Drought definitions for groundwater recharge, groundwater depth and streamflow: Poelsbeek and Bolscherbeek catchments (the Netherlands)

Liesanne Verwij

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Drought definitions for groundwater recharge, groundwater depth and streamflow: Poelsbeek and Bolscherbeek catchments (the Netherlands)

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Summary

Because of the slow development of a drought, people are often not aware of the emerging of droughts in time. More insight in the development of a drought can help the people to be aware of a drought in an earlier stage. Therefore it is important to study droughts. For the study of droughts a consistent set of drought definitions is needed.

The time series which are used in this research were simulated with the model *SIMGRO* in an earlier study. *SIMGRO* is a physically based hydrological model. The model has different modules in which groundwater flow, streamflow, flow in the unsaturated zone and evapotranspiration are simulated. The model uses a horizontal schematization (subregions and nodal points are divided according to land use) and a vertical schematization (different geological layers with different hydrological characteristics).

The time series were simulated for two catchments (i.e. the Poelsbeek and Bolscherbeek) in the east of the Netherlands. The Poelsbeek has a flashy discharge regime and in summers the brook is often dry. The Bolscherbeek has a minimum summer flow of 0.1 m^3s^{-1}, due to the effluent of a sewage plant.

The threshold level method (TLM) is a drought definition, based on the choice of a threshold (Q_0). If the flow is below the threshold there is a drought. Time series of deficits can be derived with equation 4.1 and the characteristics, which can be derived, are duration (d_i), deficit volume (s_i), onset (τ_i) and the minimum flow (Q_{min}) (figure 4.1). When using TLM it is often necessary to apply a pooling procedure. Pooling can be done when the inter-event time (t_i) is shorter then a critical inter-event time (t_c) and/or when the previous inter-event volume (v_i) is smaller then a fraction p_c of the previous deficit volume. Adapted characteristics are calculated according to equation 4.2 or 4.3. Another pooling criterion is applying a moving average to the time series.
The sequent peak algorithm (SPA) is based on storage in a reservoir. For this method also a threshold level should be chosen. Time series of deficits can be calculated with equation 4.4. Characteristics which can be determined for SPA are: deficit volume (s_i), duration till the maximum drought deficit volume (d_{max}) and duration till the storage is not negative anymore (d_{total}) (figure 4.2).
There is a difference between the dimension of fluxes (L^3T^{-1}) and state variables (L). Instead of SPA, cumulative departure is used for state variables. Basically this is the same method as SPA. The results of TLM and SPA are the same if only one peak occurs in the time series of deficits, when more peaks are present the methods produce different results.

The time series used in this research are groundwater recharge (Q_r), groundwater depth (h^*) and streamflow (Q_s). The simulated Q_r and h^* are from the middle of the catchment, the simulated Q_s is from the outlet of the Poelsbeek and Bolscherbeek. The program *NIZOWKA* was used for calculating exceedance frequencies and for calculating drought characteristics with TLM. Programs written in the program language *R* were used for calculating drought characteristics with SPA, deficit time series and supporting calculations for *NIZOWKA*. The pooling criterion which can be used in *NIZOWKA* is t_c; d_{pool} and s_{pool} are calculated according to equation 4.2. In addition *NIZOWKA* removes minor droughts, droughts which are smaller then d_{min}. Moving average should be applied to the time series prior to the use of *NIZOWKA*.

Five drought definitions for the Poelsbeek were chosen, these drought definitions fulfil the condition approximately that on average h^* has one drought per year, Q_r two and Q_s 1½ drought per year. With these definitions three major droughts (1959, 1976 and 1996) were investigated. Almost all definitions show one drought per variable, starting with Q_r, Q_s and latest h^*, this is also the order of increasing duration. The full and real duration are equal for TLM with pooling criterion and with pooling criterion and removing of minor droughts. The

time lag between the variables increases from Q_s-h^*, Q_r-Q_s to Q_r-h^*. For verifying the definitions used for the Poelsbeek on the Bolscherbeek, only three of the definitions and the year 1976 were chosen. Except for Q_s there is not much difference between drought characteristics in the Poelsbeek and Bolscherbeek. Droughts derived from Q_s are more numerously and shorter. The cumulative deficit of single droughts derived from Q_s is larger then the deficit for Q_s in the Poelsbeek. The full and real duration for TLM with pooling criterion and with pooling criterion and removing of minor droughts are not equal for the Bolscherbeek.

Reasons for the propagation of droughts in the Poelsbeek can be: the increasing persistence of h^* with increasing distance to the stream or the difference in location of Q_r, h^* and Q_s. The deviating behaviour of Q_s in the Bolscherbeek is due to the effluent of the sewage plant, this can be avoided by increasing the pooling criterion or applying a moving average.

Preface

In front of you is my thesis Hydrology and Quantitative Water Management (HWM-80427, 27 ECTS). I worked on it during my MSc study, Hydrology and Water Quality, as a minor thesis. I hope you enjoy reading it.

This thesis is my first experience with droughts and it was not a bad one. Like with many hydrological time series my work had ups and downs and experienced sometime droughts. I enjoyed developing programs in *R* and working with *NIZOWKA*, although both programs caused also some droughts in the research, because they did not do what I wanted and what they should do. But after all I found a solution and everything worked well.

Finally I want to thank my supervisor, Henny van Lanen, for his help and support during my thesis. I also want to thank Erik Querner for providing the simulated data, Wojciech Jakubowski for the help with *NIZOWKA* and Lena Tallaksen for sending me an article about droughts. At last I want to thank my mother for her understanding and the other thesis students for the nice chats and card playing games during the breaks.

Liesanne Verwij
17 June 2005

Contents

1 Introduction

This introduction deals with some background information to the subject, followed by the research questions, which are tried to be answered in this report and last guidance is given for the reader what can be found in this report.

1.1 Background

Drought is one of nature's natural disasters. In contrary to disasters as floods and heavy rainfall, a drought develops very slowly. It can be that people are, in the beginning of the drought, not aware of the development of a drought event. In that case people do not take preventing actions against the drought. When a drought is a fact, it can affect many social and economic aspects in society, like destruction of forested areas by fire, harvest losses, cut down of power and problems with transport. The problems caused by drought affect large areas and large damage (millions/billions) can occur (Tallaksen and Van Lanen, 2004). See for more details on the impact of drought the international disaster database EM-DAT (OFDA/CRED, 2005).

Drought can be divided in different types of drought (table 1.1). After a meteorological drought, drought can propagate through the hydrological system, depending on the severity of the meteorological drought, to soil moisture drought, groundwater drought and streamflow drought. Groundwater drought and streamflow drought are also known as hydrological drought. The effects of hydrological or soil moisture drought on ecology, agriculture, society and economy are called ecological, agricultural and socio-economic drought, respectively (Tallaksen and Van Lanen, 2004).

Table 1.1 Drought types and its characteristics.

Type of drought	Characteristics
Meteorological drought	Lack of precipitation.
Soil moisture drought	Soil water deficiency, caused by low precipitation and high evapotranspiration.
Groundwater drought	Lack of groundwater recharge, low groundwater depths and low groundwater discharge.
Streamflow drought	Low streamflow.
Hydrological drought	Groundwater drought and/or streamflow drought.
Ecological drought	Negative effects of drought on ecosystems.
Agricultural drought	Insufficient soil moisture for supporting crops.
Socio-economic drought	Negative effects of drought on society and economy.

In order to prevent or decrease the damage caused by drought, it is important to know when a drought might take place, or when a drought takes place, to know that it is taking place in an early stadium. Therefore it is important to investigate drought.

The problem in studying drought is that there are many ways to define drought; examples are the threshold level method and the sequent peak algorithm (Hisdal *et al,* 2004). When using the different definitions, different drought events and drought characteristics (e.g. duration and deficit volume) will be derived. With all these definitions it is hard to investigate drought (Tallaksen and Van Lanen, 2004). To investigate drought it is important to have a consistent set of definitions of drought.

In defining drought, there is also a difference in fluxes (e.g. groundwater recharge and streamflow) and state variables (e.g. groundwater level and soil moisture content). It is not very well known how to deal with these in relation to drought definitions.

1.2 Research questions

The research questions are:

- What drought definitions are used in literature?
- Which set of drought definitions describes the drought propagation in a catchment (Poelsbeek) correctly?
- Is the same set of drought definitions also a good choice for another catchment (Bolscherbeek)?
- How to deal with fluxes versus state variables in relation to drought definitions

1.3 Set up of the report

In this report the research questions are tried to be answered with available simulated time series, which are generated with the program *SIMGRO* (chapter 2). The groundwater recharge, groundwater depth and streamflow are simulated in two catchments in the east of the Netherlands, the Poelsbeek and the Bolscherbeek catchment, respectively (chapter 3). Chapter 4 gives a description of the drought definitions, which are often used in literature (threshold level method and sequent peak algorithm). Material (the datasets), methods (*NIZOWKA* and *R*) and approach are treated in chapter 5. Chapter 6 gives an overview of the results and last conclusions, discussion and recommendations are presented in chapter 7.

2 SIMGRO

In an earlier study, the model *SIMGRO* was applied to simulate the time series, which were used in this thesis to investigate drought definitions. The simulated time series and the information in this chapter are from Querner (1993) and from Van Lanen and Querner (2004a), unless stated otherwise.

SIMGRO stands for SIMulation of GROundwater and surface water levels; it is a distributed physically-based hydrological model that solves several equations representing hydrological transient flow processes like: crop evapotranspiration, unsaturated flow, saturated groundwater flow and streamflow. The model takes into account among others the following spatial characteristics: land use, soil conditions, hydrological setting, stream network, precipitation and abstraction. The model can handle complicated spatial variable boundary conditions like: measured precipitation time series and abstraction rates.

The area which is planned to be simulated has to be schematized horizontally and vertically. There are three levels of schematizing; the first level is the land use, the second level is the subregion and the third level is hydrogeological stratification, like aquifers and aquitards (figure 2.1).

