highly regulated river system (see chapters 1 and 2) that is flowing through remote areas for most of the time. This results in a lot of uncertainties and inaccuracies of the collected information. Next to the problem mentioned in the previous section, several other potential difficulties can arise. Some of the biggest problems that need to be tackled are listed below [157]:

- The major problem is the lack of accurate low-flow monitoring data. The existing weirs on the LOR are actually too wide as they mostly extend over the whole width of the river. Originally, weirs were built to feed irrigation canals, but now they are also used for flow measurement. Weirs that are more recent (e.g. Neusberg Weir, constructed in the early 1990's (see figure 11.2)) are made up of different notches separated by director walls. For example Neusberg Weir has three different notches, each designed for a different flow level. The lowest notch will measure flows up to 140 m^3/s before the second notch comes into effect. The central notch comes into effect at flows in excess of 1870 m^3/s [167]. This results in a more accurate flow measurement under low-flow conditions. Because most of the existing weirs on the LOR are not capable of measuring low-flow conditions, an accurate calibration of the model is difficult, if not impossible, to achieve;

- Furthermore, abstractions from the river are not recorded. That's why it is not possible to include accurate abstraction data in the river model. Irrigation abstractions (and the related return flows afterwards) in particular, accounting for the majority of all abstractions, are difficult to model. Although, a maximum annual quota for each region is known. This figure is the total amount which may be pumped from the river on an annual basis. Nevertheless, it is not necessarily always used. Irrigation amounts vary with a seasonal trend. Due to this variation and to climatic changes, the daily abstractions may differ from the annual quota;

- Irrigation can result in substantial return flows, depending on which irrigation technique is applied. Both the quantity and timing of these flows are very uncertain. It is particularly difficult to model the return flows accurately when the amount of water being used for irrigation is also not certain;

- Taking the climatic conditions into consideration, losses from the LOR are significant. Evaporation losses depend on the current weather conditions, which are usually hot and dry, and also on the surface area of the water and therefore the local flow conditions. The abundance level of riparian vegetation plays also an important part in the total evapotranspiration;

- The Vaal River (i.e. the largest tributary of the Orange River) is usually not operated to contribute to the flow in the LOR during low flow conditions. Even though, it has been observed that inflow from the Vaal River does occur, particularly at the start of the winter period. These 'spills' are mainly originated from return flows from irrigation areas along the Vaal River. If these return flows can be quantified and included in the model, releases from Vanderkloof Dam may be reduced;

- Inflows from tributaries (except for the Vaal River) are nowadays not recorded in real-time. Model results can be improved obviously by implementing a system to include these useful real-time data.

From all difficulties discussed above, the first one is undeniably the most important. As some gauging stations are not able to record water levels and discharges at an acceptable level of accuracy, it is indeed infeasible to estimate the losses accurately.

11.2.2 Modelling related difficulties

Besides the physical difficulties discussed in section 11.2.1, some problems characteristic of the modelling process also arise when building this model. One of these difficulties was already mentioned in the list of physical problems, to wit the implementation of the Vaal River as a tributary of the river reach between Marksdrift Weir and Irene/Katlani. Even though the possibility to incorporate a tributary into a model is already implemented in the STRIVE software, some modifications and considerations have to be made. A satellite photograph of the Vaal River-Orange River confluence near Bucklands is depicted in figure 11.3. This matter will be further discussed in section 11.5.2.

When the LOR is flowing from Neusberg Weir to Vioolsdrift Weir, it has to pass Augrabies Falls (see figure 11.4). These waterfalls are situated in the Augrabies Falls National Park. As the Orange River approaches Augrabies Falls it divides itself into numerous channels before cascading down the waterfall. The river then continues its path through an 18

Figure 11.2: Neusberg Weir with three different notches, each with a different top level (the lowest notch is situated on the left bank of the river). Aerial photograph: R. McKenzie [167].

kilometre gorge (see figure 11.5). Augrabies gorge is a nine kilometre granite cleft through which the river plunges 146 m in total through a series of spectacular cataracts into a deep pool. During peak floods which occur approximately every ten years, the flow over the falls exceeds 9000 m^3/s [167].

The Khoi people (i.e. the original inhabitants of these areas) called the waterfalls 'Auko-erebis' or place of Great Noise, referring to the falls in the case that the Orange River is in full flood [168]. The abrupt change of longitudinal profile can cause modelling problems. Due to this high irregularity, the results of the software model may end in a stack overflow (i.e. the computer program makes too many subroutine calls and its call stack runs out of space) with the result that no output is created. A solution for this problem is presented in section 11.5.7.

Figure 11.3: Confluence of the Vaal River and the Orange River. Satellite photograph: Google Maps.

11.3 Dealing with inaccurate gauging data

As it was already stated before, the 'Model v1.0' cannot be used for the modelling of the reaches 2 to 7 of the LOR. Indeed, accurate gauging data is required in order to define accurate lateral inflow functions. In order to build a correct model accurate flow data are necessary, both upstream (to use as model input) and downstream (to compare with the output of the model). For the LOR (downstream of Marksdrift), these accurate data are not available.

Most of the time, the river is in low-flow condition. As only two LOR weirs (i.e. Marksdrift Weir and Neusberg Weir (see section 11.5)) can measure low flows accurately, it's impossible to build a hydraulic model with a certain level of correctness [157]. In chapter 9, a model was built using data of both Dooren Kuilen and Marksdrift Weir. The level of inaccuracy of the measurements at Dooren Kuilen is hugely uncertain. Nonetheless, the observed losses and surpluses can be logically explained (i.e. losses according to seasonal trends, losses due to floods and surpluses due to rainfall). That makes it quite understandable why good

Figure 11.4: Photograph of Augrabies Falls: P. Fourie [169].

results were obtained for this river reach (see chapter 10).

Manual flow measurements need to be undertaken to accompany the inaccurate gauging results [158]. As a field study with measurements on the spot was not feasible in the framework of this Master thesis, another ‘solution’ needs to be sought for.

There seems to be no other possibility than accepting (and keeping in mind) the impact of inaccurate flow data on the modelling results. The inaccuracies of the data can be found in the measured discharges, where the time components of the data on the other hand are well recorded. This results in only a vertical shift between the actual and recorded flow in a traditional ‘discharge versus time’ plot. Although the vertical shift differs in size all the time, any flow pattern can easily be recognised out of the data.

Keeping this at the back of our mind, a model can be built in order to predict the time shifts in flow series. This model can be used to forecast the propagation of any possible flow series through the riverbed. On the other hand, it may not be forgotten that there

Figure 11.5: Photograph of Augrabies gorge: R. McKenzie [167].

does exist a difference between the actual flow and the flow predicted by the model (i.e. the vertical shift). In any case, 'Model v2.0' can be perfectly used to forecast the propagations of particular flow patterns through the LOR.

Due to the inaccurate flow data, it is impossible to create a function that deals with the different losses. Such a function, like the function implemented in 'Model v1.0', can give added value to a hydraulic model. Because a similar function couldn't be defined in 'Model v2.0' (due to inaccurate data), the model will be less accurate than the model that was built in chapter 9.

11.4 Estimation of water demands

As a consequence of the inaccurate flow data, the lateral inflow function (see section 9.4.4) cannot be evaluated anymore. In any case, it cannot be justified to implement any kind of loss function that is based on inaccurate, not to mention incorrect, data. It is impossible to perform the analysis prescribed in chapter 9 for the reaches 2 to 7.

In order to incorporate any kind of abstractions and losses in the model, some monthly figures (obtained in the framework of a study commissioned by DWA) were used [3]. These monthly demands include environmental requirements (i.e. water consumed by evapotranspiration), irrigation and urban demands and all kind of losses (see section 8.3). These figures are quite recent and applicable for the period considered in this study (i.e. from 2003 until 2009). For many places along the river, the abstractions were given on both an annual and a monthly basis. For several irrigation schemes, which are the most important water users, the abstractions exceed a level of 100 million m^3/a. These abstractions, as well as the river losses, may affect the flow in the downstream parts of the LOR.

On figure 11.6 a distribution of the monthly evaporation losses for the entire LOR is plotted. The seasonal trend in these figures is obviously clear. On the other hand, a plot of irrigation requirements throughout the year is depicted in figure 11.7. These graphs prove that the patterns in monthly demands distribution are completely different.

11.5 Overview of the different river reaches of the Lower Orange River

Nowadays, the telemetry system on the LOR includes 11 real-time gauging stations (see table 11.1). The recorded data is transmitted to the Department of Water Affairs (DWA) head office in Pretoria, where it is saved in a central database. Only two out of eleven weirs are capable to measure low flows for the moment, i.e. Marksdrift Weir and Neusberg Weir [157]. The currently executed upgrading of the weir at Zeekoebaart (see figure 11.8) is meant to improve its accuracy. As it was already stated above, the problem is that the weirs are too wide and therefore they are not capable to measure flow precisely. Designing weirs with a different notches may offer a solution.

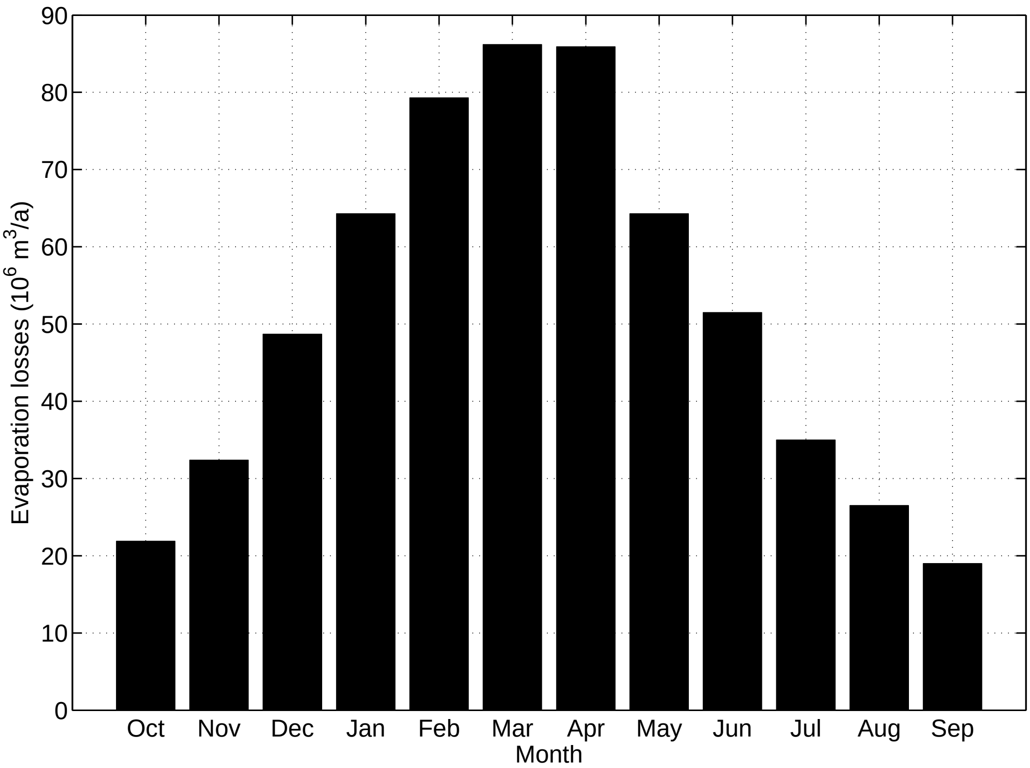


Figure 11.6: Monthly evaporation losses for the entire length of the Lower Orange River. Losses (10^6 m^3/a) versus month.

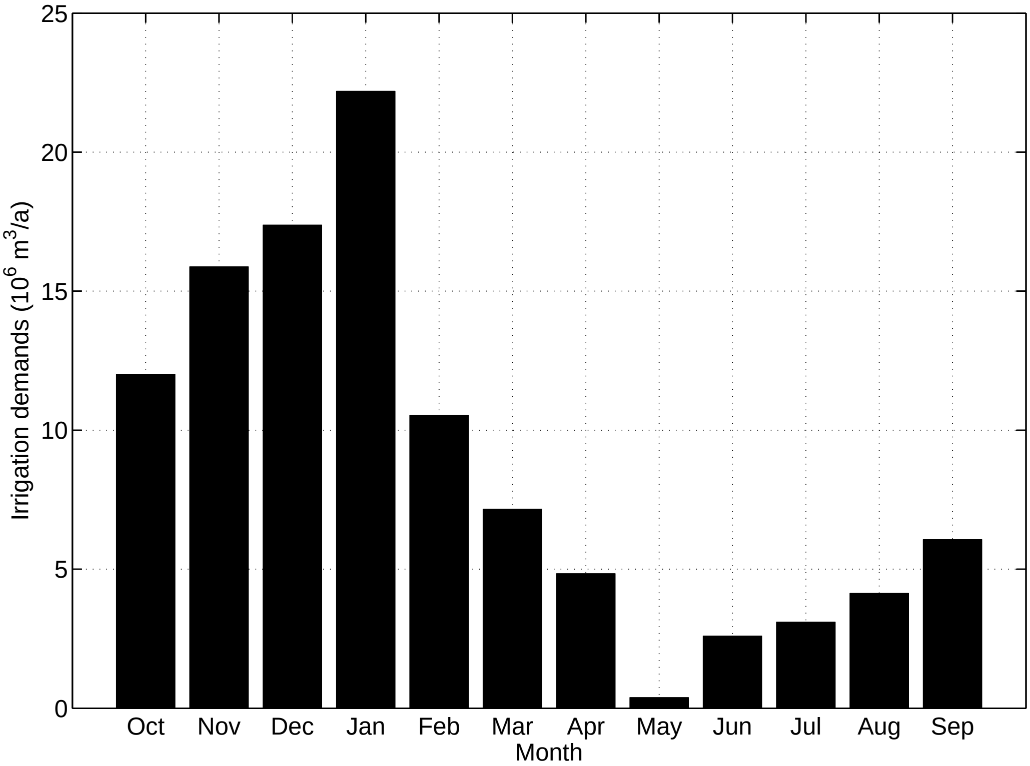


Figure 11.7: Monthly water requirements for the irrigation area near Kakamas. Water demands (10^6 m^3/a) versus month.