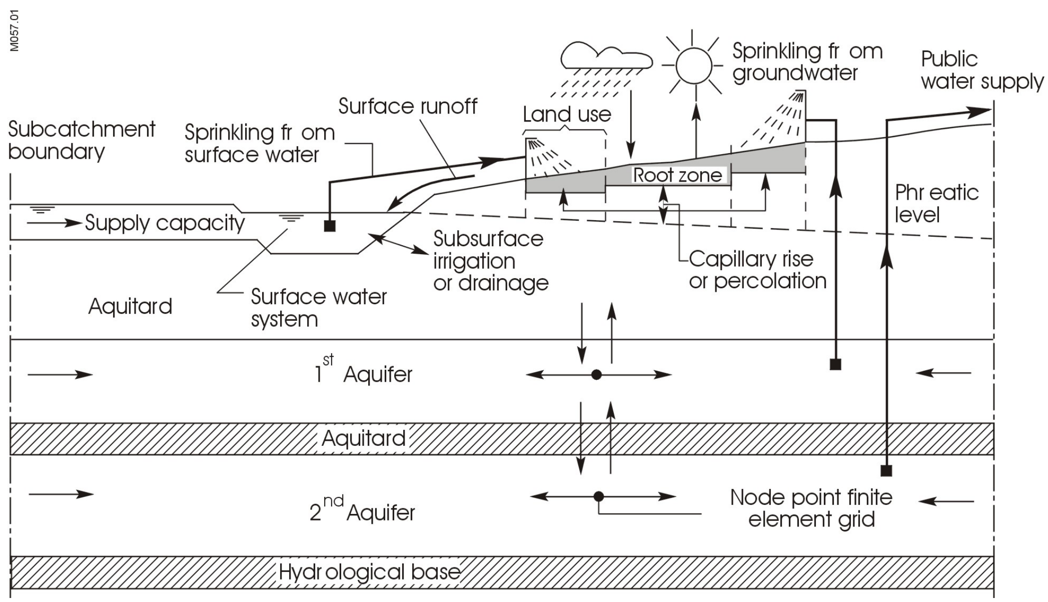

Figure 2.1 Schematization of the hydrological system in SIMGRO in a subregion (Querner and van Bakel, 1989; in Querner, 1993).

The subregions are divided according to land use. Only the percentage of land use is important, not the locations of land use type. Querner (1993) distinguishes four important types of land use:
Agriculture; divided in land use with different situations, with respect to potential evapotranspiration, root depth and irrigation regime.
Urban area; divided in impermeable (e.g. streets and houses) and permeable area (e.g. gardens and parks).
Nature; mostly natural grasses, divided in wet and dry conditions.
Woodlands; divided in different potential evapotranspiration regimes (e.g. deciduous or coniferous forest) and root zone depth.

The groundwater system can be divided in permeable layers, with predominantly horizontal flow (aquifers) and less permeable layers, with predominantly vertical flow (aquitards). For each layer the hydraulic parameters have to be known, for example: transmissivity (*kD*), vertical resistance (*c*) and the storage coefficient (μ). At the bottom of the groundwater system there is an impermeable layer.

2.1 Groundwater flow

To simulate the groundwater flow, *SIMGRO* uses the following basic partial differential equation:

$$\frac{\partial}{\partial x}\left(k_x D \cdot \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y D \cdot \frac{\partial H}{\partial y}\right) = A_e \cdot \mu \cdot \frac{\Delta H}{\Delta t_g} + Q_t \tag{2.1}$$

Where:

H	=	hydraulic head (L)
k	=	hydraulic conductivity (LT^{-1})
D	=	thickness of layer (L)
x,y	=	horizontal plane coordinate system (L)
A_e	=	area (L^2)
μ	=	storage coefficient (-)
Q_t	=	fluxes such as percolation q_w, capillary rise q_c, and extractions for water supply or sprinkling (L^3T^{-1})
Δt_g	=	time step (T)

Equation 2.1 is numerically approximated with equation 2.2 for *x*, *y*, *z* and t, using the finite element method (Wang and Anderson, 1982).

$$A_i \cdot \mu \cdot \frac{\Delta H_{i,t}}{\Delta t_g} = W \cdot \left[\sum_j Q_{ji} + Q_a\right]_{t+\Delta t_g} + (1-W) \cdot \left[\sum_j Q_{ji} + Q_a\right]_t \tag{2.2}$$

Where:

A_i	=	influence area of node *i* (L^2)
ΔH	=	change in hydraulic head over a time step (L)
W	=	weighing factor between the time levels t and $t+\Delta t_g$ (-)
Q_{ji}	=	flow from adjacent nodes j to node *i* (L^3T^{-1})
Q_a	=	all fluxes from adjacent saturated layers, the unsaturated zone, interaction with the surface water and extraction (L^3T^{-1})

The groundwater flow is simulated per node (figure 2.2). A node only influences the elements surrounded by the node. For every position between the nodal point (*x,y*) the flow can be simulated, using linear interpolation. If the weighing factor is 0.5, it is called the Crank-Nicolson approximation.
The storage coefficient μ in a node varies with the depth of the groundwater level (section 2.3). Therefore the storage coefficient is updated during the calculation. Boundary conditions for equation 2.2 can be (time) specified hydraulic head (Dirichlet) or specified flux (Neumann).
SIMGRO makes calculations for a predefined time span, e.g. days, weeks, years. The time span is subdivided in stress periods, which is subdivided in time steps (e.g. hours, days). The stress period is important for boundary conditions like precipitation, groundwater abstraction and the predefined hydraulic head on the boundaries of the model.

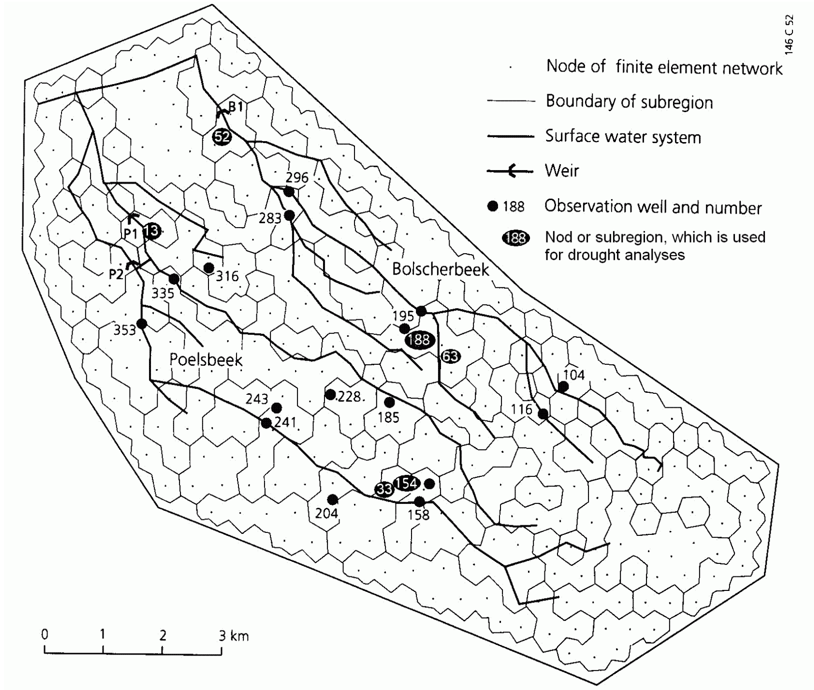

Figure 2.2 Network of nodal points and subregions of the Poelsbeek and Bolscherbeek, used in SIMGRO (Querner, 1993).

2.2 Streamflow

SIMGRO distinguishes different subsystems of water courses to simulate drainage from the aquifers; i.e. ditches, secondary and tertiary water courses and rivers (figure 2.3). Because there are usually so many water courses in lowland areas it is not feasible to take account for all of them explicitly. The small water courses are important for simulations of drainage and subsurface irrigation, the larger water courses are important for flow routing.

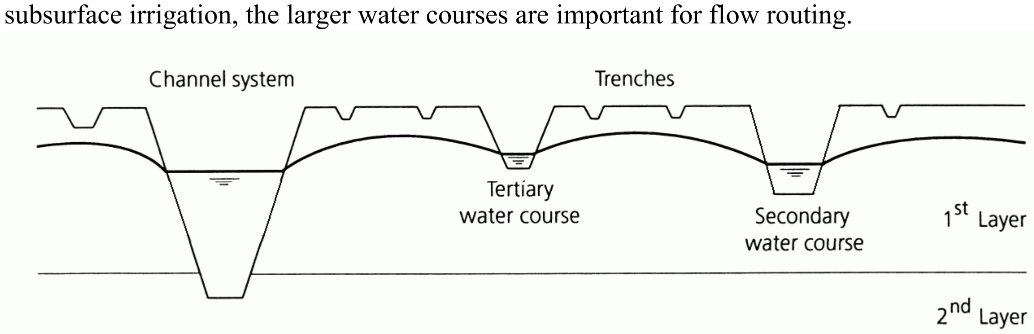

Figure 2.3 Schematizations of four subsystems (Querner, 1993).

The ditches (trenches), secondary and tertiary water courses are assumed to be equally distributed over the subregion and the interaction with the groundwater system is simulated for each subsystem with equation 2.3, which uses the drainage resistance and the difference between the surface water level and the groundwater level (Ernst, 1978, in van Lanen and Querner, 2004a).

$$Q_{gr} = A_{el} \cdot \sum_{k=1}^{3} \frac{H - H_{su}(k)}{CR(k)} \qquad (2.3)$$

Where:

Q_{gr} = groundwater discharge (L^3T^{-1}), part of Q_a in equation 2.2.
A_{el} = area of the element (L^2)
H_{su} = surface water level for drainage subsystem k (L)
CR = drainage resistance for drainage subsystem k (T)

Rivers can also be included in *SIMGRO*. This can be done by defining specific nodes for rivers. The equation for rivers is the same as for the other subsystems (equation 2.3); only A_{el} is in this case the influence area of the river node. The function of rivers is to transport and distribute water, but also to drain, or infiltrate water from or to the groundwater system.
Only the upper part of the saturated zone plays a role in the interaction with the surface water systems. The complete surface water system can be seen as a network of reservoirs. The outflow of one reservoir is the inflow of another reservoir. The simulated surface water level depends on the surface water storage and the inflow and outflow of the surface water system. Relations for “stage versus storage” and “stage versus discharge” are specified.

Time steps of the groundwater and surface water modules

The groundwater module and the surface water module have their own time step, because of the different reaction time of both systems. The groundwater system reacts slower then the surface water system and therefore the groundwater system has a larger time step. In one time step of the groundwater system, more time steps of the surface water system fit. During one time step of the groundwater system the groundwater level (H in equation 2.3) in the calculations for the surface water system is assumed to be constant. Flow between the modules, during one groundwater time step is accumulated and the actual surface water level (H_{su}) is stored.

2.3 Unsaturated flow

The unsaturated zone is subdivided into two reservoirs; the root zone and the zone between the bottom of the root zone and the groundwater level. The root zone thickness is assumed to be constant during a year.
To model the unsaturated zone, Richards’ equation is used (equation 2.4, Van Lanen and Querner, 2004a).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[k_{unsat}(h) \cdot \left(\frac{\partial h}{\partial z} + 1\right)\right] - SR(h) \qquad (2.4)$$

Where:

θ = volumetric soil moisture content (L^3L^{-3})
t = time (T)
z = vertical coordinate (L)
h = pressure head (L)
k_{unsat} = unsaturated hydraulic conductivity (LT^{-1})
SR = root water uptake ($L^3L^{-3}T^{-1}$)

SIMGRO assumes, when using equation 2.4, steady-state conditions in the unsaturated zone during one time step (De Laat, 1980, in Van Lanen and Querner, 2004a). With this steady-state solution, relationships are derived, which control storage coefficient (μ) and percolation (q_r). Storage coefficient and percolation depend on crop data (rooting depth) and soil characteristics like rootable depth, soil moisture retention data and unsaturated hydraulic conductivity.

The best way to simulate flow and storage in the unsaturated zone is to make calculations for every node and for every land use type to take all relations into account, because of the non-linearity of the equations. This is a very data, time and storage demanding approach for the computer. Therefore Querner (1993) proposed some simplifications. The simulations are done per subregion for all combinations of land use and soil type. For each combination of land use and soil type the soil moisture storage, evapotranspiration, capillary rise or percolation with the average hydrological conditions is calculated. These simplifications mean that homogeneous conditions prevail. This implies that the hydrological conditions may not vary too much in one subregion.

For each subregion the average hydraulic head (H), derived from the simulated levels at the nodal points, is used. The soil moisture storage and depth of the groundwater table, which are simulated, are linked to tables with hydraulic head versus capillary rise. For each combination of land use and soil type a table is available.

Surface runoff is simplified to one reservoir (depression storage). When the reservoir is full and more precipitation is added the excess water is classified as surface runoff. The reservoir is emptied by infiltration in the soil.

Link between unsaturated zone and saturated zone

The link between the unsaturated and saturated module are through the recharge (I). The state variables and fluxes for the saturated zone are simulated per nodal point and for the unsaturated zone per combination land use and soil type that occur in a particular subregion. Some state variables or fluxes (e.g. soil moisture storage and capillary rise) are related to the groundwater depth; for the calculations in the unsaturated zone considering the groundwater level, a weighted-average groundwater depth from the involved nodal points is used.

2.4 Evapotranspiration

As input data the potential evapotranspiration of a reference crop is used. For other vegetation types the potential evapotranspiration is derived from the evapotranspiration of the reference crop by using a crop factor (Feddes, 1987; in Van Lanen and Querner, 2004a). The potential evapotranspiration of a reference crop is simulated from meteorological data with the Makkink equation for grass (De Bruin, 1987; in Querner, 1993). For woodlands the sum of transpiration and interception is used, bare arable land is included in the soil evaporation (Querner, 1992; in Querner, 1993).

In urban area the impermeable part is assumed to have no evaporation and the rest is treated as grass.

2.5 Urban area

This area can be subdivided in permeable and impermeable land. The rain which precipitates on the impermeable area is collected in a combined storm water and sewage system. This is modelled as a reservoir with a specific storage capacity. The inflow is rain- and sewage water and the outflow is the effluent of the sewage plant. The outflow cannot exceed the maximum pump capacity of the plant. When the storage capacity is exceeded, the excess water (rainwater and sewage water) flows to the surface water (Querner, 1997; in Van Lanen and Querner, 2004a).

3 Study area

The catchments, which are used for the simulations, are the catchments of the Poelsbeek and the Bolscherbeek. The information in this chapter is derived from Van Lanen and Querner (2004b) and from Querner (1993), unless stated otherwise.

The catchments of the Poelsbeek and Bolscherbeek are situated in the east of the Netherlands, near the German border and 10 km southeast of the city of Enschede. The city of Haaksbergen is located in the catchment (figure 3.1). The areas of the catchments are 41 and 23 km^2 for the Poelsbeek and Bolscherbeek, respectively. The elevation is sloping from 30 m + NAP (Dutch reference level) in the southeast to 12 m + NAP in the northwest.

The Poelsbeek and Bolscherbeek used to drain on the river Regge, which was part of the catchment of the river Overijsselse Vecht, a tributary of the Vecht. A great part of the discharge of the river Regge came from the surrounding of Haaksbergen. Till 1870 there were no substantial changes due to human interference; the brooks changed there way once in a while, due to natural conditions. After 1870 the water boards came in the area; water courses were constructed and brooks were canalized. This had a major impact on the hydrology. In 1932 a shipping route between Zutphen and Enschede was dug, the Twentekanaal (figure 3.1). The Twentekanaal also had a major impact on the hydrology and the groundwater levels in some regions. However, the effects of the Twentekanaal in the catchments of the Poelsbeek and Bolscherbeek were minimal. The Poelsbeek and the Bolscherbeek do not discharge on the Regge anymore, but drain directly on the Twentekanaal; this is to protect the Regge from too high surface water levels and flooding of adjacent regions (Querner, 1993).

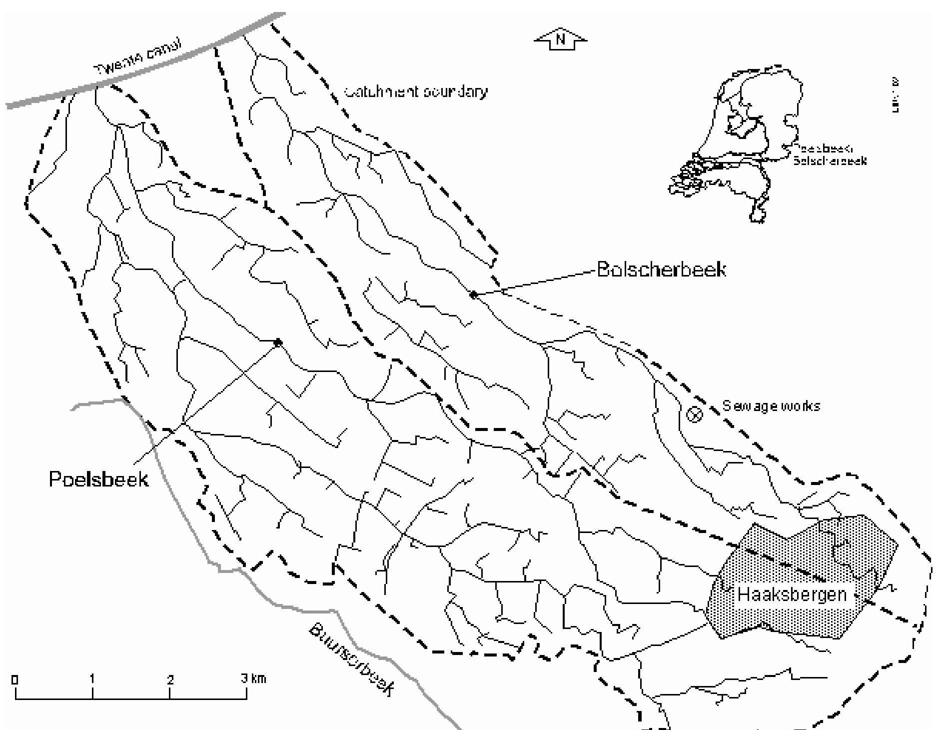

Figure 3.1 Location of the catchments of the Poelsbeek and Bolscherbeek, showing the water courses and the sewage plant that discharges into the Bolscherbeek (Van Lanen and Querner, 2004b).

3.1 Geology

In the catchment area Tertiary (Miocene) marine clay deposits are overlain by Pleistocene sediments. East of Haaksbergen the Miocene deposits are close to the surface and on some places the Miocene outcrops. West of Haaksbergen the Miocene dips deeper in the underground.

During the Pre-Saalian, rivers deposited fluvial sediments in the area. In the Saalian (second last glacial) the area was covered with land ice. When the ice retreated, ice-pushed ridges and some glacial material (Drente Formation) were left. Also a glacial gully developed, which was eroded by melt water. The direction of the gully is north south. Later the gully was filled with coarse fluvioglacial material and fine-grained brook deposits. Outside the gully, fluvial and fluvioglacial medium-coarse material was deposited and also some non-continuous thin till layers are present (figure 3.2). During the Weichselian (last glacial) the land ice did not reach the Netherlands and the catchments, although the climate was periglacial. In this period the catchment was covered with a thick layer of cover sands (Twente Formation).

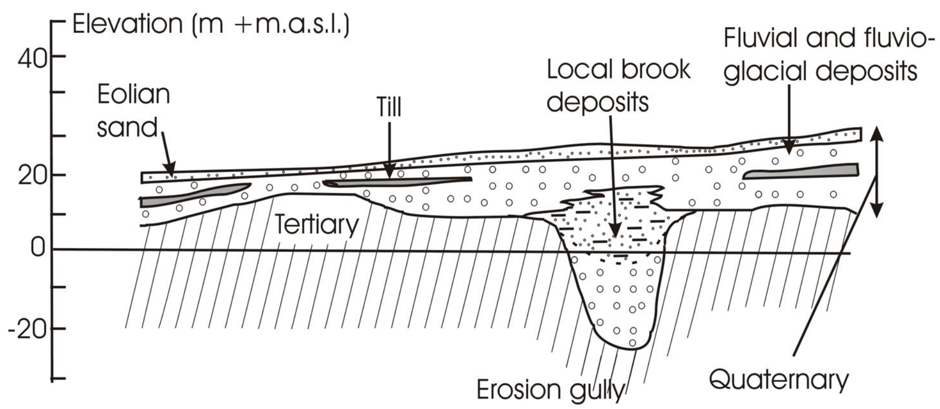

Figure 3.2 Cross-section (east-west) of the Poelsbeek and Bolscherbeek catchment, with glacial gully (Van Lanen and Querner, 2004b)

Hydrogeology

The Tertiary clays have a low permeability and hence they are assumed to be the impermeable basis, whereas the Pleistocene sediments are an unconfined aquifer, with a thickness ranging from 10 to 60 meter. The transmissivity of the aquifer ranges from 100 to 700 m^2d^{-1}.

3.2 Soils and land use

The area consists mostly of sandy soils with a shallow water table; 25% of the area consists of wet podzols. Other soil types are wet valley bottom soils and man-made soils (Bodemkaart van Nederland, 1979).