Table 11.1: Overview of the existing real-time gauging stations on the LOR [157]

Station name	**DWA gauge number [151]**	**Distance downstream from Vanderkloof Dam (km)**
Vanderkloof Dam	D3R003	0
Dooren Kuilen	D3H012	1
Marksdrift Weir	D3H008	174
Irene/Katlani	D7H012	204
Prieska	D7H002	355
Boegoeberg Dam	D7R001	471
Zeekoebaart Weir	D7H008	473
Upington	D7H005	635
Neusberg Weir	D7H014	708
Vioolsdrift Weir	D8H003	1100
Brandkaros	D8H007	1365

All the gauging stations mentioned in table 11.1 are used in the hydraulic 'Model v 2.0', except for Vanderkloof Dam (because this station doesn't measure the flow but only the reservoir level), Zeekoebaart Weir (because this weir is situated only 2 km downstream of Boegoeberg Dam) and Brandkaros (because this station is highly inaccurate). Vioolsdrift (see figure 11.9) is effectively the last point along the Orange River where a reasonable estimate of the river flow can be obtained [167]. Therefore, the 'Model v 2.0' consists of seven river reaches.

The characteristics of all seven reaches will be discussed below. For all reaches, some geometrical characteristics will be enumerated and the longitudinal profile will be plotted. A weir forms the downstream boundary condition (relation between water levels and discharges) in each case. In fact, the methods to determine geometry, rating curves of the downstream weirs, forcing files, etc. are explained in section 9.4. The longitudinal profile of the modelled part of the LOR is plotted in figure 11.10.

All rating curves were fitted using TableCurve software (see figure 9.2 as an example). The different weir rating curves for the other reaches have not been plotted nor discussed. Only

Figure 11.8: Renovated part of Zeekoebaart Weir (including a fish ladder). Photograph: field trip September 2009.

for low flows, the typical spillway function $Q = a \cdot z^b$ is valid. For high flows, these curves are sometimes described by several functions, each having its own range of application (the river has overflowed its banks). As a consequence, the general formulation of the rating curve is no longer valid. It doesn't make sense to summarise all these functions and parameters. Just as for reach 1, the functions have been implemented in the model as a downstream boundary condition (see chapter 16 and the attached DVD).

In the sections below, only the results of these methods are presented. Moreover, the difficulties concerning the Orange River - Vaal River confluence and Augrabies Falls (see section 11.2.2) will also be considered.

11.5.1 Reach 1: Dooren Kuilen - Marksdrift Weir

In chapter 9, the first river reach (i.e. Dooren Kuilen - Marksdrift) was already presented in detail in section 9.4. Figure 9.4 shows the longitudinal profile of that specific reach. Characteristics and geometry were given in table 9.5 and the rating curve of the downstream

Figure 11.9: Photograph of Vioolsdrift Weir: R. McKenzie [167].

weir at Marksdrift was determined (see figure 9.2 and table 9.6).

11.5.2 Reach 2: Marksdrift Weir - Irene/Katlani

With a length less than 30 km, the second reach is by far the shortest. Nevertheless, this part contains the confluence of the Vaal River and the Orange River. The main characteristics are listed up in table 11.2. The longitudinal profile is depicted in figure 11.11.

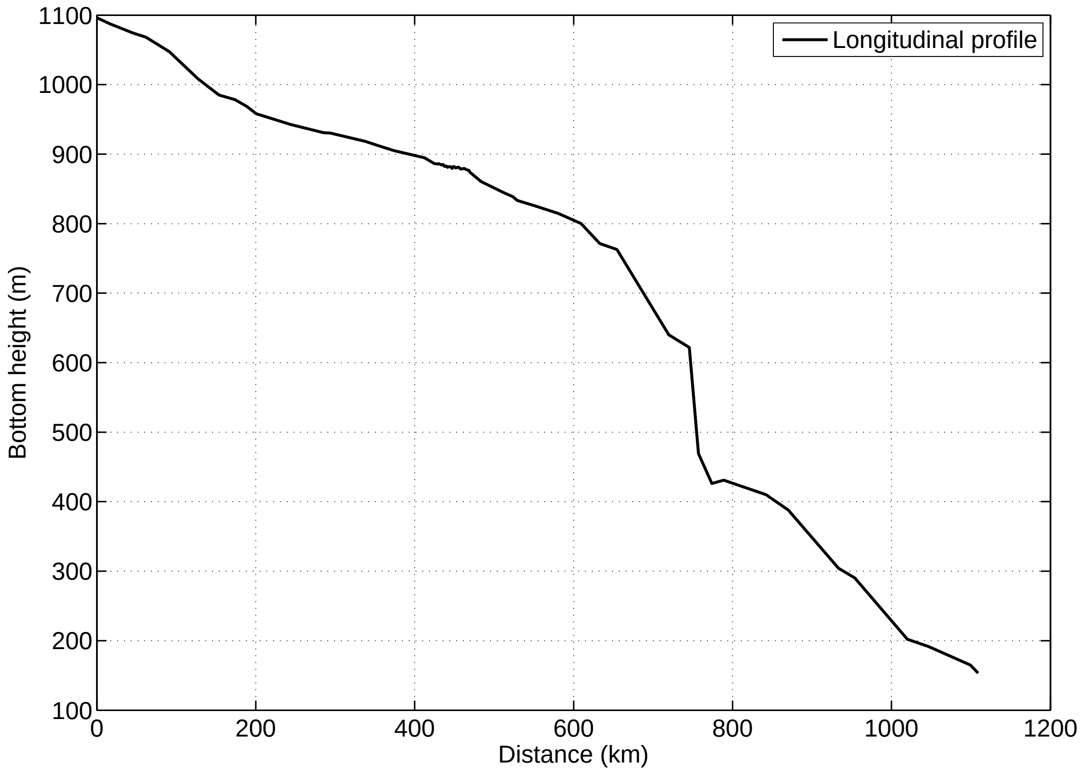


Figure 11.10: Longitudinal profile of the Lower Orange River between Dooren Kuilen and Vioolsdrift. Bottom height (m) versus distance (km).

Table 11.2: Details on reach 2: Marksdrift Weir to Irene/Katlani

StreamLength	28 896 m
ZbottomUpstream	978.5 m
ZbottomDownstream	957.3 m
Number of cross sections	3
Number of boxes	1000
Box length	29 m

Data from the Vaal River is obtained by the gauging station at Douglas Weir (see 11.12). This weir with DWA gauge number C9R003 [151] is situated on the Vaal at 24 km upstream of the confluence. As this 'reach' has a non-negligable length, especially when related to reach 2 of the LOR, the measured data at Douglas may not be directly used as a sideways inflow. In the following paragraphs a method to by-pass this obstacle is explained.

At first, a model for the reach 'Douglas - confluence' needs to be built and the output of this model can then be used as a boundary condition for the model of reach 2 (LOR). Another problem arises as there is no data available for this last part of the Vaal River. As both reach 2 (LOR) and the reach 'Douglas - confluence' are situated in the same area, both having a limited length, it may be assumed that their characteristics will hardly differ. Withal the consequences of these potential differences will be rather restricted due to the short length of this river reach. Beside the width of the river sections, all other characteristics (i.e. Manning's roughness coefficient and inclination of riverbed and slopes) can be estimated to have the same value. These assumptions were more or less confirmed after a field visit. The width of the river is estimated by comparison with the width of reach 2 (LOR) at satellite photographs (see figure 11.3).

Contrary to the other reaches of the Orange River, there is no weir at the end of the reach 'Douglas - confluence'. Therefore, the downstream boundary condition must be determined by means of fZdownstream forcing variables. First of all, the particular flow series of reach 2 (LOR) must be modelled in the supposition that the Vaal River tributary is absent. This means that the modelling process will be exactly the same as for any other reach. Subsequently, the water depth at the point of the confluence (i.e. 15 300 m downstream

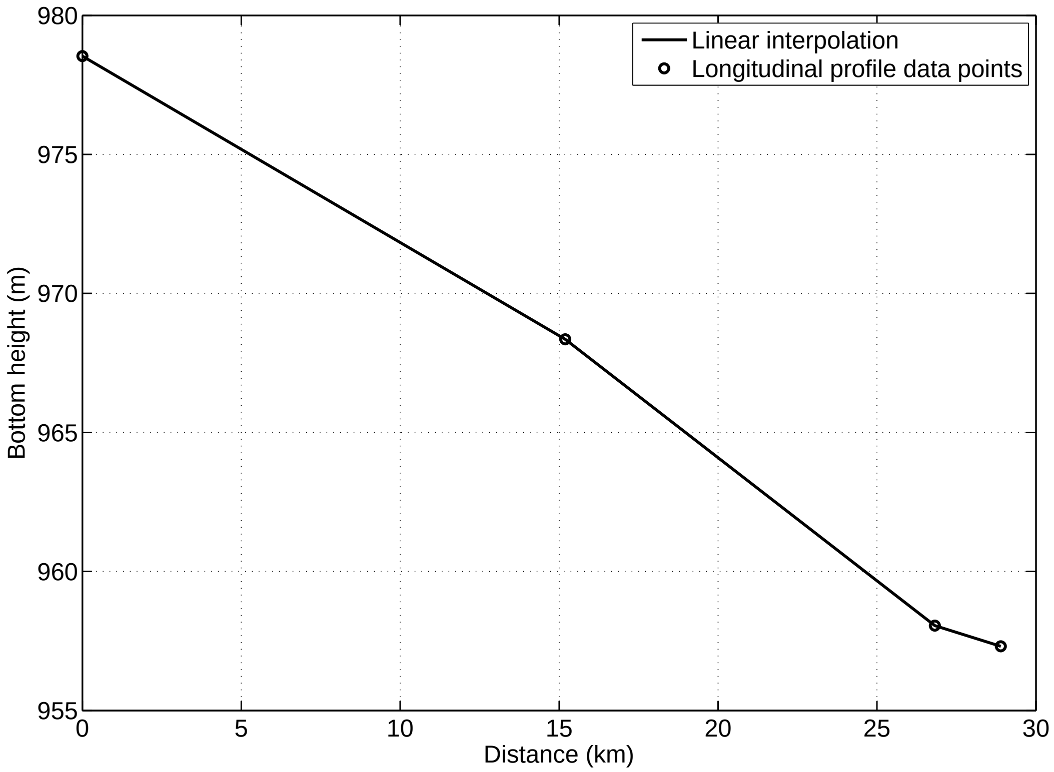


Figure 11.11: Longitudinal profile and linear interpolation (reach 2). Bottom height (m) versus distance (km).

of Marksdrift Weir) is determined by reading the model output. This list of water depth values can be used in the 'Douglas - confluence' model as a forcing variable. The simulated water depths are transformed in a list of fZdownstream values.

At this point, one should be able to run the 'Douglas - confluence' model. Instead of a rating function for the downstream weir, which was used for all other reaches, the downstream water level (i.e. the fZdownstream forcing variables) is now used as a boundary condition for the model. The output of the 'Douglas - confluence' model can for its part now be used as another forcing variable for the ultimate model of reach 2 of the LOR. The downstream discharges (i.e. at the confluence) can be implemented in the STRIVE software by using the forcing variable fSideStream1. These forcing variables are implemented in the 'Model v2.0' by a new developed forcing file, called *douglas_'flowseries'_'year'.frc.* The system

Figure 11.12: Photograph of Douglas Weir: R. McKenzie [167].

constant *Sideriver1*, which represents the node of the confluence, has been fixed at a value of 530.

Logically, the new water depths at the confluence should now be read and used in the next step of an iterative process to come closer to a solution. Nevertheless, it has been found that the exact value of the downstream water level in the 'Douglas - confluence' model hardly affects the propagation of flood waves in the Vaal River. So in practice, estimating the water depth at the confluence (to use as fZdownstream in the 'Douglas - confluence' model) will be sufficient to determine the values for the fSideStream1 forcing variables.

11.5.3 Reach 3: Irene/Katlani - Prieska

The geometric characteristics of this river reach are listed in table 11.3. The longitudinal profile is plotted in figure 11.13. This model will conceptually be the same as that of reach 1, as no specialities can be reported.

Table 11.3: Details on reach 3: Irene/Katlani to Prieska

StreamLength	151 106 m
ZbottomUpstream	957.3 m
ZbottomDownstream	912.5 m
Number of cross sections	5
Number of boxes	1700
Box length	89 m

11.5.4 Reach 4: Prieska - Boegoeberg Dam

Like reach 1 and 3, the fourth river reach is also very common. Table 11.4 contains the features of this part of the river. A linear profile of this reach is shown in 11.14. Boegoeberg Dam (see figure 11.15) is the oldest dam on the LOR. Originally, this construction was built in the 1930's. Due to important accumulations of sediments in the reservoir, the dam lost his function and is nowadays used as a weir providing several irrigation canals with the necessary water amounts.

Table 11.4: Details on reach 4: Prieska to Boegoeberg Dam

StreamLength	116 658 m
ZbottomUpstream	912.5 m
ZbottomDownstream	873.2 m
Number of cross sections	34
Number of boxes	1200
Box length	97 m

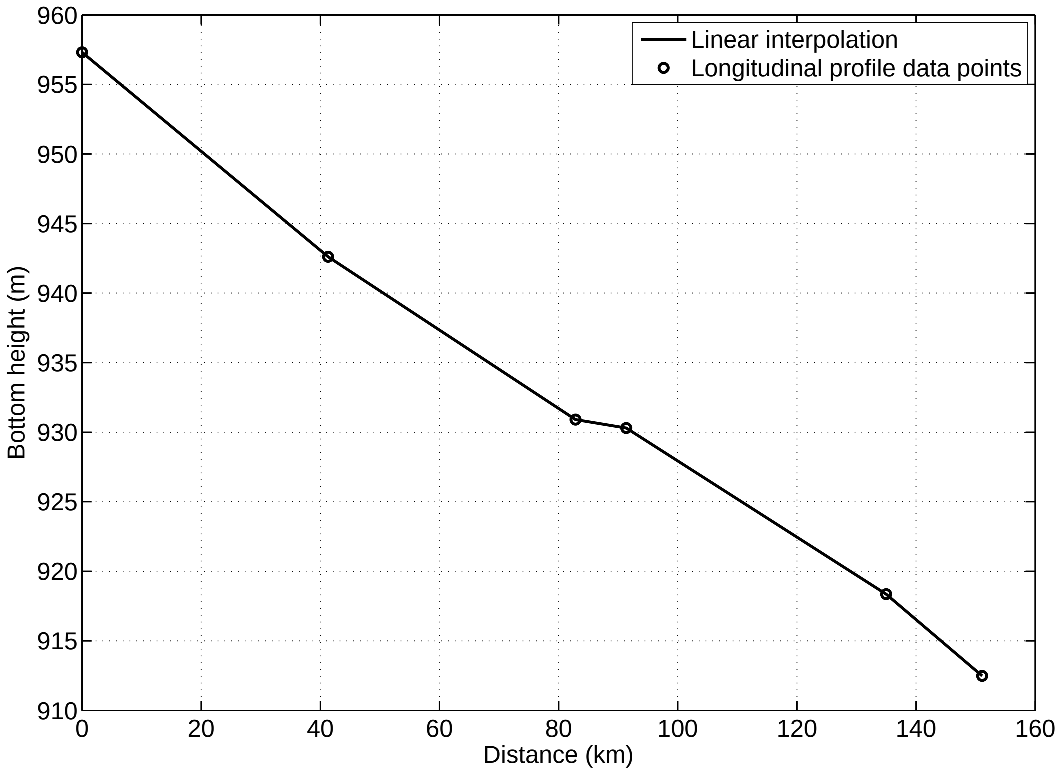


Figure 11.13: Longitudinal profile and linear interpolation (reach 3). Bottom height (m) versus distance (km).