In the past the cover sand area was bare land, except for some spots near Haaksbergen, which were used as pasture and agricultural land. Manure from the cattle was used as fertilizer. After the introduction of chemical fertilizers (1880) the bare land was cultivated. The land use is mainly agricultural; 56% is pasture land, 19% is arable land (mainly silage maize), 16% is woodland, 8% is residential area and the rest (1%) is nature reserve (wet meadows).

3.3 Hydrology

The Poelsbeek and Bolscherbeek flow approximately from Haaksbergen in northwestern direction and are draining in the Twentekanaal (figure 3.1). The water courses have a length of 83 and 45 km for the Poelsbeek and the Bolscherbeek, respectively (20 mha^{-1} both). These water courses are managed by the water board. To control the water level and flow there are several weirs, most adjustable, in the water courses.

The Poelsbeek drains mainly farmland and has a flashy discharge regime. In summer the brook is almost always dry, the average winter discharge is 0.3 m^3s^{-1}. The Bolscherbeek, however, has a minimum flow in summer of 0.1 m^3s^{-1}, because it receives effluent of two sewage treatment plants (figures 3.1 and 3.3), which treat the sewage water of all the urban area in the catchments. Abstraction for drinking water takes place outside the catchments; some abstractions for industrial uses inside the catchment occur and it is maximally 138 m^3d^{-1}.

In figure 3.4 groundwater recharge (Q_r) and depth (h^*) can be seen. In appendix A the duration curves can be seen for precipitation, groundwater recharge, groundwater depth and streamflow. The duration curve for precipitation is almost identical for the Poelsbeek and the Bolscherbeek, so an average duration curve is presented. The groundwater recharge is part of the time negative; this is due to capillary rise, which is a common phenomenon in lowland areas.

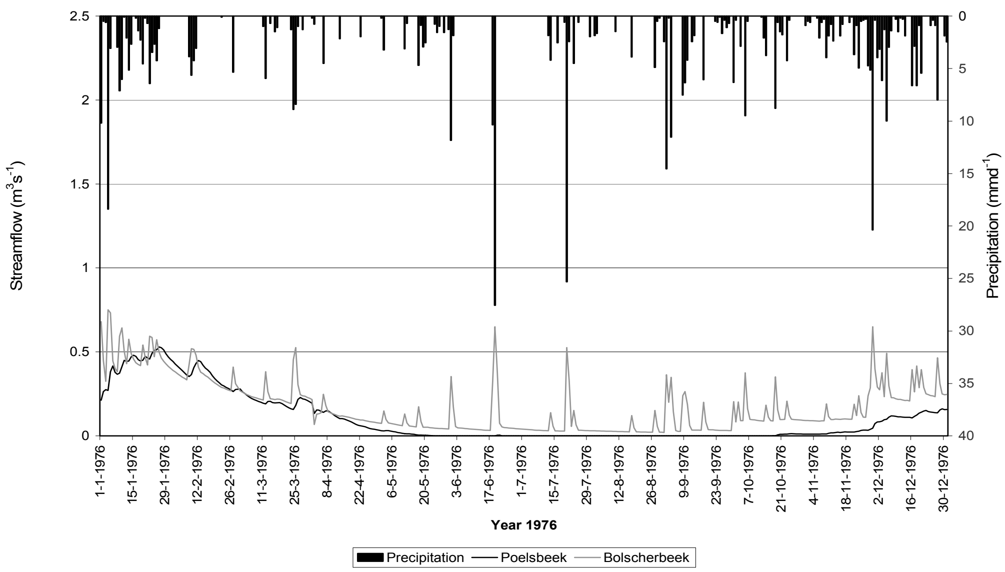

Figure 3.3 Precipitation and streamflow in 1976 for the Poelsbeek and Bolscherbeek.

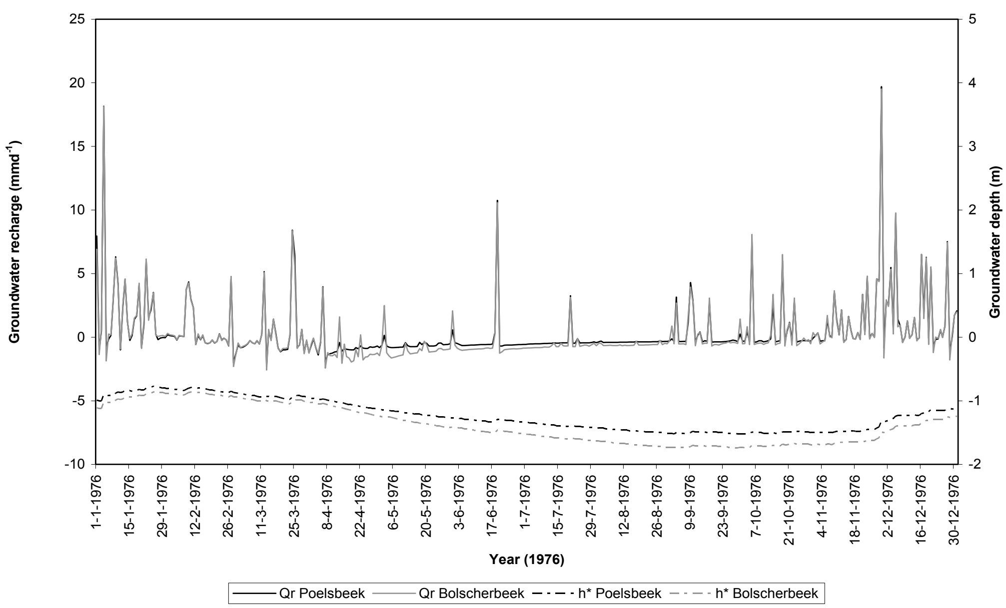

Figure 3.4 Groundwater recharge and depth for the Poelsbeek and Bolscherbeek in 1976.

3.4 Climate

The Netherlands have a *Cf* climate, according to the Köppen division of climates. This means that the average temperature of the coldest month lies between -3 and 18 °C, the average temperature of the warmest month is above 10 °C and the precipitations falls during the whole year (figures 3.5 and 3.6).

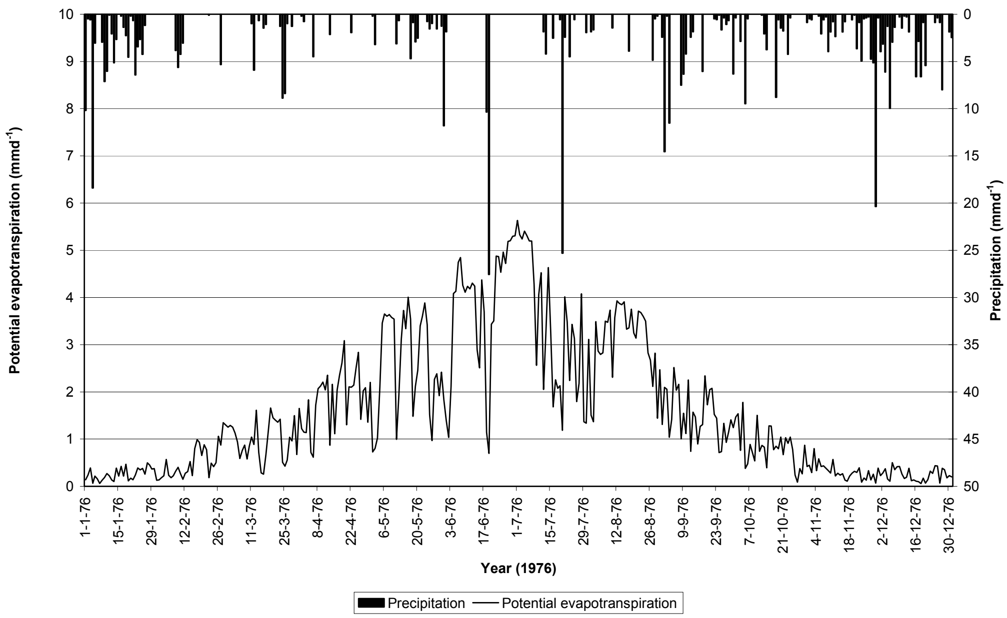

Figure 3.5 Precipitation and potential evapotranspiration in the year 1976 in the Poelsbeek and Bolscherbeek catchments.

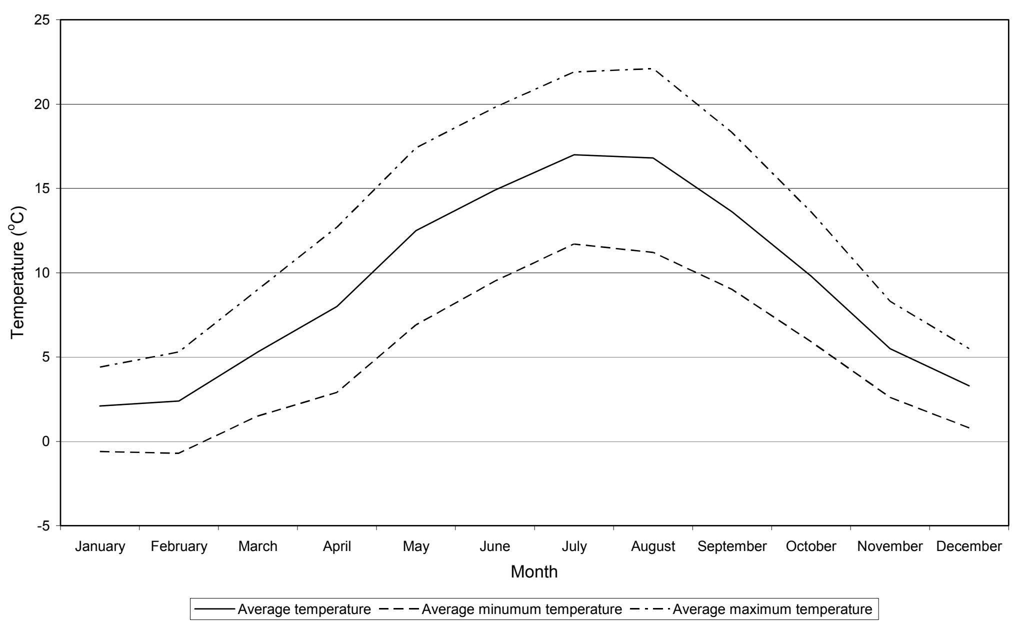

Figure 3.6 Average temperatures of the years 1971 till 2000, at meteorological station Twente, situated approximately 15 km northeast of the study area, data obtained from KNMI (2005).