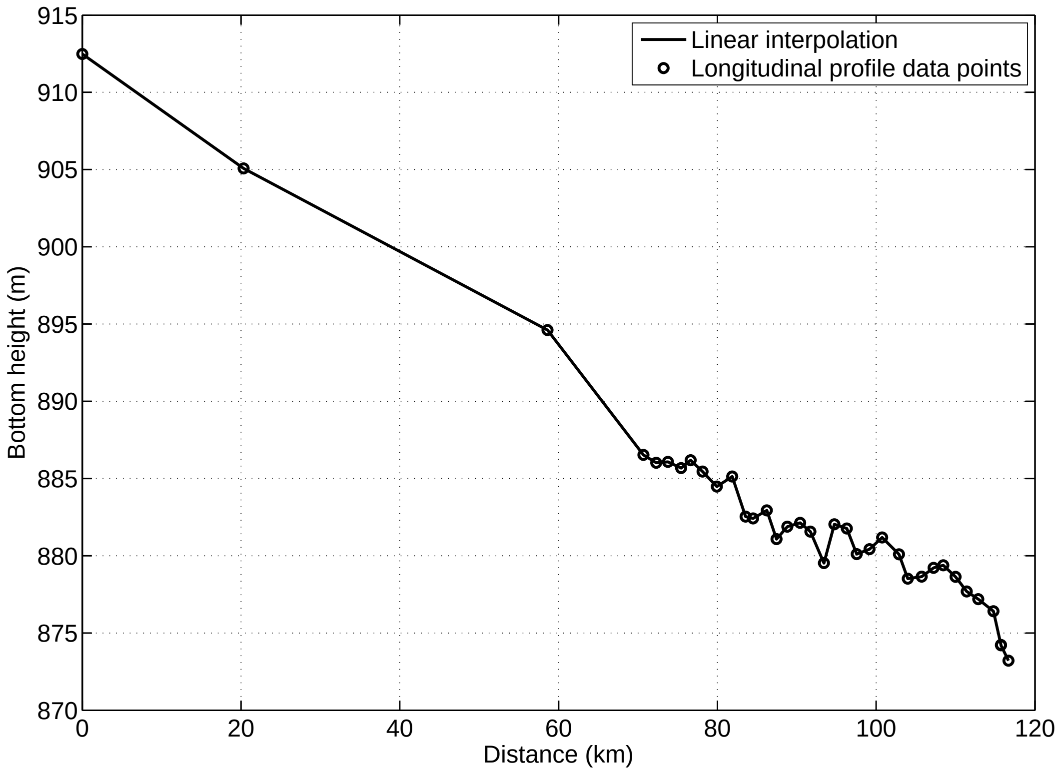


Figure 11.14: Longitudinal profile and linear interpolation (reach 4). Bottom height (m) versus distance (km).

Figure 11.15: Photograph of Boegoeberg Dam: R. McKenzie [167].

11.5.5 Reach 5: Boegoeberg Dam - Upington

Reach 5 is another very common part. Details of this river reach can be found in table 11.5 and on figure 11.16.

Table 11.5: Details on reach 5: Boegoeberg Dam to Upington

StreamLength	163 024 m
ZbottomUpstream	873.2 m
ZbottomDownstream	771.3 m
Number of cross sections	12
Number of boxes	1700
Box length	96 m

11.5.6 Reach 6: Upington - Neusberg Weir

The sixth river reach can be considered as rather short. Features of it are summarised in table 11.5. Figure 11.16 shows the longitudinal profile of this reach.

Table 11.6: Details on reach 6: Upington to Neusberg Weir

StreamLength	70 676 m
ZbottomUpstream	771.3 m
ZbottomDownstream	669.6 m
Number of cross sections	2
Number of boxes	750
Box length	94 m

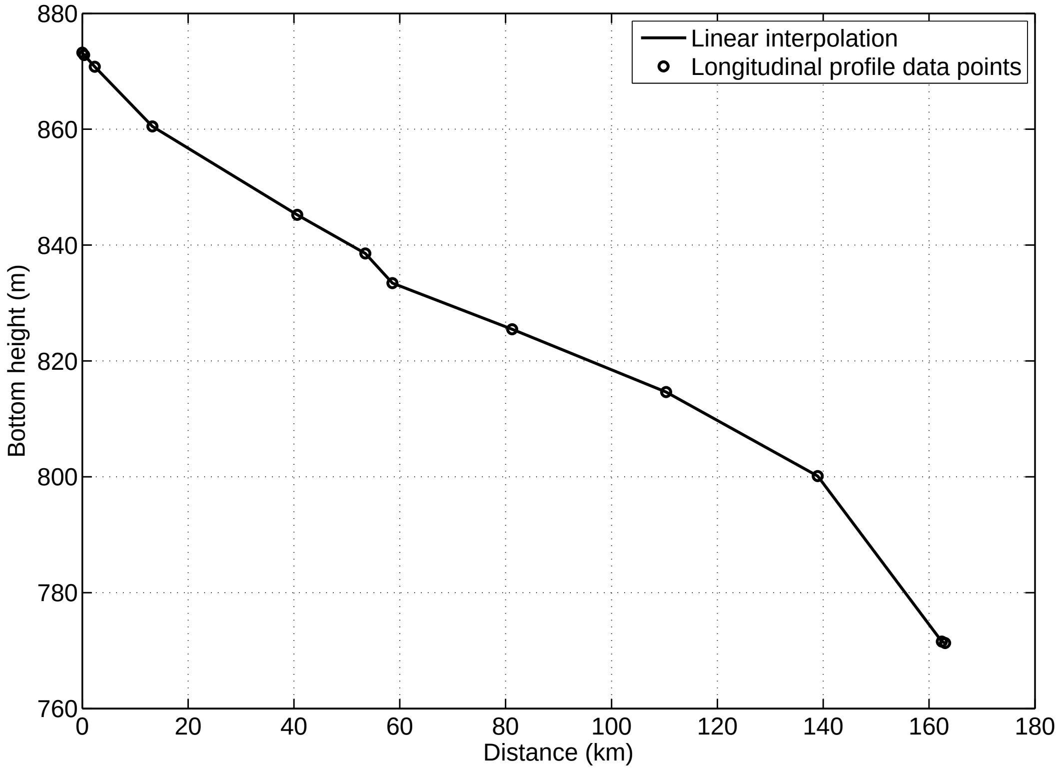


Figure 11.16: Longitudinal profile and linear interpolation (reach 5). Bottom height (m) versus distance (km).

11.5.7 Reach 7: Neusberg Weir - Vioolsdrift Weir

The last reach of 'Model v2.0' of the LOR is situated downstream of Neusberg Weir (near Kakamas). The difference with the previous reaches is the existence of the Augrabies Falls. The important characteristics of reach 7 are listed in table 11.7. The longitudinal profile of this reach is shown in figure 11.18. While all preceding river parts had a rather smooth linear profile, this reach is characterised by a fair-sized shift in altitude.

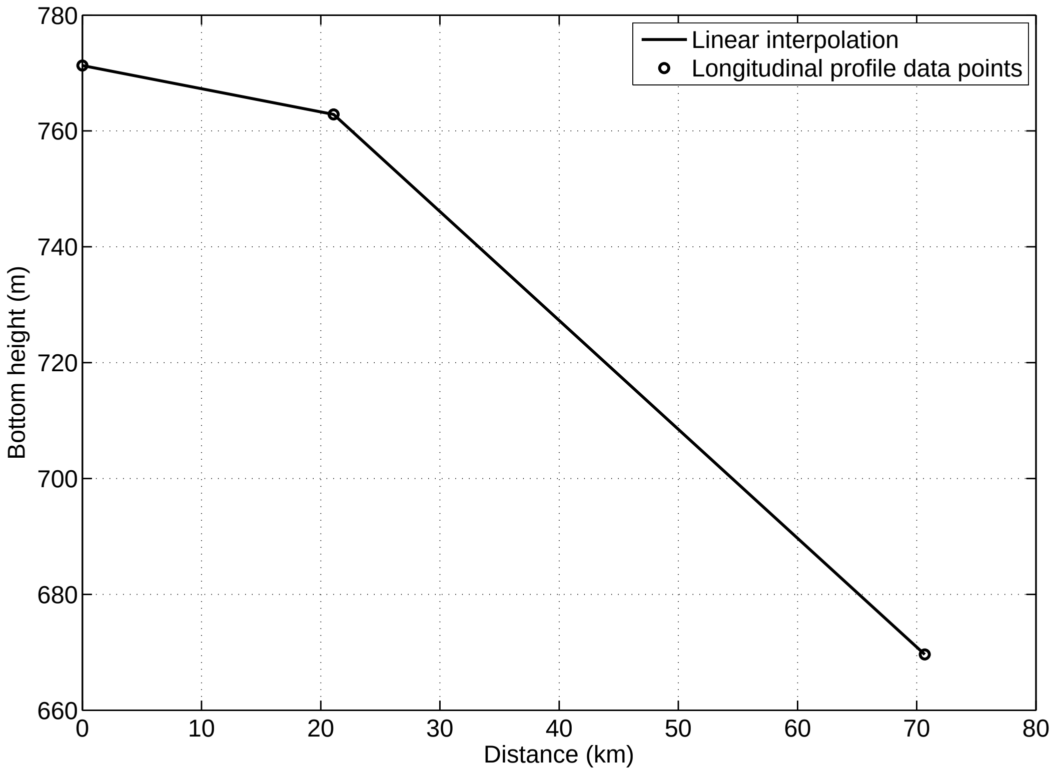


Figure 11.17: Longitudinal profile and linear interpolation (reach 6). Bottom height (m) versus distance (km).

Table 11.7: Details on reach 7: Neusberg Weir to Vioolsdrift Weir

StreamLength	405 000 m
ZbottomUpstream	669.6 m
ZbottomDownstream	153.4 m
Number of cross sections	14
Number of boxes	1700
Box length	238 m

Besides the abstractions for irrigation purposes, important amounts of water are abstracted for urban and industrial requirements. Two big abstraction points are situated along this reach. The first one is the intake tower at Pella (see figure 11.19). This structure abstracts water for the urban demands of the city of Pofadder and for the demands of the large zinc mine at Aggeneys. The second abstraction point is located at Goodhouse. At the Goodhouse pump station (see figure 11.20) water is abstracted and pumped to the cities of Steinkopf, O'Kiep, Springbok and Kleinsee.

As it was already stated above (see section 11.2.2), calculation runs of the hydraulic model can end in a stack overflow due to the abrupt geometry of this river reach. The most simple solution consists of adapting the longitudinal profile. By 'eliminating' the vertical shift, the profile gets smoother and in such a way overflows are avoided. This hypotheses can be set up on the basis that a waterfall has only a local effect on the hydraulics. As the distance between Augrabies and Vioolsdrift is up to 350 km, no noticeable effect may be expected. Now it only remains to be said how exactly the geometry is modified and whether there are any consequences associated with this way of proceeding.

The vertical shift in the geometry can easily be removed. At first, the average longitudinal slope is determined for the second part of the reach, i.e. downstream of Augrabies. Then the first three cross sections (i.e. those upstream of the falls) are lowered in such a way that the average longitudinal slope stays fixed. The new artificial linear profile has no physical meaning, but it helps preventing stack overflows. The modified longitudinal profile is also depicted in figure 11.18.

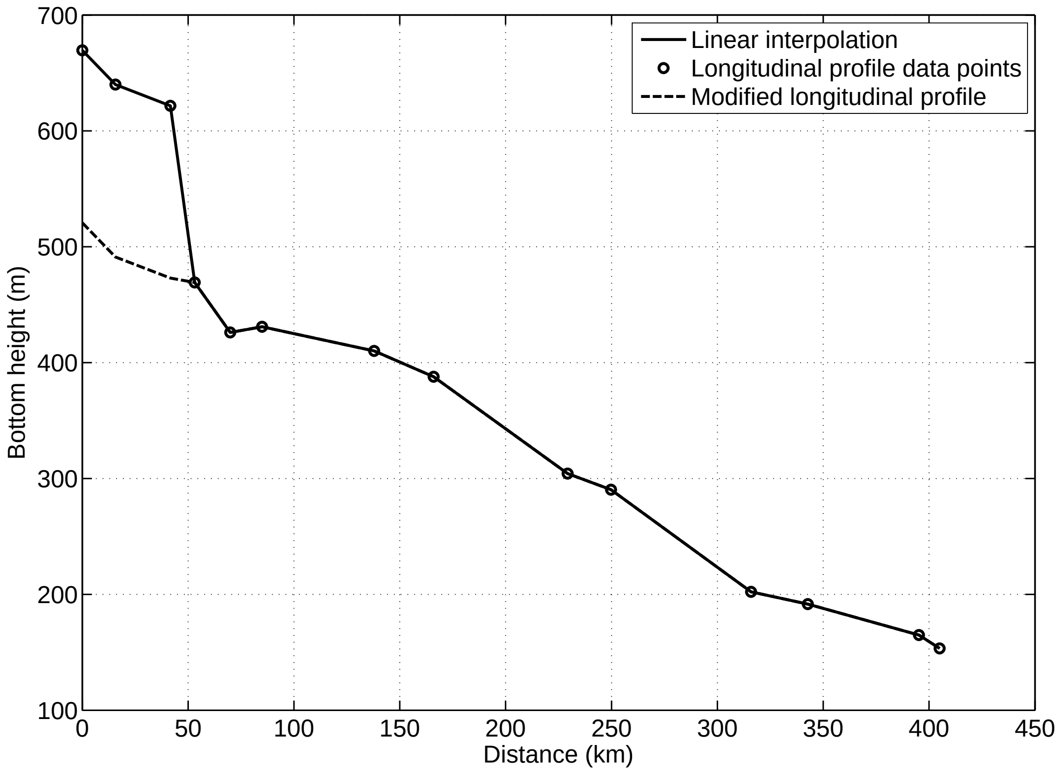


Figure 11.18: Longitudinal profile (real and artificial) and linear interpolation (reach 7). Bottom height (m) versus distance (km).

Figure 11.19: Photograph of the intake structure at Pella: R. Palmer [167].

Figure 11.20: Photograph of the pump station at Goodhouse: R. Palmer [167].

The solution for this difficulty seems very simple. Anyway, as long as this hypothesis is not been proved, it may not be accepted. A typical flow series was used in order to test this adaptation. The flow series, recorded in March and April 2006, didn't turn into a stack overflow when the original geometry was used. Comparison of the two simulated outputs (i.e. one was created with the original geometry, while the other was calculated with the new, artificial one) shows that there is almost no difference (see figure 11.21). This justifies the assumption that was made.

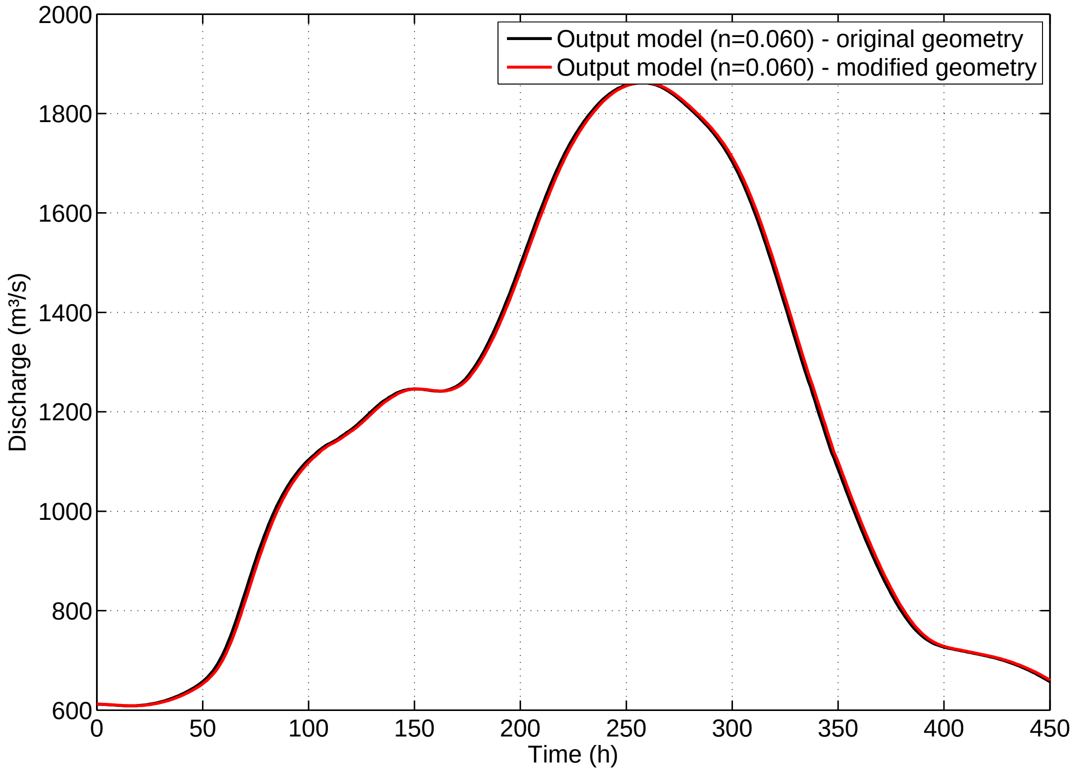


Figure 11.21: The influence of modifying the longitudinal profile (26/03/2006 - 13/04/2006 (series 3_2006)). Discharge (m^3/s) versus time (dd/mm).

11.6 Implementation into the existing STRIVE model

11.6.1 Forcing files

As no loss function could be implemented in 'Model v2.0' due to inaccurate data, not all forcing files of 'Model v1.0' (see section 9.5.1) are necessary. Only two of them will be kept, namely *HourlyFlow_'flowseries'_'year'.frc* and *HourlyMonth_'flowseries'_'year'.frc*. The former still contains the upstream discharges, where the latter is used to select the correct monthly abstraction value in order to deal with the water requirements (see further).

The 'Model v2.0' for reach 2 uses one additional forcing file. *douglas_'flowseries'_'year'.frc* contains a list of the fSideStream1 forcing variables as a function of time. These additional data are needed to deal with the contribution of the Vaal River tributary. Starting from the flow data at Douglas Weir, a method was set up in order to obtain these necessary forcing values (see section 11.5.2). An extract of this forcing file is presented below (see table 11.8). The forcing file under concern contains data for the 2_2006 flow series, recorded during February and March 2006.

Table 11.8: Extract from *douglas_'flowseries'_'year'.frc*

@Variable	**@Time** (s)	**@Value** (m^3/s)
fSideStream1	0	142.764
fSideStream1	3600	141.886
fSideStream1	7200	139.824
fSideStream1	10800	137.151

11.6.2 Parameter files

As it was already explained in chapter 9, these parameter values are fixed values. In other words, they are time-independent and do not vary with the flow series. In fact, only the parameters that define the downstream weir rating curves are implemented in 'Model v2.0'. Each reach has its own set of parameter values, depending on the specific rating functions. These values are mentioned in *Orange_geometry.par*.

11.6.3 Initialisation files

In the framework of this Master thesis, one tries to implement monthly abstractions in the model. These abstraction estimates are obtained in the scope of a study commissioned by DWA [3]. It is recommended to anticipate changes in demand patterns. Moreover, new abstraction points may arise in the future. Therefore, the figures that contain the demands should not be implemented directly in the code. Withal it's preferable to read in these data from external data files.

In order to do so, an additional initialisation file was created. *abstraction.ini* contains the exact locations of the abstraction points. Actually, two types of abstractions exist: a point abstraction (i.e. the abstraction occurs in a fixed point) and a diffuse abstraction (i.e. the abstraction occurs uniformly over a specified interval). Two new variables were declared (see section 11.10). An example of an initialisation file is shown in table 11.9. These .ini-files are only used to determine the exact locations of abstraction. The abstraction amounts will be read in afterwards so as to stipulate how much water may be abstracted in each point or interval (see section 11.6.4).

The first variable *pointabs* indicates where point abstractions occur along the considered reach. Starting upstream at a value of 0, the variable is increased by unity if the following abstraction point is reached. Referring to the example shown in table 11.9, four abstraction points are determined. These points are located at 13 710 m, 225 090 m, 328 920 m and 405 000 m respectively from the upstream weir (i.e. Neusberg Weir in this particular example). At the downstream weir of any reach, abstractions may be expected. No matter how, if this does not apply in a specific case, a text line should be added to the initialisation file. After the last abstraction point, a line will be added with following information: '*pointabs*' - 'stream length of reach' - 'value'. The value that needs to be added, equals to the value of *pointabs* in the preceding line. In the example of table 11.9, the '4' on the 5th line,

Table 11.9: *abstraction.ini* of reach 7

@Variable	**IntDistanc** (m)	**@Value**
pointabs	0	0
pointabs	13 710	1
pointabs	225 090	2
pointabs	328 920	3
pointabs	405 000	4
diffabs	0	1
diffabs	50 610	1
diffabs	50 611	2
diffabs	94 820	2
diffabs	94 821	3
diffabs	225 090	3
diffabs	225 091	4
diffabs	328 920	4
diffabs	328 921	5
diffabs	405 000	5

corresponding with the fourth abstraction point of this reach, should be replaced by '3', the previous *pointabs* value, if no abstraction would occur at Vioolsdrift Weir. If not even one abstraction point exists along a river reach, this value should logically be set to '0'.

Secondly, the variable *diffabs* indicates the length of an interval over which a uniform abstraction takes place. As it can be seen in table 11.9, the first interval (beginning at the upstream weir of the reach) starts with value '1'. Both start and end point of the interval have the same value. Diffuse abstractions are always occurring, as evaporation losses must always be considered.

This .ini-file is only used to determine the exact places of abstraction, no matter whether these are point or diffuse abstractions. The abstraction amounts will be read in afterwards in order to determine how much water may be abstracted in each point or interval.

11.6.4 Abstraction files

Starting from monthly water requirements (see [3]), these abstractions are transformed to m^3/s-values. These monthly abstraction values are stored in separate files. Two kind of abstraction files exist: *point_ 'number' .txt* and *diffuse_ 'number' .txt*. Referring to the example that was used in table 11.9 to explain the function of the *abstraction.ini* file, there exist 4 files of the former type and 5 of the latter.

The content of the abstraction files exists of 12 values of abstraction amounts, each for one month, from January to December. These values are only separated by a comma. In the *point_ 'number' .txt* files 12 abstractions (m^3/s) are stored, while in the *diffuse_ 'number' .txt* files, twelve diffuse abstractions (m^3/s·m) are listed.

11.6.5 Variables

'Model v2.0' tries to take the water requirements of several users into consideration (see section 11.4). In order to be able to incorporate these water demands, some variables need to be declared. As it was already explained in chapter 9, these variables have been declared as ordinary variables, which means that they do only occur within the model, so they do not require any input. The variables are described in table 11.10.

Table 11.10: Variables added to the TransWater module

Variable name	**Description**
monthnumber	Reads the forcing parameter fMonth for the current time step
monthlylosspoint	Abstracted discharge (m^3/s) in case of a point abstraction
monthlylossdiffuse	Abstracted discharge (m^3/s·m) in case of a diffuse abstraction
pointabs(NoI)	Variable used to determine whether a point abstraction occurs in node I
diffabs(NoI)	Variable used to determine which diffuse abstraction occurs in node I
subtractpointabs	Variable used to determine the exact node of a point abstraction
prevdiffabs	*diffabs* value of the previous node

11.6.6 Abstractions as programmed in Fortran

The structure and syntax of the abstractions are described in the following frames. Just like in chapter 9, the developed Fortran code has been split up into several components in order to allow a clear description and understanding of each part.

```
DO I=1, NoI
pointabs(I)=0
ENDDO
prevdiffabs=0
```

At First, the new variables are initialised in the InitialiseTransWater subroutine. This initialisation process is only performed once, that is before the evaluation of time step 0.

```
DO I=1, NoI-1
IF (pointabs(I) .NE. nint(pointabs(I))) THEN
subtractpointabs=floor(pointabs(I+1))-floor(pointabs(I))
IF (subtractpointabs .GT. 0) THEN
IF (pointabs(I+1)-FLOOR(pointabs(I+1)) .GE. floor(pointabs(I+1))-pointabs(I)) THEN
pointabs(I)=floor(pointabs(I+1))
ELSE
pointabs(I+1)=floor(pointabs(I+1))
pointabs(I)=0
ENDIF
ELSE
pointabs(I)=0
ENDIF
ENDIF
ENDDO
```

This part of the code is also used in the initialisation phase, but only after reading initial conditions and forcing function files (i.e. the .ini and .frc files). Therefore, these commands should be added to the InitialiseTransWater2 subroutine (i.e. this part is only performed once, that is before time step 0). The operator .NE. can be read as 'does not equal'. Operators .GT. and .GE. mean 'is greater than' and 'is greater than or equals' respectively.

These commands check whether an abstraction point is located between two nodes. If so, the model assigns the abstraction point to the nearest node, a '0' is assigned to the other node. On the other hand, when no abstraction point occurs, also a '0' is assigned. The command line *IF (pointabs(I) .NE. nint(pointabs(I)))* prevents that an assigned abstraction point should be overwritten with a '0' in the next step (i.e. when the next box is evaluated).

```
character(20) :: numstr
character(60) :: parname
REAL :: jan
REAL :: feb
REAL :: mar
REAL :: apr
REAL :: may
REAL :: jun
REAL :: jul
REAL :: aug
REAL :: sep
REAL :: oct
REAL :: nov
REAL :: dec
```

From now on, all additional codes should be added to the DynamicsTransWater subroutine. Two text variables and 12 real numbers are declared. The two text variables are used to read in the correct abstraction files *point_ 'number' .txt* and *diffuse_ 'number' .txt*. The content of these files (i.e. the monthly water demands) is stored in the 12 declared numbers.

```
DO I=1, NoI
IF (pointabs(I) .GT. 0) THEN
write(numstr,'(i5)') nint(pointabs(I))
parname='data\\point_'//numstr//'.txt'
open (unit=1, file=parname)
read (1,*) jan,feb,mar,apr,may,jun,jul,aug,sep,oct,nov,dec
close (1)
```

This part of the code reads in the abstraction data, in case of point abstractions. For all 12 months, the corresponding discharges that need to be abstracted are read in.

monthnumber=fmonth
IF (monthnumber .EQ. 1) monthlylosspoint=jan
IF (monthnumber .EQ. 2) monthlylosspoint=feb
IF (monthnumber .EQ. 3) monthlylosspoint=mar
IF (monthnumber .EQ. 4) monthlylosspoint=apr
IF (monthnumber .EQ. 5) monthlylosspoint=may
IF (monthnumber .EQ. 6) monthlylosspoint=jun
IF (monthnumber .EQ. 7) monthlylosspoint=jul
IF (monthnumber .EQ. 8) monthlylosspoint=aug
IF (monthnumber .EQ. 9) monthlylosspoint=sep
IF (monthnumber .EQ. 10) monthlylosspoint=oct
IF (monthnumber .EQ. 11) monthlylosspoint=nov
IF (monthnumber .EQ. 12) monthlylosspoint=dec
ELSE
monthlylosspoint=0
ENDIF

For each time step of the calculation, the current month is read from the fMonth forcing variable and this value is stored in the variable *monthnumber*. The current *monthnumber* defines which value for the variable *monthlylosspoint* has to be used. This defines an abstraction discharge (m^3/s). The operator .EQ. can be read as ‘equals’.

```
IF (diffabs(I) .GT. 0 .AND. diffabs(I) .NE. prevdiffabs) THEN
write(numstr,'(i5)') floor(diffabs(I))
parname='data\\diffuse_'//numstr//'.txt'
open (unit=2, file=parname)
read (2,*) jan,feb,mar,apr,may,jun,jul,aug,sep,oct,nov,dec
close (2)
```

The diffuse abstraction data are read in, just as was done before in case of point abstractions. The monthly discharges are read in. As reading data from the *diffuse_ 'number' .txt* files takes a while, the total calculation time would increase noticeably. Therefore, the reading procedure takes place only when necessary. If the diffuse abstraction file was already read in at the previous node, then this value will be used (i.e. the previous *monthlylossdiffuse* value is still stored in the memory) instead of reading in this abstraction discharge again. In this way, the model gains efficiency as the total calculation time is reduced.

```
monthnumber=fmonth
IF (monthnumber .EQ. 1) monthlylossdiffuse=jan
IF (monthnumber .EQ. 2) monthlylossdiffuse=feb
IF (monthnumber .EQ. 3) monthlylossdiffuse=mar
IF (monthnumber .EQ. 4) monthlylossdiffuse=apr
IF (monthnumber .EQ. 5) monthlylossdiffuse=may
IF (monthnumber .EQ. 6) monthlylossdiffuse=jun
IF (monthnumber .EQ. 7) monthlylossdiffuse=jul
IF (monthnumber .EQ. 8) monthlylossdiffuse=aug
IF (monthnumber .EQ. 9) monthlylossdiffuse=sep
IF (monthnumber .EQ. 10) monthlylossdiffuse=oct
IF (monthnumber .EQ. 11) monthlylossdiffuse=nov
IF (monthnumber .EQ. 12) monthlylossdiffuse=dec
ELSE IF (diffabs(I) .EQ. 0) THEN
monthlylossdiffuse=0
ENDIF
```

Just like the determination of the point abstractions, the diffuse abstractions are defined by the current *monthnumber*. The variable *monthlylossdiffuse* expresses an abstraction discharge per unit of length (m^3/s·m).

```
prevdiffabs=diffabs(I)
qlat(I)=monthlylossdiffuse+(monthlylosspoint/(StreamLength/NoB))
ENDDO
```

The value of *diffabs(I)* is stored in the *prevdiffabs* variable to use in the next step of the calculation. Finally, the amount of water that is abstracted from the river is evaluated for node I. This abstraction is defined as a lateral, diffuse abstraction spread over an interval of 1 box length. This abstraction *qlat(I)* is determined for each node. The unit of *qlat* is m^3/s·m.