4 Drought definitions

This chapter gives an overview of available drought definitions and the associated drought characteristics. The first section describes the threshold level method and methods for pooling droughts and removing minor droughts. The second section describes the sequent peak algorithm. The third section describes the difference between fluxes and state variables and the way to deal with the differences. In the last section the difference between the threshold level method and the sequent peak algorithm is explained with examples.

4.1 Threshold level method

The threshold level method (TLM) uses a key parameter, i.e. the threshold level, Q_0. If the hydrological variable, e.g. discharge (Q), drops below the threshold, there is a drought according to the definition (Yevjevich, 1967). Characteristics of the drought are shown in figure 4.1. The magnitude of the drought characteristics depend on the level of the threshold. For each drought event the characteristics are the drought duration, time between down-crossing and up-crossing from the threshold (d_i), the maximum drought deficit volume, area beneath the threshold (s_i), time of occurrence, τ_i and for each drought the minimum flow or groundwater level (Q_{min} or h_{min}) (e.g. Hisdal *et al.*; 2004, Tallaksen *et al.*, 1997; Peters, 2003). The maximum deficit volume always occurs at the end of the drought (d_i). Drought deficit volume can be calculated according to equation 4.1.

$$s_t = \begin{cases} s_{t-\Delta t} + (Q_0 - Q_t) \cdot \Delta t & \text{if } Q_t \leq Q_0 \\ 0, & \text{otherwise} \end{cases} \tag{4.1}$$

Where:

s = Drought deficit volume (L^3)
Q_0 = Threshold level (L^3T^{-1})
Q = Discharge (L^3T^{-1})
Δt = Time step (T)

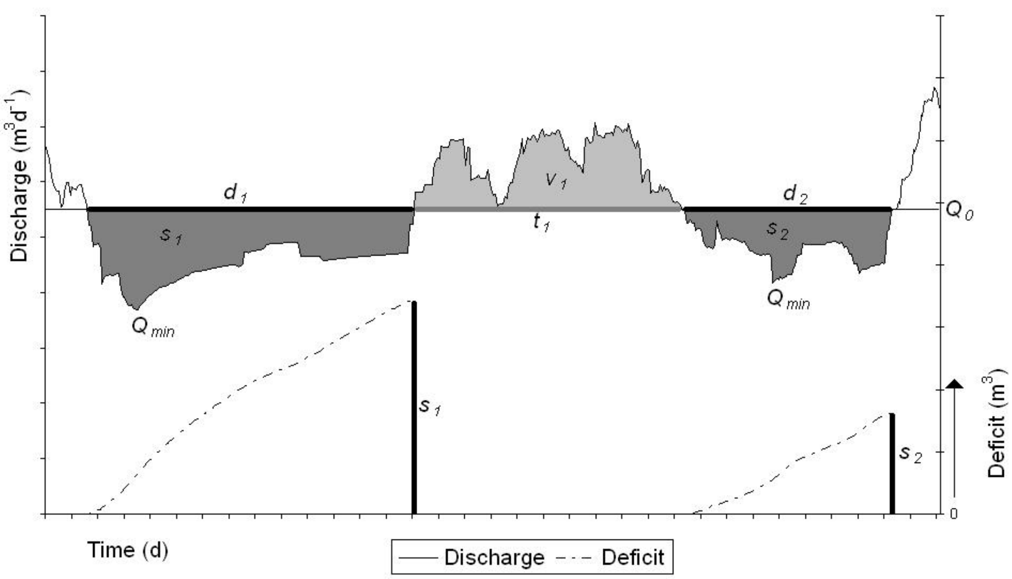

Figure 4.1 Drought characteristics derived with the threshold level method.

Severity of drought is a characteristic which can be determined in different ways. Tallaksen *et al*. (1997) determine it as the drought deficit volume (*s*); Peters (2003) states that severity also can be drought duration (*d*) or intensity (*I*). Peters (2003) defines drought intensity as deficit volume divided by drought duration.
To choose an appropriate threshold level, for most perennial rivers the Q_{90} is a good choice. Q_{90} is the discharge which is equalled or exceeded in 90% of the time. For ephemeral rivers, however, Q_{90} will be in most cases 0 m^3s^{-1}, a higher threshold level should be chosen, like Q_{20} (Santos and Gonçalves-Henriques, 1999; in Peters *et al*., 2003). A new approach is introduced by Peters *et al*. (2003) to derive the threshold level, which is based on the ratio of the total deficit below the threshold level and the total volume below the average level. A threshold level which is based on a percentile flow of each month or for the dry and wet season can also be used. By using different threshold levels, anomalies from the normal situation are investigated rather then droughts (Hisdal *et al*., 2004).
When using the threshold level method, not only major droughts are identified, but also minor droughts, which are more common then major droughts. Some droughts can be mutually dependent; this can be seen when, during a prolonged drought the discharge exceeds for a short period the threshold level. To avoid that a large drought falls apart in several smaller droughts, it is necessary to use a kind of pooling.

Inter-event time and volume based criterion (IC)

The inter-event time is a way of pooling droughts; it is introduced by Zelenhasić and Salvai (1987). If the time between two succeeding droughts, the inter-event time (t_i), is relatively short or if the volume above the threshold, inter-event volume (v_i), is relatively small, then the droughts are assumed to be mutually dependent. Mutually dependent droughts (*i* and *i+1*) can be pooled in one drought, with new characteristics:

$$\begin{aligned} d_{pool} &= d_i + d_{i+1} \\ s_{pool} &= s_i + s_{i+1} \end{aligned} \tag{4.2}$$

This can be done when the inter-event time is equal to or smaller then a predefined critical duration, (t_c), or when the ratio between the inter-event volume and the previous deficit volume is equal to or smaller then a predefined critical value, (p_c) (Tallaksen *et al*., 1997). In many cases this will not be a consistent way of defining mutually dependent droughts, therefore Madsen and Rosbjerg (1995; in Tallaksen *et al*., 1997) suggested a combination of both criteria, both criteria have to be fulfilled before droughts can be pooled. Madsen and Rosbjerg (1995; in Tallaksen *et al*., 1997) also suggested to calculate the drought characteristics slightly different from Zelenhasić and Salvai (1987):

$$\begin{aligned} d_{pool} &= d_i + d_{i+1} + t_i \\ s_{pool} &= s_i + s_{i+1} - v_i \end{aligned} \tag{4.3}$$

The drought period is extended to the inter-event time (t_i). During this time, there is more water available, but not enough to fully recover the drought, that is why the inter-event time is also included in the total drought duration time (d_{pool}) and the inter-event volume (v_i) is subtracted from the total deficit volume (s_{pool}).

Moving average procedure (MA)

By applying a moving average to a time series, before using a drought definition (e.g. the threshold level method), the time series will become smoother (Tallaksen *et al*., 1997). In this case mutually dependent droughts will be pooled to one larger drought. Peaks, which separate dependent droughts, will be reduced and deficit volumes will also be reduced, but the duration of the drought will not decrease. This is consistent with the inter-event criterion from Madsen and Rosbjerg (1995; in Tallaksen *et al*., 1997), equation 4.3.

4.2 Sequent peak algorithm

The sequent peak algorithm (SPA) is another procedure to define droughts. For this procedure it is not necessary to apply pooling. It is based on storage in a reservoir (e.g. a surface water reservoir or an aquifer). To calculate drought deficits the following equation is used (e.g. Hisdal *et al*., 2004; Tallaksen *et al*., 1997):

$$s_t = \begin{cases} s_{t-1} + (Q_0 - Q_t) \cdot \Delta t, & \text{if } s_t < 0 \\ 0, & \text{otherwise} \end{cases} \qquad (4.4)$$

Where:

s = Storage deficit (L^3)

A period of positive s_t, defines a period of storage depletion and subsequent filling up (figure 4.2). Just like for the threshold level method a threshold (i.e. required minimum flow) needs to be defined (Q_0). The storage (depletion) is dependent on this threshold level. The deficit volume (s_i) is defined as the maximum storage deficit, the drought duration (d_{max}) is defined as the time from onset of the drought, (τ_0), to the maximum storage deficit, (τ_{max}), ($d_i = \tau_{max} - \tau_0 + 1$). Extra drought characteristics can also be determined from the sequent peak algorithm, e.g.: total drought duration (d_{total}), this is the total time of a positive sequence of storage (deficit), the ratio d_{total}/d_{max}, the number of peaks in the deficit, during one drought event.

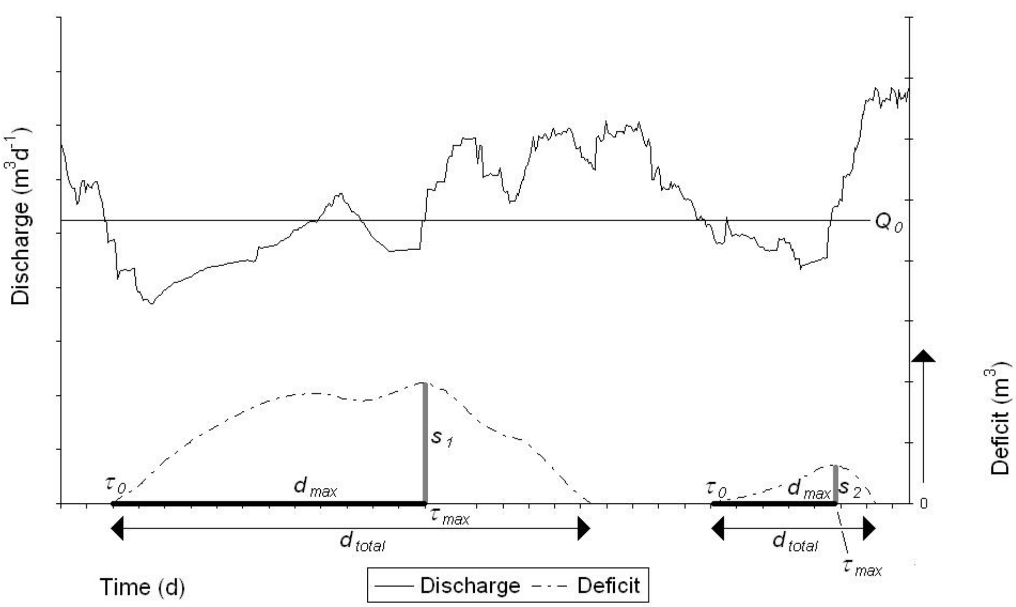

Figure 4.2 Drought characteristics, defined with the sequent peak algorithm.