Chapter 12

Model evaluation - part 2

12.1 Introduction

In this chapter, the calibration and validation processes for ‘Model v2.0’ (see chapter 11) are discussed. Presenting a huge amount of flow series would not add any surplus value to this report. Therefore, it isn’t useful to describe the whole process for all reaches. Calibration and validation runs are described for only one reach, viz reach 3 (Irene/Katlani - Prieska). The method is actually the same for all reaches, so it will be sufficient to go through the process only once.

The model will be calibrated and validated for the different reaches in order to find a more or less correct value for the Manning’s roughness coefficient. Again, a range of roughness coefficients is chosen in accordance with the value that was used in the model of the Danish Hydraulic Institute (DHI), using MIKE 11 [154]. For reach 3, a Manning value of 0.026 was used in the MIKE 11 model. Just like in chapter 10, three runs are used for the calibration of this river reach while afterwards two more runs are used as validation.

One has to keep in mind that ‘Model v2.0’ was created so as to predict flow patterns rather than exact discharges, due to the inaccurate gauging data. So, vertical shifts between the recorded data and the model results can be expected in the following plots. It’s rather important to choose a correct value for the roughness. In this way, time shifts of floods could be well predicted.

Both calibration and validation of ‘Model v2.0’ were executed for all 7 reaches. At the end of this chapter, the results of calibration and validation processes will be presented. All output files that were used to determine the Manning's roughness coefficients are available on the DVD attached to this report (see chapter 16).

12.2 Calibration process

12.2.1 First calibration run (3_2006 - March until April 2006)

The first flow series contains a flood where discharges reached up to 2000 m^3/s. This flood took place in the autumn of 2006. Keeping in mind that the flow measurements at the upstream and downstream weir are labelled as 'inaccurate', it may be expected that the model results won't be extremely satisfying. Nonetheless, the results were surprisingly good in this case. The different outputs for the 3_2006 series are shown in figure 12.1.

The influence of the Manning's roughness coefficient is hard to see in figure 12.1. Therefore, more detailed zooms of the above period are plotted (see figures 12.2 and 12.3) to emphasise the differences according to different Manning values.

According to figure 12.2, a value of 0.036 (or even a little bit higher) would be chosen for the Manning's roughness coefficient. Figure 12.3 shows that a value of 0.036 is acceptable.

12.2.2 Second calibration run (8_2006 - September 2006)

For this run (see figure 12.4), the effect of the non-existence of a flood loss function in 'Model v2.0' can clearly be seen. Between the recorded data and the calculated values, there exists a difference of almost 50 m^3/s during the flood event. The differences between the different roughness coefficients are rather small. Anyway, a value of 0.032 seems to give the best result, especially in the first hours of this record.

12.2.3 Third calibration run (10_2006 - Octobre 2006)

The absence of a function that deals with flood related losses, is also noticeable in the last calibration run (see figure 12.5). A certain shift between record and result can be observed. In spite of this vertical shift, the output of the model is almost exactly the same as the recorded flow pattern. A Manning's roughness coefficient of 0.032 leads to nearly perfect results, when denying the vertical shift of course.

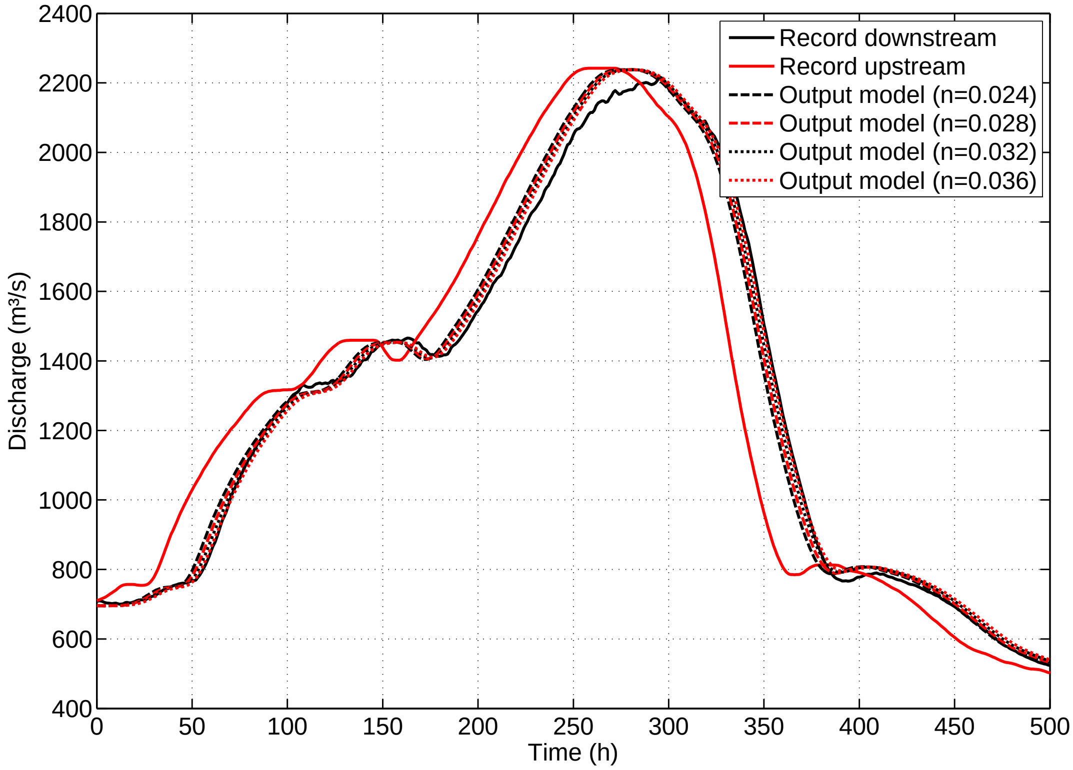


Figure 12.1: Influence of Manning's roughness coefficient (21/03/2006 - 10/04/2006 (series 3_2006)). Discharge (m^3/s) versus time (h).

12.2.4 Conclusion

From the three previous calculations, it may be clear that a value of 0.032 for the roughness coefficient will be the best choice.

12.3 Validation process

12.3.1 First validation run (4_2006 - April until May 2006)

The results of the first validation run for the third reach are prove that 0.032 was a good choice for the Manning's roughness coefficient (see figure 12.6). The differences in

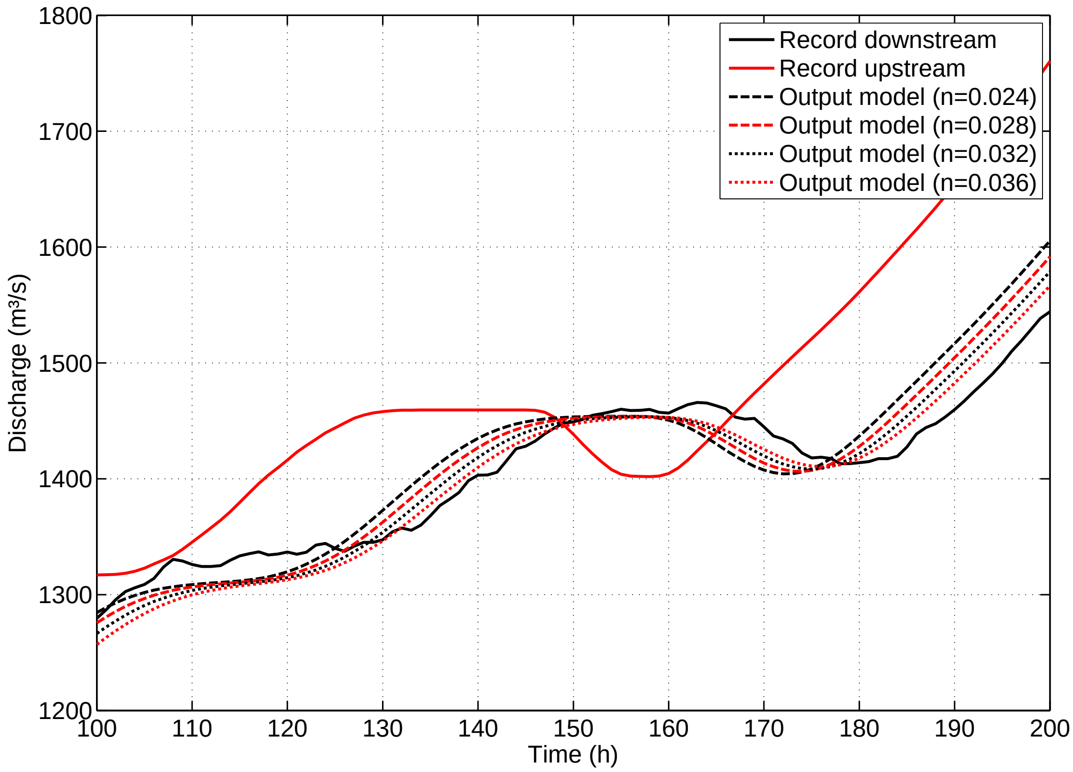


Figure 12.2: Influence of Manning's roughness coefficient (21/03/2006 - 10/04/2006 (series 3_2006)). Discharge (m^3/s) versus time (h).

discharges between measurements and calculations are rather small (i.e. more or less 10 m^3/s).

12.3.2 Second validation run (11_2006 - November until December 2006)

The second run took place in the summer of 2006. A period of almost 2 month was modelled. Despite a constant vertical shift between the recorded data and the model results, the output is very satisfying (see figure 12.7). No time shift could be noticed for this flow series.

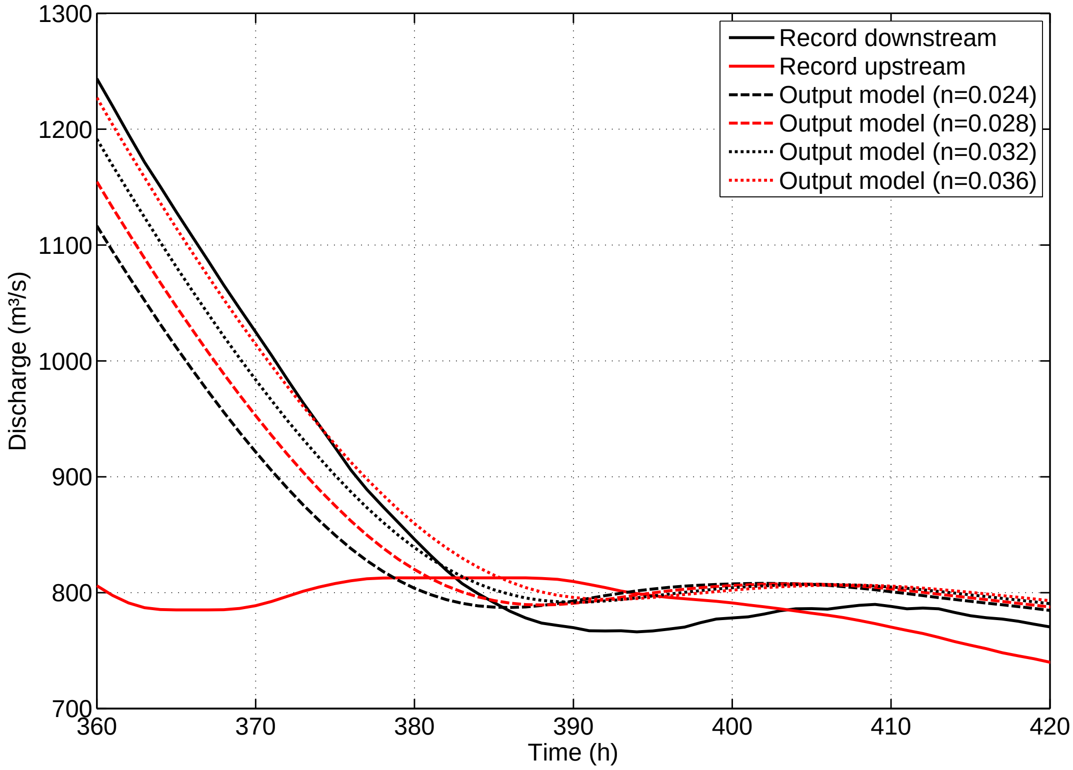


Figure 12.3: Influence of Manning's roughness coefficient (21/03/2006 - 10/04/2006 (series 3_2006)). Discharge (m^3/s) versus time (h).

12.3.3 Conclusion

A value of 0.032 for the Manning's roughness coefficient seemed to be a very good estimation. Taking the restrictions of 'Model v2.0' into consideration, the results of the examined flow series were acceptable.

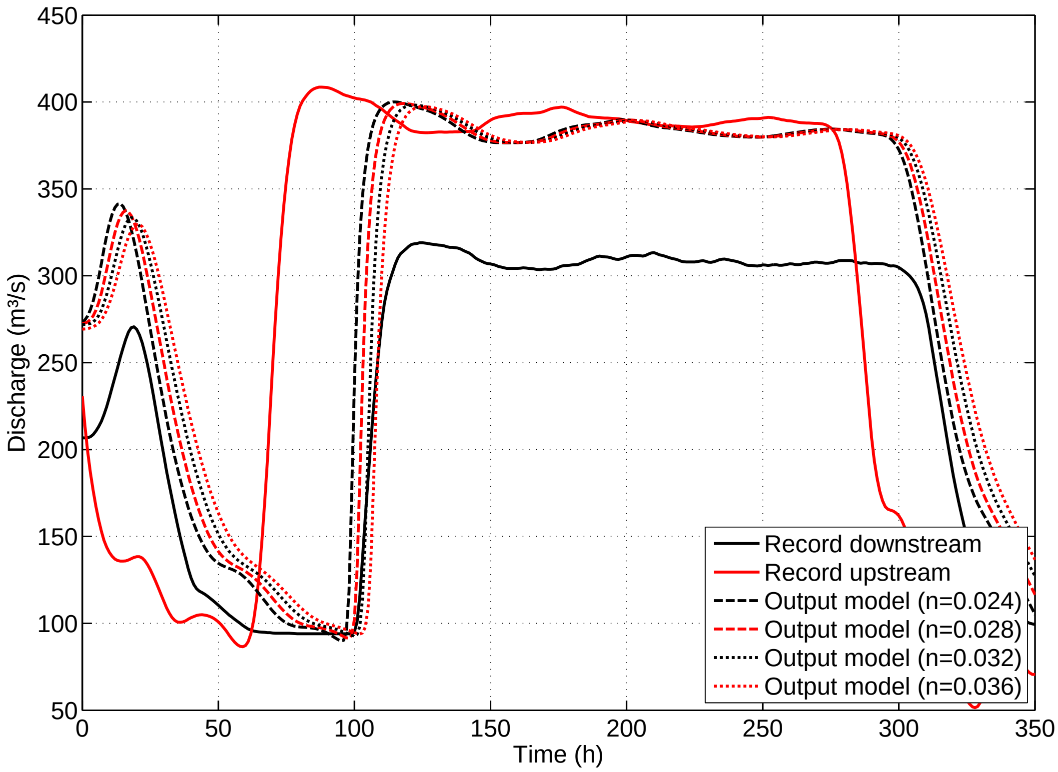


Figure 12.4: Influence of Manning's roughness coefficient (01/09/2006 - 15/09/2006 (series 8_2006)). Discharge (m^3/s) versus time (h).

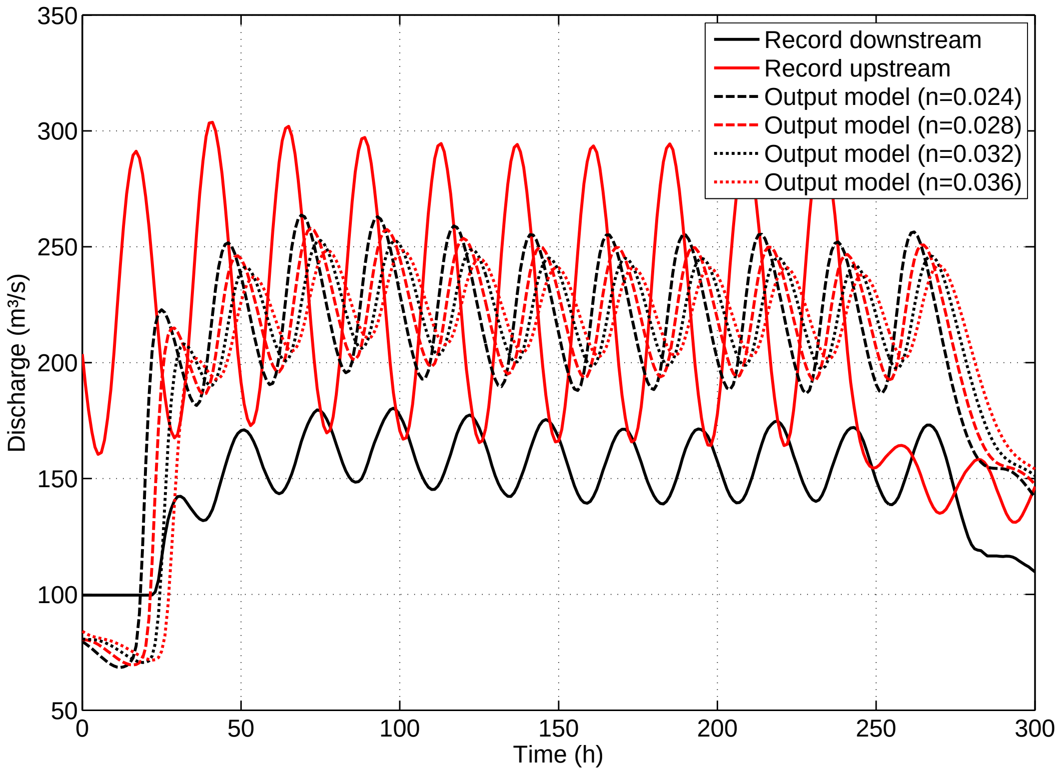


Figure 12.5: Influence of Manning's roughness coefficient (07/10/2006 - 19/10/2006 (series 10_2006)). Discharge (m^3/s) versus time (h).

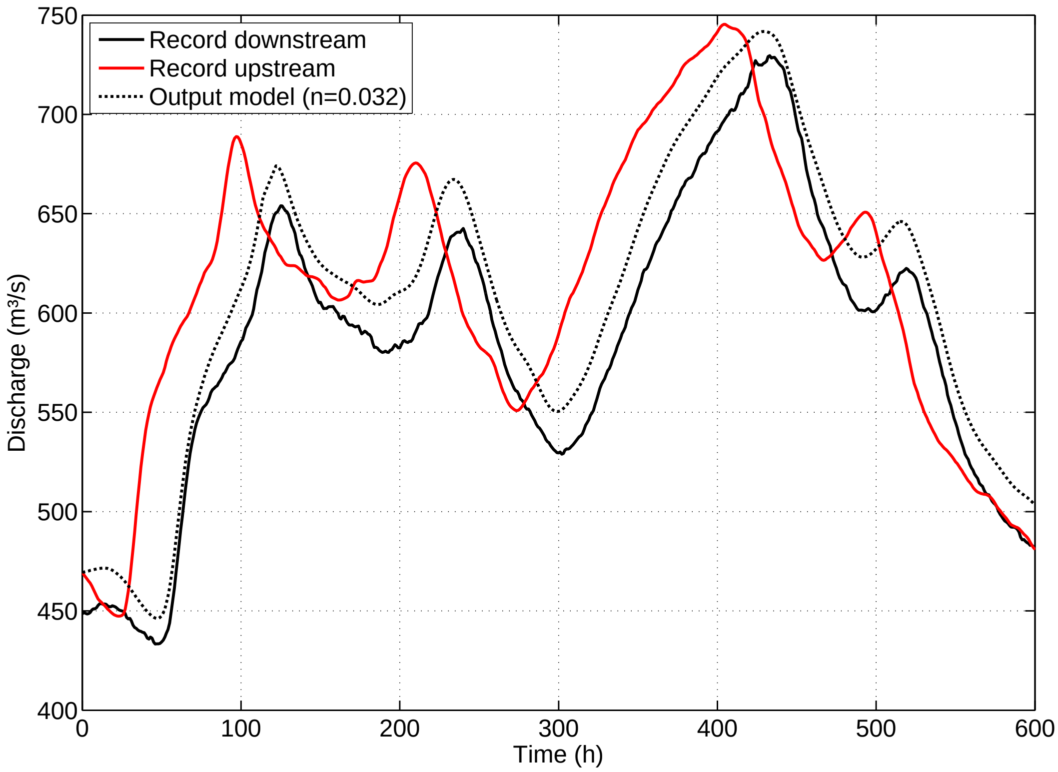


Figure 12.6: Result of the first validation run (15/04/2006 - 09/05/2006 (series 4_2006)). Discharge (m^3/s) versus time (h).

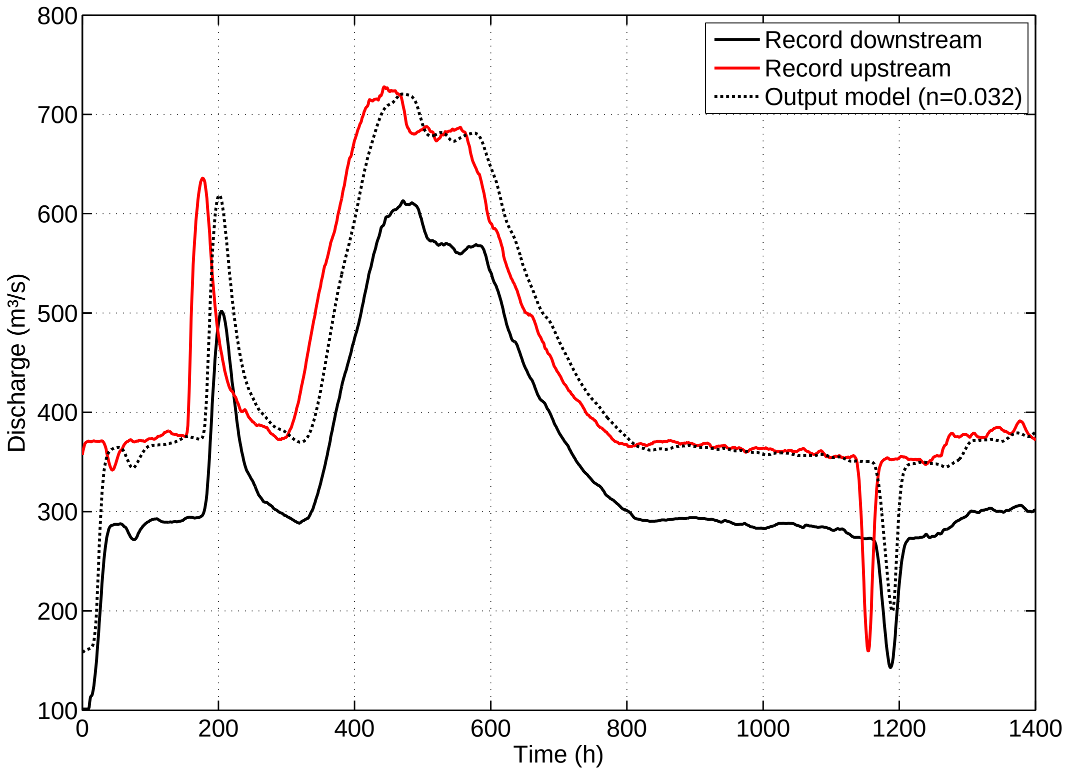


Figure 12.7: Result of the second validation run (30/10/2006 - 27/12/2006 (series 11_2007)). Discharge (m^3/s) versus time (h).

12.4 Overview of the different reaches

For each reach, calibration and validation runs were executed to test the 'Model v2.0' on one hand and to determine the values for the Manning's roughness coefficient on the other hand. The results are listed below in table 12.1. All output files of the calculated flow series are available on the DVD (see chapter 16).

Table 12.1: Outline of the different reaches

Reach number	**Upstream weir - downstream weir**	**Manning value**
1	Dooren Kuilen - Marksdrift Weir	0.040
2	Marksdrift Weir - Irene/Katlani	0.024
3	Irene/Katlani - Prieska	0.032
4	Prieska - Boegoeberg Dam	0.024
5	Boegoeberg Dam - Upington	0.036
6	Upington - Neusberg Weir	0.080
7	Neusberg Weir - Vioolsdrift Weir	0.048

Chapter 13

Conclusion concerning the hydraulic modelling of the Lower Orange River

13.1 Model v1.0

This model is applicable for the first reach of the Lower Orange River (i.e. Dooren Kuilen - Marksdrift). As the flow measurements on this reach are quite accurate, it is possible to estimate the losses quite exactly. A mathematical function is implemented in this model. This function takes rainfall, losses and flood events into consideration. The model can detect rainfall and floods itself. Therefore, some thresholds were defined. These parameters can easily be changed in the *Orange_latinflow.par* file if this should be necessary.

The results of this model are very satisfactory, especially the loss function leads to good results. The Manning's roughness coefficient was used to calibrate the model. This calibration process showed clearly that this coefficient varies with discharge and obviously also with other variables. This is an issue that should be examined more in the future.

13.2 Model v2.0

As the gauging data of most of the weirs on the Lower Orange River can be estimated as inaccurate under low-flow conditions, 'Model v1.0' can not be used for other reaches. Despite the good results of 'Model v1.0', it was essential to build a new model. This model is by far less accurate than the former model, as it uses inaccurate flow data. Moreover, a similar loss function as in 'Model v1.0' couldn't be built.

Monthly water demands for several users were implemented in the system, to replace the loss function that could not longer be used. Monthly water abstractions (i.e. for irrigation, urban demands, losses, environmental requirements) where implemented to take place along the Lower Orange River.

The 'Model v2.0' is of course less usable, in comparison with 'Model v1.0', as an exact management tool. This model is not able to predict exactly the discharges and water levels along the river. Nonetheless, it can forecast how flow patterns will propagate through the riverbed. Despite of the inaccurate flow data, this model is not devaluated concerning the prediction of time shifts between dam releases and abstractions.

Chapter 14

Recommendations for further research

This Master thesis is conceived as the first volume of a future series. Due to the large amount of data, articles and reports gathered in the framework of this study it seemed not feasible to process all data in a proper way in the scope of this Master thesis. However, the research on the topics broached in this report has been completed. This creates a chance for future last-year students to continue the research without having to deal with unfinished fragments of research. On the contrary, the authors want to provide a solid basis for further research by recommending some meaningful ideas for future research activities.

This Master thesis is subdivided in 2 main parts. The first part describes aspects related to IWRM. The second part deals with the development of a numerical model for the Lower Orange. Although both parts have been initiated in the framework of this study, work still needs to be done.

This chapter describes the opportunities for further research. These include fine-tuning and future extensions of the numerical model, compliance to the Ecological Reserve, new infrastructure in the Orange River, water management procedures and the continuation of the evaluation of IWRM.

Further research may benefit from additional flow data available in the future. Flow data can be requested (for free) via e-mail at the DWA office in Pretoria. The contact details of the person in charge of the flow database are added to the DVD attached to this report (see chapter 16).

14.1 Calibration of Manning's coefficient

In chapters 10 and 12 the hydraulic model is calibrated. The Manning's roughness coefficient was adjusted so as to obtain a best match between the simulated and the recorded hydrogram. In particular, the Manning's coefficient was used to make remarkable events (e.g. floods, peaks and drops of the discharge) of both simulated and recorded hydrogram correspond with the same point on the time axis. The hydraulic model developed in the framework of this study does not take into account the variability of the Manning's coefficient, neither in time nor according to discharge or water level. In section chapters 10 and 12 it was concluded that higher Manning's coefficients are suitable for high discharges and flood events, while lower values are more suitable during 'normal' flow conditions. Higher water levels result in a higher flow resistance as the river banks and its vegetation (e.g. reeds) become part of the flow channel. This is illustrated by figure 14.1, representing the last 100 hours of the 1_2009 flow series (February and March 2009). The first 50 hours of the hydrogram are characterised by higher discharges than would normally occur. A Manning's coefficient of 0.048 is most suitable. At lower (i.e. normal) discharges, 0.032 or 0.036 seems to yield the best results.