4.3 State variables

The dimension of a state variable, e.g. groundwater level (L) or soil moisture content (L^3L^{-3}), is different then for a flux like discharge (L^3T^{-1}). Therefore one should take into account that the storage deficit is not a volume, but a variable with dimension (LT or T). The cumulative departure is proposed by Peters and Van Lanen (2000) to derive droughts from groundwater levels; this is the same method as the sequent peak algorithm and will therefore referred to as the sequent peak algorithm. Some others use the maximum deviation as a drought characteristic for state variables (e.g. Van Lanen *et al*., 2004).

4.4 Threshold level method versus sequent peak algorithm

Using the threshold level method and the sequent peak algorithm with the same threshold Q_0, the outcome of the drought characteristics, deficit volume and duration, will be the same, when there is only one peak in the deficit (table 4.1). When there are more peaks, close to each other, the sequent peak algorithm, will pool them automatically into one drought, whereas the threshold level method will distinguish different droughts, unless a pooling criteria is applied (table 4.2)

Table 4.1 Computed deficit volume and duration with the threshold level method and the sequent peak algorithm, for only one peak in the deficit volume.

Threshold level 4320.0 m^3d^{-1}			
		Deficits (m^3)	
Time (d)	**Streamflow (m^3d^{-1})**	**TLM**	**SPA**
1	4579.2	0.0	0.0
2	4233.6	86.4	86.4
3	3974.4	432.0	432.0
4	3628.8	1123.2	1123.2
5	3801.6	1641.6	*1641.6*
6	5529.6	0.0	432.0
7	6480.0	0.0	0.0
Maximum deficit volume (s_i)		*1641.6*	*1641.6*
Duration (d_i or d_{max})		*4*	*4*
Total duration (d_{total}, only SPA)		-	*5*

Table 4.2 The use of the threshold level method and the sequent peak algorithm, for two peaks in the deficit volumes.

Threshold level 4320.0 m^3d^{-1}			
		Deficits (m^3)	
Time (d)	**Streamflow (m^3d^{-1})**	**TLM**	**SPA**
1	4320.0	0.0	0.0
2	3974.4	345.6	345.6
3	3542.4	1123.2	1123.2
4	2246.4	3196.8	3196.8
5	3196.8	4320.0	*4320.0*
6	5961.6	0.0	2678.4
7	6566.4	0.0	432.0
8	4406.4	0.0	345.6
9	3974.4	345.6	691.2
10	3628.8	1036.8	1382.4
11	3369.6	1987.2	2332.8
12	3196.8	3110.4	3456.0
13	67132.8	0.0	0.0
14	67910.4	0.0	0.0
15	23673.6	0.0	0.0
Maximum deficit volume event 1 (s_1)		*4320.0*	*4320.0*
Maximum deficit volume event 2 (s_2)		*3110.4*	-
Duration event 1 (d_1 or d_{max})		*4*	*4*
Duration event 2 (d_2)		*4*	-
Total duration event 1 (d_{total})		-	11

5 Material, methods and approach

The first section in this chapter deals with the datasets (groundwater recharge, groundwater depth and streamflow), which were available for this research. The second section deals with the programs, which were used to compute drought characteristics (*NIZOWKA* and *R*), deficit time series (*Excel* and *R*) and necessary steps in the analysis process (*R*). The last section deals with the approach, which is followed to acquire the results.

5.1 Data

For the drought analyses there were daily time series of different variables available from the Poelsbeek and Bolscherbeek catchments, which were simulated by the program *SIMGRO* (chapter 2) by Querner (1993) and revised by Van Lanen *et al*. (2004). Each time series starts at the first of January 1951 and ends on July 19, 1999. The 29th of February for leap years was not present in the time series.
For the groundwater recharge (Q_r) and the groundwater depth (h^*), simulation results from the middle of the catchment were used. The simulated streamflow (Q_s) came from the outlet of the Poelsbeek and Bolscherbeek, respectively (figure 2.2 and table 5.1). The groundwater recharge was simulated for a subregion, the streamflow for a set of subregions (catchment) and the groundwater depth refers to a nodal point (chapter 2).

Table 5.1 Available simulation results.

		Poelsbeek	**Bolscherbeek**
Variable/Flux	Dimensions	Filename	Filename
Groundwater recharge (Q_r)	mmd^{-1}	SIM_0033.SUB	SIM_0063.SUB
Groundwater level (h^*)	m	SIM_0154.NOD	SIM_0188.NOD
Streamflow (Q_s)	m^{3}s^{-1}	SIM_0013.SUB	SIM_0052.SUB

5.2 Programs to define droughts

In order to extract droughts from the time series, different programs were used. To identify droughts characteristics with the threshold level method the program *NIZOWKA* was used, for the identification of drought characteristics with the sequent peak algorithm the program language *R* was used to program. *R* was also used to produce deficit time series for the threshold level method with pooling criteria and criteria for removing minor droughts. For the more simple operations *Excel* was used.

NIZOWKA

NIZOWKA• is a computer program for estimating and analyzing drought characteristics. For the purpose of this research, *NIZOWKA* was used to calculate exceedance frequencies for the different time series and to derive droughts and calculate its characteristics according to the threshold level method. Drought characteristics can be calculated from the time series by using the threshold level method with or without pooling criteria. The pooling criterion which can be used is based on the inter-event criterion (t_i), as proposed by Zelenhasić and Salvai (1987) (section 4.1). Both durations (d_{pool}, excluding t_i and including t_i, in *NIZOWKA* called τ_{real} and τ_{full}, respectively, equations 4.2 and 4.3) can be calculated. In addition minor droughts can also be removed, by using minimum drought duration (d_{min}). Droughts with a duration smaller then d_{min} are removed. Also droughts can be removed, if the deficit volume is smaller then a fraction (α) of the maximum drought deficit volume in the complete time series. Pooling by means of a moving average cannot be done by *NIZOWKA*. This has to be done prior to analysis with *NIZOWKA*. Other characteristics, which *NIZOWKA* calculates, are

• Authors of the program are: Dr. Wojciech Jakubowski, Department of Mathematics, Agricultural University of Wroclaw, Poland (wj@ozi.ar.wroc.pl) and Prof. Laura Radczuk, Institute of Hydrology, Agricultural University of Wroclaw, Poland.

deficit volume, average (event) deficit, minimum runoff, and the day of minimum runoff, average (event) runoff and the starting and end day. A more extensive description of *NIZOWKA* can be found in Tallaksen (2004) and in Tallaksen *et al*. (2004). How *NIZOWKA* was used in this research is explained in Appendix B.

R

R is a programming environment for statistical computations and graphics. One of the things the environment provides is a programming language, which is similar to *S*. In *R* it is possible to write programs, which are called functions (*R* Development Core Team, 2004). *R* is downloadable from the internet for free. In this study five programs were written for the data analyses; two are to support *NIZOWKA* and are described in appendix B. The purpose of the other three programs is described below.

- For the sequent peak algorithm, a program (*SPA()*) was compiled to extract droughts and its characteristics from a time series (figure 4.2). The characteristics are: the starting day (τ_0), the duration till the maximum deficit volume (d_{max}), the duration till the storage is positive (d_{total}), the maximum deficit volume (s) and the date of the maximum deficit volume (τ_{max}). This program is relatively easy to expand to more characteristics.
- A program (*deficits_TLM()*) was written to generate time series of deficits with the pooling criterion (t_i) and removing drought criterion (d_{min}) similar to *NIZOWKA*. The program was required because *NIZOWKA* does not provide deficit time series. The program *deficits_TLM()* it is possible to vary with t_i and d_{min}. *Excel* could not be used because only time series of deficits could be generated without pooling or removing criteria.
- The last program (*dates()*) was written to generate a time series with only dates; this is done to display the dates in graphs, because in the files simulated with *SIMGRO* only numbers and years were present to indicate the date. Creating dates for the time series could not be done in *Excel*, because the files simulated with *SIMGRO* did not contain data for February 29 in leap years.

How to use these programs is described in appendix B.

5.3 Approach

This section describes what actions were followed to obtain results. Because it was not known in advance what all steps would be, some preliminary results are shown in this section. The preliminary results were used to decide on how to proceed with the research. The final results are presented in chapters 6.

Step 1: Data conversion and filling in

The groundwater depth is given positive below soil surface. For the convenience of this research, the groundwater depth was multiplied with minus one to have a negative groundwater depth below surface level. For *NIZOWKA* it was needed to make a special input file and add February 29 in leap years (*input_NIZOWKA()*, appendix B). In each leap year the simulated data shifts one day (the value for the first of March 1952 becomes the value for February 29 and so on).

Step 2: Initial choice threshold level

Before starting to analyze the data with the different drought definitions, threshold levels should be chosen. As an initial choice threshold levels of 70%, 75%, 80%, 85%, 90% and 95% were calculated. The computed levels for the different variables and the two catchments can be found in table 5.2. To limit the number of options, only 70%, 80%, 90% and 95% were used in the rest of the research. For Q_r a moving average of 30 days was taken, because Q_r is very irregular and peaky. This transferred Q_r has other threshold levels (table 5.2).

Table 5.2 Threshold levels for Poelsbeek and Bolscherbeek for different exceedance frequencies.

	Threshold levels				
	Exceedance frequency (%)	Q_r (mmd^{-1})	Qr (with MA of 30 days, mmd^{-1})	h* (m)	Q_s (m^{3}s^{-1})
Poelsbeek	70	-0.750	0.128	-1.110	0.085
	75	-0.860		-1.150	0.063
	80	-1.010	-0.209	-1.190	0.045
	85	-1.200		-1.230	0.026
	90	-1.470	-0.549	-1.270	0.010
	95	-1.940	-0.748	-1.350	0.000
Bolscherbeek	70	-1.080	0.031	-1.230	0.176
	75	-1.260		-1.280	0.152
	80	-1.500	-0.350	-1.330	0.129
	85	-1.780		-1.380	0.103
	90	-2.150	-0.790	-1.440	0.079
	95	-2.810	-1.054	-1.550	0.050

Step 3: Application of drought definitions

The drought definitions which were used in this research are summarized in table 5.3. These definitions were applied to the time series with the earlier selected threshold levels (table 5.2). The choice for the value of t_i and d_{min} was based on the default values of *NIZOWKA*. The choice for a ten days moving average is a common choice for moving averages (e.g. Tallaksen *et al*., 1997). *NIZOWKA* needs full years as input in this case from the first of January 1951 till December 31 of 1998, only for the input with a moving average of 30 days the time series starts at January 16 of 1951 and end at January 15 of 1999. The analysis on the time series is done for the period from January 16 1951 till December 31 1998, in order to investigate for each drought definition the same period.