It is obvious that the Manning's roughness coefficient is a function of the present water level. The interdependence of water level and Manning's coefficient needs to be thoroughly analysed during further research, so as to improve the accuracy of the hydraulic model. A function relating the Manning's coefficient to the water level should be developed and consequently implemented into the code of the model. Although part of the recorded flow data is not very accurate, this kind of fine-tuning of the hydraulic model is practically feasible as the occurrence of remarkable flow events (e.g. floods, peaks and drops of the discharge) still can be linked to a point in time. One should compare the exact moments of the occurrence of remarkable flow events so as to improve the calibration of the hydraulic model.

Seasonal macrophyte growth is known to largely influence Manning's roughness coefficients in some rivers [160]. Although the authors have no further information on the occurrence of this phenomenon in the Orange River, the (possible) occurrence of this phenomenon needs to be investigated, and, if necessary, implemented into the model.

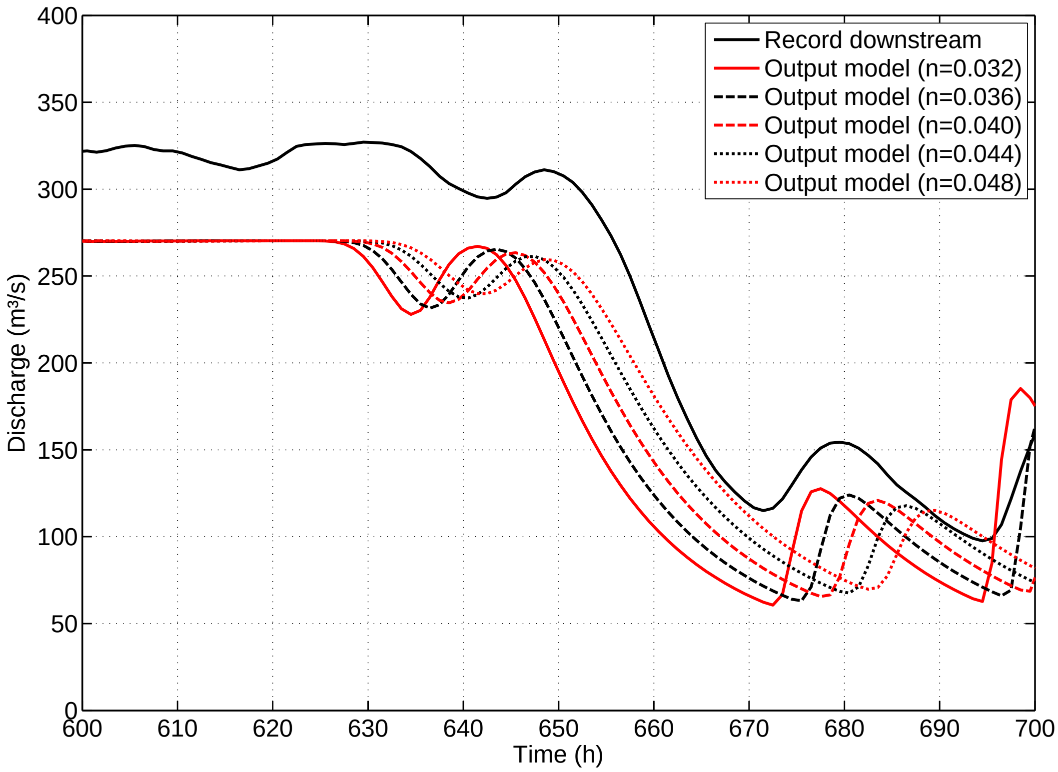


Figure 14.1: Influence of Manning's roughness coefficient on the simulated hydrogram (reach 1, March 2009). Discharge (m^3/s) versus time (h).

14.2 Compliance to the Ecological Reserve

The implementation of the new National Water Act provides a legal base for new water management policies in South Africa. Part of this legislation refers to the need to ensure that the requirements for both basic human needs and the environment are met before potential users can be licensed to abstract water. These two requirements are referred to as the 'Basic Human Needs Reserve' and the 'Ecological Reserve'. Quantifying the Ecological Reserve is about determining the water quantity and quality requirements of rivers, estuaries and wetlands in order to ensure that they are sustained in a pre-determined condition. This pre-determined condition is referred to as the ecological management class (EMC) and is related to the extent to which the required condition differs from the pristine conditions. There are four main classes (A to D), where A refers to a condition that is largely natural, while D assumes a largely modified condition where there is a large loss of natural habitat, biota and basic ecosystem functioning. The EMC which should be aimed for is determined by a political decision depending on stakeholder interaction [170].

In order to achieve the EMC goals, one should be able to translate the desired ecological status to practical operational management procedures. The concept of instream flow requirements (IFR) fulfils this task. For each EMC, a set of instream flow requirements can be created. The resulting IFR values impose restrictions on flow volumes and flow variability so as to establish hydrological conditions resulting in the desired ecological status. Several methods have been developed in order to determine instream flow requirements. The Desktop approach is a low-cost method, used for quick assessment of IFR. The Desktop approach is almost completely based upon the hydrological characteristics of rivers and the biotic component is included through a series of (fairly subjective) parameters. The Desktop approach should be interpreted as a preliminary, low-confidence approach which nevertheless gives the initial impetus to a sound operational management. The basic principle is that the modified flow regime designed to fulfil the requirements of the reserve should reflect the natural flow regime, as hydrological variation is a primary driving force within riverine ecosystems [170].

The IFR concept is illustrated by figure 14.2 and figure 14.3. The instream flow requirements are represented for quaternary catchment D82L (Orange River mouth) for management classes C, CD and D. Depending on whether it is a drought ('without high flows') or a normal year ('with high flows'), the appropriate distribution of monthly averaged discharges is depicted. A hydrological year is classified normal or drought according to the recorded flow volumes.

This kind of IFR data is available for all the quaternary catchments along the Lower Orange River, and has been added to the DVD attached to this report (see chapter 16). This data can be used for further research, in order to:

- Assess the evolution of hydrological conditions and the related ecological impact consequent to different stages of river regulation;
- Determine the shortcomings of the current flow regime in relation to the environmental condition associated with the different management classes;
- Suggest a more environmentally sound flow pattern, taking into account the requirements of the different stakeholders.

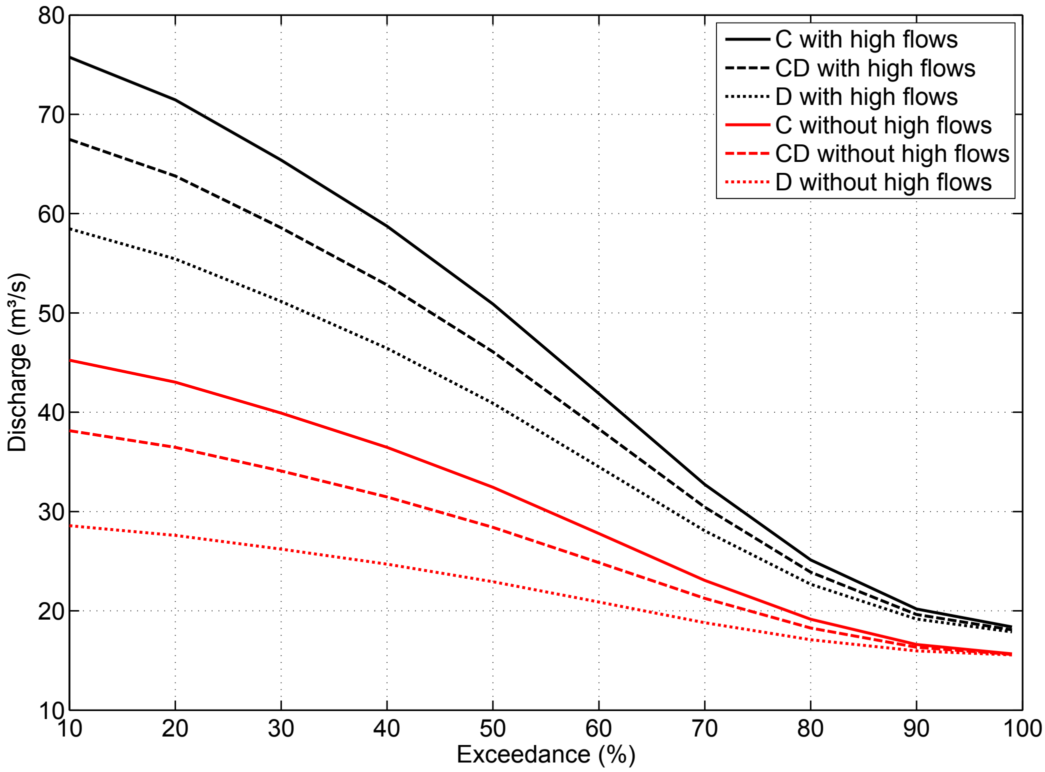


Figure 14.2: Instream flow requirements for October for quaternary catchment D82L. Discharge (m^3/s) versus exceedance (%).

14.3 New infrastructure and related flow scenario's

At the moment, the construction of a new dam in the Lower Orange is a hot topic among South African hydraulic engineers. Proper literature is available on this topic [55] [3] [171]. A new dam in the lower reaches of the Orange will allow to minimize operational losses. In fact, all water that has not been used by users downstream of Vanderkloof Dam is stored into the dam reservoir if this dam is situated in the lower reaches. The water of this new dam reservoir could subsequently be used in order to supply local irrigation demands. A new dam situated within a short distance of the Orange River mouth can favour the ecological condition of the river mouth if it is managed properly. Indeed, a more natural

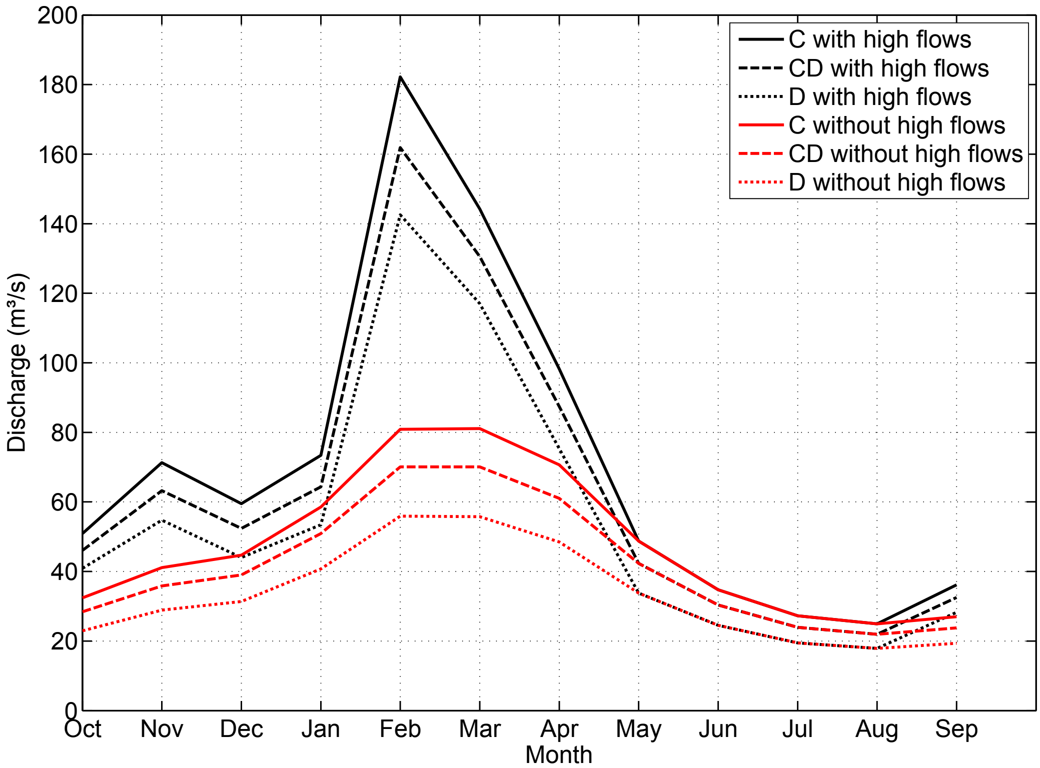


Figure 14.3: Instream flow requirements for the 50$^{\text{th}}$ percentile for quaternary catchment D82L. Discharge (m^3/s) versus month.

flow regime could be established at the Orange River mouth without affecting water users in the whole river reach downstream of Vanderkloof Dam. A literature review would be useful in comparing the different locations for dam construction by assessing their benefits for water users and their environmental impacts. Subsequently, more environmentally sound water releases by this new dam can be suggested, taking into account the available water volume and several boundary conditions (such as water demand patterns [3]). The result should be subjected to the requirements of the Ecological Reserve (section 14.2).

14.4 Water quality and water temperature

The STRIVE package consists of several modules. In the framework of this Master thesis, the hydraulic module has been adapted to the part of the Orange downstream of Vanderkloof Dam. The hydraulics can be considered as the drive for the mathematical description of several processes related to biotic and abiotic matter. A next logical step would be the implementation of other modules.

The addition of water quality modules to the model will allow to study the interaction between hydraulics and water quality, and to link the artificial flow patterns to water quality issues. Analysis of historical water quality data could reveal certain trends resulting from human impacts. The following water quality data is recorded on a regular basis by the Department of Water Affairs (DWA) [70]:

- Electrical conductivity (EC)
- Major ionic composition
- Alkalinity
- pH
- Suspended solids
- Nitrate-nitrogen
- Phosphorus

Recent weekly recorded water quality data for 7 locations within the range of the hydraulic model is added to the DVD. Historical water quality data also exists for some surplus stations. Additional (more recent) data should be asked for at the Resource Quality Services of the DWA (see DVD for contact details). This data can be obtained for free via e-mail.

The dam reservoir hypolimnion (see section 5.2) severely impacts on water temperatures in a 130 to 180 km long reach downstream of Vanderkloof Dam. Furthermore, artificial flow patterns resulting in less flow during summer and more flow during winter impact on the temperature regime of the whole river section downstream of Vanderkloof Dam.

Implementation of a water temperature module in the numerical model provides the opportunity to assess the impact of the regulated river flow on the water temperature regime, to conduct a sensitivity analyses and to suggest operational procedures so as to guarantee environmentally sound water temperatures. Weather data can be obtained easily at the South African Weather Service (see DVD for contact details). Most probably, water temperature is not recorded on a regular basis by the DWA. However, water temperature data of additional surveys is available [70]. One should try to gather all data available and consequently evaluate whether the available data is sufficient for conducting research on water temperature issues.