Table 5.3 Drought definitions which were used.

Drought definitions			
	Threshold level method		
	t_i (d)	d_{min} (d)	Moving Average (d)
TLM_0_0_XX•	0	0	0
TLM_3_0_XX•	3	0	0
TLM_0_5_XX•	0	5	0
TLM_3_5_XX•	3	5	0
TLM_MA_XX•	0	0	10
SPA_XX•	Sequent peak algorithm		

• XX = exceedance frequency.

Step 4: Data treatment

After running *NIZOWKA* or *SPA()* (*R*), the output data were treated before they were ready to use. In table 5.4 an overview of the necessary treatments are presented. *NIZOWKA* assumes the input data as a discharge with units m^{3}s^{-1}, because Q_r and h^* are in mmd^{-1} and m, respectively the deficit volumes of Q_r and h^* had strange output units (mmd^{-1}s and ms, respectively) Conversion of the units of Q_r and h^* in order to get mm and md had to take place. Q_s was divided by the area of the catchment and multiplied with thousand, to get mm, in order to compare Q_s and Q_r. All deficit outputs of *NIZOWKA* are multiplied with thousand (table B.1). The program for the sequent peak algorithm already assumes the input to be in units (e.g. mm) per day, so only the output (deficit volume) of Q_s had to be transformed from m^{3}s^{-1}d into mm. Since *NIZOWKA* needs data input with February 29 in leap years and the simulated data with *SIMGRO* did not have those days, February 29 should be removed from the *NIZOWKA* output dates (*remove_leap()*), February 29 was first added by *input_NIZOWKA()*.

Table 5.4 Data treatment for the output of NIZOWKA *and the* SPA() *program.* s_N *and* s_R *are the output deficit volumes of* NIZOWKA *and* SPA()*, respectively.* A *is the catchment area* (m^2)*. The units of the deficit volumes after treatment are:* s(Q_r) *(mm),* s(h*) *(md) and* s(Q_s) *(mm).*

Data treatment			
	Threshold level method		
	Q_r	h^*	Q_s
Deficit volume (s)	s_N*1000/86400	s_N*1000/86400	s_N*1000/A*1000
Day of minimum runoff	remove February 29 with *remove_leap()* (appendix B)	remove February 29 with *remove_leap()* (appendix B)	remove February 29 with *remove_leap()* (appendix B)
Starting day	remove February 29 with *remove_leap()* (appendix B)	remove February 29 with *remove_leap()* (appendix B)	remove February 29 with *remove_leap()* (appendix B)
End day	remove February 29 with *remove_leap()* (appendix B)	remove February 29 with *remove_leap()* (appendix B)	remove February 29 with *remove_leap()* (appendix B)
Full duration (τ_{full})	calculate: End day - Staring day + 1	calculate: End day - Staring day + 1	calculate: End day - Staring day + 1
	Sequent peak algorithm		
	Q_r	h^*	Q_s
Deficit volume (s)	-	-	s_R*86400/A*1000

Step 5: Choice of drought definitions

Since it was not feasible to continue with all combinations of definitions presented in table 5.2 and 5.3, finally five definitions were chosen. The choice is fairly arbitrary, but based on the assumptions that h^* has on average one drought per year, Q_r two droughts per year and Q_s 1½ droughts per year. With these chosen definitions droughts in the Poelsbeek were investigated.

Step 6: Comparing different drought definitions

For the different drought definitions, time series of deficits were made. For the threshold level method, without pooling and removing minor drought and the sequent peak algorithm the generation of time series was simply done in *Excel*, with equation 4.1 and 4.4, respectively. For the other cases it was done with the program *deficits_TLM()* (appendix B). With the program *dates()* the dates were created for the time series.
To compare drought characteristics for different major droughts in the time series, the three most severe droughts in the deficits time series were selected from h^* (1959, 1976 and 1976). For these years the duration (full and real) and the time lag in starting date between Q_r, h^* and Q_s were compared for each drought definition.

Step 7: Verifying results Poelsbeek on droughts in Bolscherbeek

With three of the definitions used for the Poelsbeek, the droughts in the Bolscherbeek were investigated. This was done in order to find out whether definitions which seems reasonable for one catchment can be applied to another catchment, with the same climatological and geological conditions, although due to the sewage plant the flow regime is somewhat different (section 3.3).

In figure 5.1 a flowchart is presented with an overview of all necessary steps to come to drought characteristics and time series with deficits.

5 Material, methods and approach

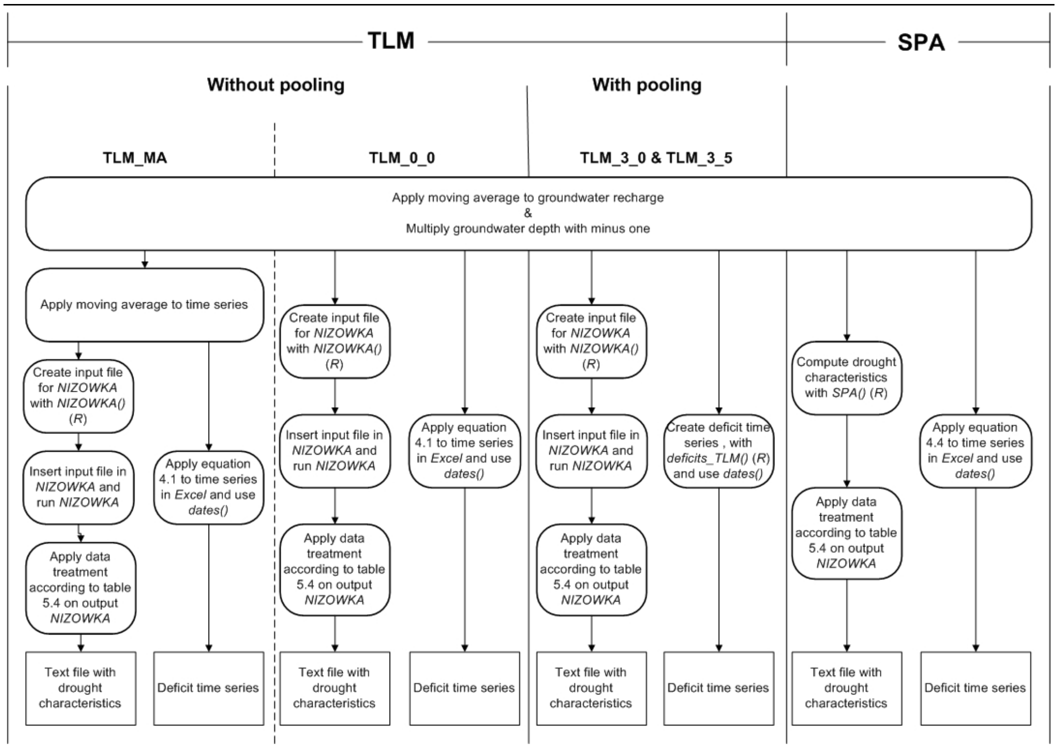

Figure 5.1 Flow chart of all nececcary steps in drought analysis.

6 Results

For each drought criteria (step 3, section 5.3) characteristics were calculated for the Poelsbeek and Bolscherbeek, the most important characteristics are tabulated in appendix C, table C.1-C.4. The tables give the real and full duration (or for the sequent peak algorithm d_{max} and d_{total}), the drought deficit volume, the minimum runoff (except for the sequent peak algorithm) and the number of droughts. In table 6.1 a comparison is made between the characteristics of the Poelsbeek and the Bolscherbeek. This was done per characteristic, by subtracting the average values for one drought definition of the Bolscherbeek from the Poelsbeek and then taking the average difference of all the drought definitions (except SPA, because the characteristics are not completely the same). From this table it is clear that there is a difference in the characteristics between the Poelsbeek and the Bolscherbeek, in drought durations, the deficit volume and the number of droughts in Q_s. The drought durations in Q_s for the Bolscherbeek were much higher then the durations for the Poelsbeek. The deficit volume in the Q_r and $h*$ was slightly larger for the Bolscherbeek. The number of (minor) droughts in the Bolscherbeek for Q_s was much larger then for the Poelsbeek.

Table 6.1 Difference in drought characteristics between the Poelsbeek and the Bolscherbeek.

	Q_r		$h*$		Q_s	
Real duration (τ_{real})	0.1	d	0.2	d	24.4	d
Full duration (τ_{full})	-0.1	d	0.5	d	25.8	d
Deficit volume (s)	-2.1	mm	-1.2	md	-0.2	mm
Minimum runoff	0.3	mm	0.2	m	0.0	m^3s^{-1}
Number of droughts	-1.9		-1.9		-171.5	

6.1 Application of definitions to the Poelsbeek

Choice of definitions

In table 6.2 the number of droughts is sorted for the Poelsbeek. The drought definitions in the box are the selected droughts according to the criterion described in section 5.3, step 5. Per flux (Q_r and Q_s) or state variable ($h*$) different definitions were identified. From this the five most common definitions were chosen, which were applied to all fluxes and state variables. The definitions are: TLM_MA_80, TLM_3_0_90, TLM_3_5_90, SPA_90 and SPA_80 (indicated in *italic* in table 6.2).

Selection of three major droughts

In appendix D graphs with the deficit volumes derived from the groundwater depth, groundwater recharge and streamflow are presented (figure D.1). For the groundwater depth it is clear that the three major droughts are the years 1959, 1976 and 1996, which also applies to the streamflow. The groundwater recharge, however, has different years with major droughts, namely 1959, 1983 and 1995. In this research the major droughts derived from the groundwater depth were used.

Table 6.2 Number of droughts per flux or state variable in increasing order.