14.5 IWRM issues

The first part of this Master thesis deals with aspects related to integrated water resources management. Within the framework of this Master thesis a lot of articles and reports on IWRM topics have been gathered. Unfortunately, the authors of this report were not able to process all this information due to time restrictions. A continuation of the evaluation of IWRM within the river catchment will prove to be useful. Furthermore, this master thesis and future dissertations will form a entity presenting a global overview of IWRM within the Orange-Senqu-Fish catchment.

Chapter 15

Conclusion

Water demands in the Orange-Senqu-Fish basin are still increasing. The ecosystem associated to the river is deteriorating since decades. It is obvious that environmental requirements should be considered when defining water release patterns.

A more sustainable operational management of the river catchment should be established within the framework of the new National Water Act. Many studies have been conducted on the subject of environmental flow releases. A next logical step should be the actual implementation of environmentally sound flow releases. Until now, this goal has not been achieved. On the contrary, as water abstractions from the Lesotho Highlands Water Project are expected to increase in the future, the situation in the Lower Orange is likely to become even more stressed. One cannot diminish the fact that economic development relies on the availability of fresh water. Political incentive is required to convert the intentions of the NWA into concrete actions.

The development of accurate hydraulic models is of major significance for solving the water allocation problem. As the water needs some time (days or weeks) to flow from Vanderkloof Dam to the water users (man or environment) in the Lower Orange, one should be able to calculate the exact moment and the exact amount of water releases in order to assure the required discharges at all time. Inaccurate modelling can result in water shortage, or in higher flows than required, resulting in amounts of water that are not anymore available for supplying water demands. This 'wastage' of water is not necessarily beneficial to the environment. Indeed, it has been argued that high winter flows severely impact on the environment.

It is obvious that the South African water resources problem is a very complicated, but also interesting subject to conduct research on. The authors of this report were not able to process all the data collected in the framework of this Master thesis. A future continuation of the research will provide further insights in the diverse problems related to the management of the Orange River.

Chapter 16

Manual to the attached DVD

The hydraulic model developed in the framework of this study is added to a DVD attached to this report. This Master thesis is conceived as the first volume of a future series. The DVD contains all data and reports obtained before, during and after the trip to South Africa. Future last year students can use these files in order to successfully continue with the research presented in this report.

A brief overview of the DVD content is presented, so as to allow the appropriate use of the data. Names of folders are displayed in bold style, file names are displayed in italic style.

Articles and reports All articles and reports digitally available and obtained before, during and after the trip of the authors to South Africa (September 2009). Most literature is arranged according to subject. Literature obtained during meetings in South Africa are ordered separately according to origin. Literature which is not digitally available will be archived at the Hydraulics Laboratory.

Data

- ▷ **Evaporation** Historical and recent monthly and daily evaporation data for 9 weather stations. For more information on the station numbers the reader is referred to [151].
- ▷ **Flow** Historical monthly flow data and recent hourly data (2002-2009) for the gauging stations in the Lower Orange. For more information on the station numbers the reader is referred to [151]. A list with all flow series and their names (i.e. 'flowseries'_'year') is added.

- ▷ **Geometry**
  ⟶**GIS** GIS relief data of the Orange River bed.
  ⟶**LOROS** River geometry as used in the South African LOROS hydraulic model, and consequently used in the hydraulic model presented in this report.

- ▷ **IFR** Desktop model instream flow requirements for quaternary catchments along the Orange for ecological categories C, CD and D.

- ▷ **Rainfall** Daily rainfall data (2002-2009) for 38 weather stations in the river catchment.

- ▷ **Water quality** Recent weekly recorded electrical conductivity (EC), major ionic composition, alkalinity, pH, suspended solids, nitrate-nitrogen and phosphorus data for 7 locations within the range of the hydraulic model presented in this report.

Pictures

- ▷ **by Dana Grobler** Photographs taken by Dana Grobler during several field trips.

- ▷ **by Jan Putteman and Bert Schepens** Photographs taken by the authors of this Master thesis during their field trip (September 2009).

- ▷ **received from Piet Huizinga** Old aerial photographs of the Orange River mouth, sent to the authors by Piet Huizinga.

STRIVE

- ▷ **MATLAB** A special MATLAB code is written by the authors of this report so as to allow quick creation of the forcing files required by the hydraulic model. For each reach a separate folder is provided. The user just needs to enter the start and end date of the desired flow series. The MATLAB program subsequently creates the forcing files required by the model. Depending on the reach, 3 or 5 forcing files *.frc* with appropriate formatting are generated.
  ⟶**Reach1** The input text documents should be imported in MATLAB. Subsequent to entering the start and end date of the desired flow series, one can run the MATLAB code *code_frcfiles.m*. 5 forcing files are generated: *HourlyFlow_'flowseries'_'year'*, *DailyFlow_'flowseries'_'year'*, *HourlyMonth_'flowseries'_'year'*, *DailyRain_'flowseries'_'year'* and *Downstream_HourlyFlow_'flowseries'_'year'*. The latter will not be used by the hydraulic model, but will be useful for calibrating the hydraulic model as this

file includes the recorded discharge at the downstream node for the interval of time under concern. The code *code_dailyflowmatrix.m* can be useful for creating a new *DailyFlow* matrix (for flood detection) with a desired time shift.
⟶**Reach2** For reach 2, 3 forcing files are generated: *HourlyFlow _'flowseries'_'year'*, *HourlyMonth_'flowseries'_'year'* and *Downstream_HourlyFlow _'flowseries'_'year'*.
⟶**...**
⟶**Reach7**

▷ **Reach1** This folder contains the complete hydraulic model for the first reach.
⟶**Forcing files** All the forcing files that have been created in the framework of this study.
⟶**Model v1.0** The hydraulic model v1.0.
⟶**Model v2.0** The hydraulic model v2.0.
⟶**Output v1.0** Output generated by model v1.0 in the framework of this study.
⟶**Output v2.0** Output generated by model v2.0 in the framework of this study.

▷ **Reach2** This folder contains the complete hydraulic model for the second reach.
⟶**Forcing files** All the forcing files that have been created in the framework of this study.
⟶**Model v2.0** The hydraulic model v2.0.
⟶**Output v2.0** Output generated by model v2.0 in the framework of this study.

▷ **...**

▷ **Reach7**

Various

▷ *ContactDetails_SA* Full list of people who can help on the subject. Telephone number, e-mail address, profession and points of special interest have been added for all the contacts. These contacts will prove to be helpful for the (future) continuation of the research on the Orange.

▷ *UNESCO_Report* Report of the trip of the authors of this Master thesis to South Africa (03/09/2009-02/10/2009). This report was sent to UNESCO in order to receive UNESCO funding.

- *MasterThesis-Putteman&Schepens_2010* Digital version of this report.

Appendix A

Orange River catchment map

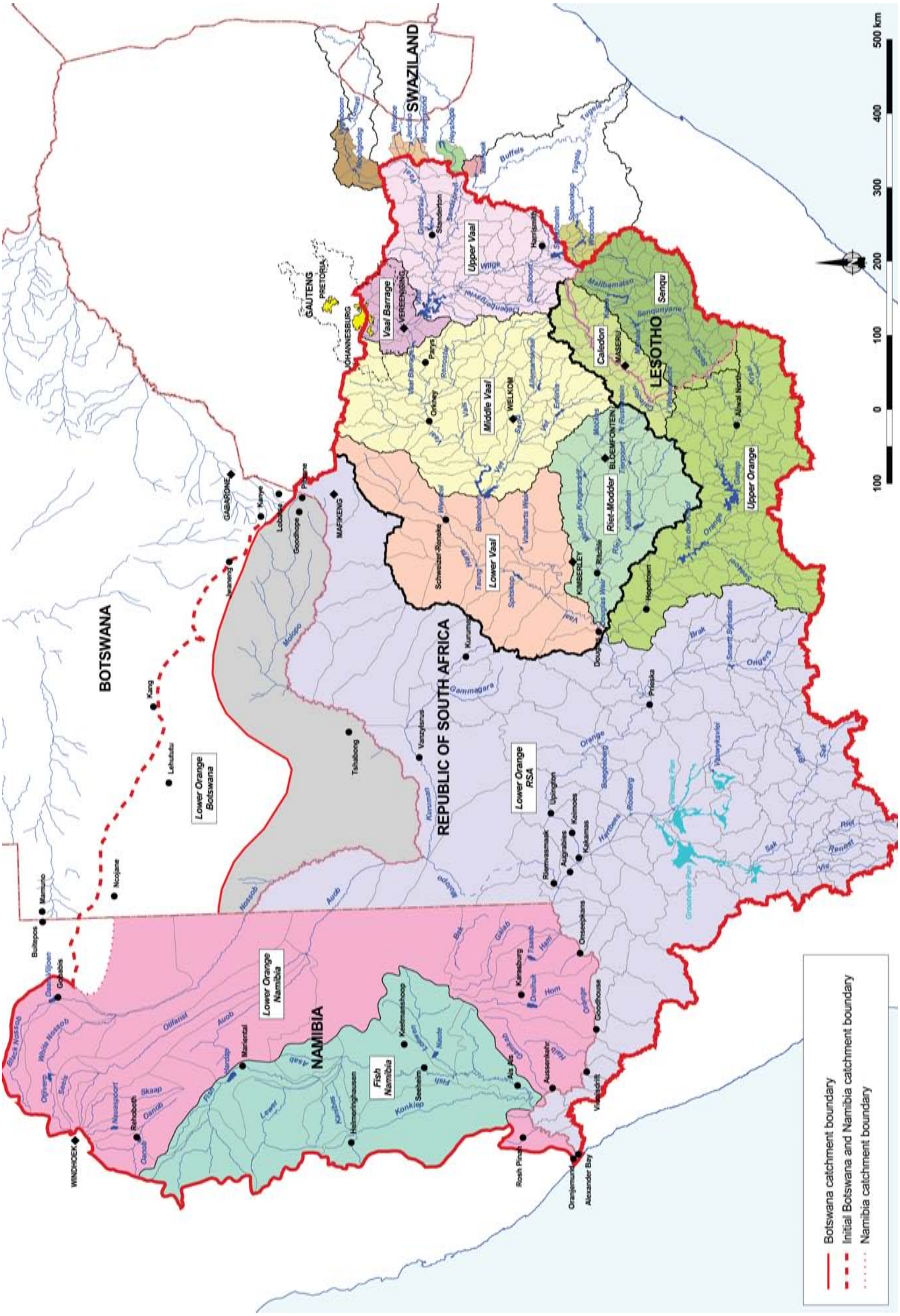


Figure A.1: Orange River catchment map and main sub-catchments [4].

Appendix B

Map of the Lower Orange

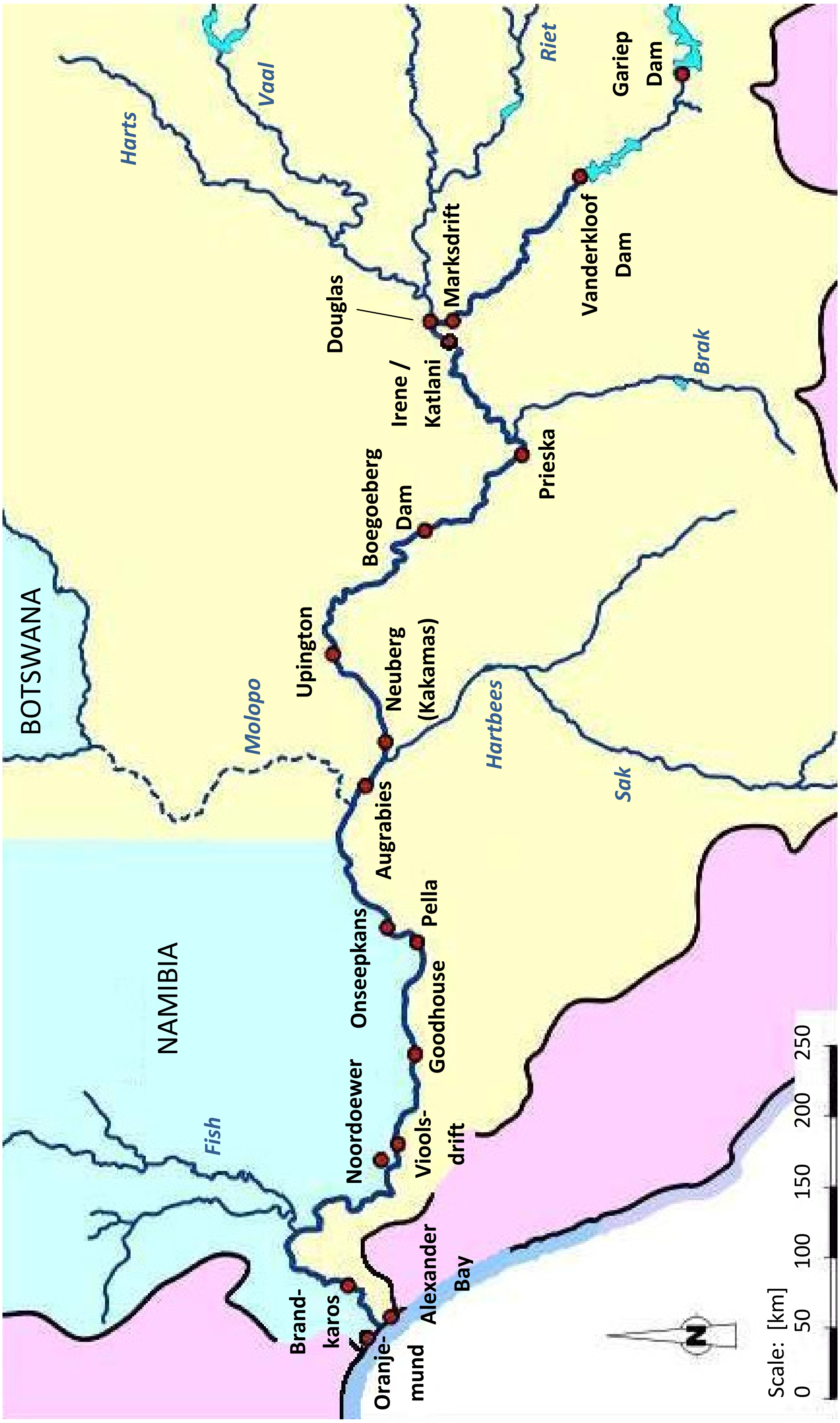


Figure B.1: Points of interest along the Lower Orange River [167].

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