Number of droughts					
Q_r		**h^***		**Q_s**	
TLM_MA_95	46	TLM_MA_95	16	TLM_0_0_95	0
TLM_0_5_95	48	SPA_95	16	TLM_3_0_95	0
TLM_3_5_95	48	TLM_3_0_95	18	TLM_0_5_95	0
SPA_95	70	TLM_3_5_95	18	TLM_3_5_95	0
TLM_3_0_95	74	TLM_0_5_95	19	TLM_MA_95	0
TLM_MA_90	74	TLM_0_0_95	20	SPA_95	0
TLM_0_5_90	77	*SPA_90*	*35*	TLM_MA_90	42
TLM_3_5_90	*78*	TLM_MA_90	37	*TLM_3_5_90*	*43*
TLM_0_0_95	88	*TLM_3_5_90*	*40*	TLM_0_5_90	44
SPA_90	*96*	TLM_0_5_90	43	*SPA_90*	*44*
TLM_3_0_90	*100*	*SPA_80*	*46*	*TLM_3_0_90*	*60*
TLM_MA_80	*101*	*TLM_3_0_90*	*50*	*TLM_MA_80*	*74*
SPA_80	*105*	*TLM_MA_80*	*54*	*SPA_80*	*74*
TLM_3_5_80	107	TLM_0_0_90	56	TLM_0_0_90	81
TLM_0_5_80	111	TLM_3_5_80	57	TLM_3_5_80	81
TLM_0_0_90	119	TLM_0_5_80	63	TLM_0_5_80	84
TLM_3_0_80	135	TLM_3_0_80	65	TLM_3_0_80	106
TLM_0_0_80	152	TLM_0_0_80	79	TLM_0_0_80	116
Average	91		41		47

The drought definitions in the boxes fulfil approximately the criterion of Q_r two droughts per year, h^* one drought per year and Q_s 1 ½ droughts per year on average. The definitions in *italic* are chosen to continue with.

Drought propagation in the Poelsbeek

Tables with drought characteristics for the selected years and drought definitions are presented in appendix E. Appendix F gives for the three selected major droughts and the selected definitions, graphs with fluxes (Q_r, and Q_s) and groundwater depth (h^*) and the threshold levels (figure F.1-3). Appendix F also presents graphs with deficit time series, derived from Q_r, h^* and Q_s (figure F.4-7).

For all selected major droughts (1959, 1976 and 1996) and drought definitions the propagation of the drought in the Poelsbeek started with a drought in groundwater recharge, after a while the drought in the streamflow followed and latest the groundwater depth also experienced a drought. All variables and fluxes had only one (single) drought. This was also the order of increasing drought duration (real or max and full or total). The time lag between drought in groundwater recharge, depth and streamflow increased from Q_s-h^*, Q_r-Q_s and Q_r-h^* (figure 6.1 and table 6.3). Exceptions to this general conclusion are described below per drought definition.

TLM_MA_80: the groundwater recharge experienced two droughts in the investigated years (table E.1 and figure F.4). The real and full duration were the same, this is in accordance with the definitions of a threshold level method with moving average.

TLM_3_0_90 and TLM_3_5_90: these definitions showed identical droughts in the investigated years (table E.3 and figure F.5). The streamflow had in the year 1996 two droughts, in the other investigated years only one. Both real and full duration were the same, which means that no pooling took place and there were also no minor droughts removed for these years. For other years and droughts the real and full duration were not the same, because the durations did not have the same averages for TLM_3_0_90 and TLM_3_5_90 (table C.1) and the number of droughts is not equal (table 6.2 and table C.4).

SPA_90: the duration and total duration were not the same (table E.3 and figure F.6). Durations were longer then for the previous definitions.

SPA_80: the order of increasing duration was different from the general conclusion; the increasing order was groundwater recharge, groundwater depth and streamflow (table E.4 and figure F.7). In 1959 the drought in groundwater depth was not yet over when new droughts in groundwater recharge and streamflow started in 1960. In 1996 the previous drought in groundwater depth was not yet over when droughts in groundwater recharge and streamflow started, the increasing order of the lag in starting date was Q_r-Q_s, h^*-Q_r and h^*-Q_s. In 1976 all droughts continued in 1977.

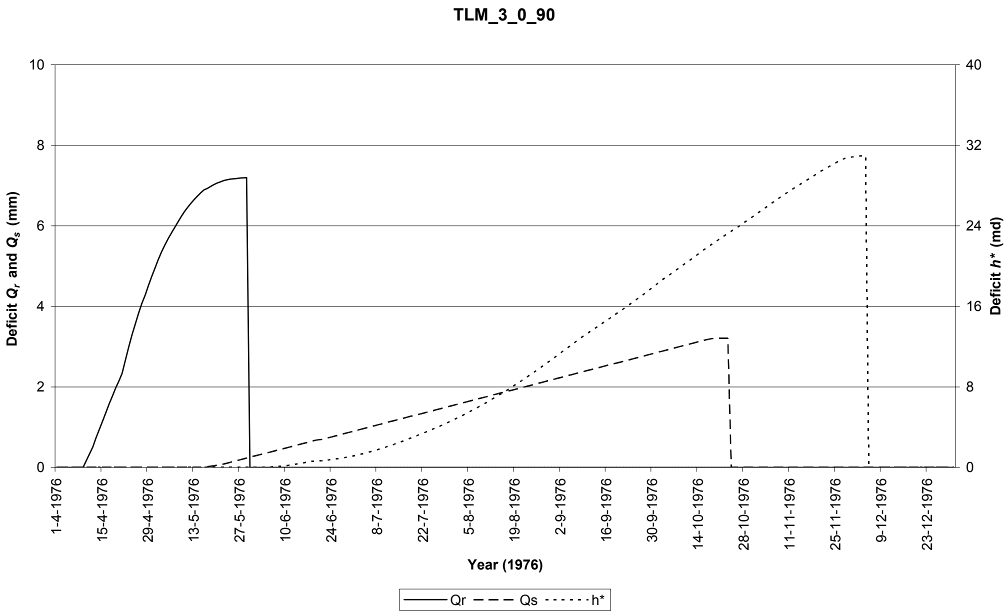

Figure 6.1 Example of deficit volumes (Q_r, h^* *and* Q_s*) for TLM_3_0_90 in the year 1976.*

Table 6.3 Example of drought characteristics in TLM_3_0_90 for the year 1976.

TLM_3_0_90 for the year 1976						Starting difference		
	start date	end date	τ_{real} (d)	τ_{full} (d)	s (mm or md)•	Q_r-h^* (d)	h^*-Q_s (d)	Q_r-Q_s (d)
Q_r	10-4-1976	29-5-1976	50	50	7.20			
h^*	30-5-1976	4-12-1976	189	189	30.96	50	-15	35
Q_s	15-5-1976	23-10-1976	162	162	3.21			

• Deficit volumes derived from Q_r and Q_s are in mm and from h^* are in md.

6.2 Illustration of definitions for the Bolscherbeek

Some of the drought definitions that were investigated for the Poelsbeek catchment (section 6.1) were also applied to the Bolscherbeek catchment. These drought definitions were the threshold level method with moving average with a threshold level of Q_{80} (TLM_MA_80) and with a pooling criterion of three days and removing minor drought criterion of five days with a threshold level of Q_{90} (TLM_3_5_90) and the sequent peak algorithm with a threshold level of Q_{90} (SPA_90). The year 1976 was used to illustrate the development of droughts in the Bolscherbeek. The droughts in the other years (1959 and 1996) deviate in a similar way from droughts in the Poelsbeek as the drought in 1976. The drought characteristics, flow graphs and deficit graphs are presented in appendix G.

The durations of droughts derived from Q_r were for all definitions longer then durations in the Poelsbeek. The deficit volumes were larger. In other aspects there were no differences in comparison with the Poelsbeek. The characteristics for h^* were quite similar to h^* in the Poelsbeek. Q_s experienced more and shorter (duration) droughts then the droughts in the Poelsbeek. The cumulative deficits of droughts streamflow had a larger volume then the deficits derived from Q_s in the Poelsbeek. The full duration and the real duration were not equal for TLM_3_5_90, in contrary to the Poelsbeek.

7 Conclusions, discussion and recommendations

This chapter contains of two sections. The first section contains conclusions and discussion, the second section contains eventually recommendations for further research.

7.1 Conclusion and discussion

In this section conclusions and discussion are given on the results from chapter 6. First conclusions are given on droughts in the Poelsbeek followed by conclusions on droughts in the Bolscherbeek and last conclusions on the difference between fluxes and state variables are given.

Propagation of droughts in the Poelsbeek

In general a drought event starts with a drought in groundwater recharge, followed by a drought in streamflow and then a drought in groundwater depth. For droughts defined with the threshold level method with a moving average of 10 days there are two droughts in groundwater recharge, droughts defined with other definitions do have one drought in groundwater recharge. The drought duration increases from groundwater recharge to streamflow; drought in the groundwater depth has the largest duration. There are several reasons for this.

The groundwater recharge starts to develop a drought first because this represents transport of water to or from the groundwater system. It would be logical if a drought in the groundwater depth starts to develop after the groundwater recharge, but apparently this is not the case.

A reason why the streamflow starts to develop a drought before the groundwater depth can be the increasing persistence (duration and deficit volume) in groundwater level droughts with increasing distance to the stream. Close to the stream the groundwater level is constrained by the level of the stream, near the catchment divide the groundwater level can move more freely and close to the stream fluctuations in groundwater recharge are smaller, because of a shallower unsaturated zone then near the catchment divide (Peters, 2003).

Another reason for the characteristic propagation is the areal representativity of the simulated time series in the catchment. The time series for the groundwater recharge and groundwater depth are representative for an element and a nodal point, respectively, in the catchment and are assumed to be representative for the whole catchment. Maybe this assumption is not a valid assumption (Peters, 2003). The streamflow is simulated in a reservoir near the outlet of the catchment and therefore representative for the whole catchment.

In this research different drought definitions were selected (TLM_MA_80, TLM_3_0_90, TLM_3_5_90, SPA_80 and SPA_90). Not all these definitions seem to be a good choice for all situations. Although the sequent peak algorithm with a threshold level of 80% was selected because of the number of droughts for the groundwater depth and streamflow, this does not seem a goods choice in retrospective, because the number of droughts is reduced as a result of the pooling caused by the filling up of the reservoir (section 4.2).

Bolscherbeek

Droughts in groundwater recharge and groundwater depth in the Bolscherbeek catchment show similar behaviour as droughts in the Poelsbeek. Droughts in the streamflow, however, show a different behaviour. There are more separated droughts. This behaviour is probably a result of the effluent of the sewage plant, which discharges on the Bolscherbeek. A way to avoid this behaviour can be to increase the pooling criteria (t_c) or apply a moving average to the streamflow.

Fluxes versus state variables

In this research for all variable (Q_r, h^* and Q_s) the same definitions were used. For the groundwater depth, however the sequent peak algorithm might not be a good choice. This is because the groundwater depth is not a volume and consequently there is no reservoir which has to be filled up after the depth has crossed up the threshold level.

7.2 Recommendations

It was not possible to investigate all aspects of groundwater droughts and during the research new aspects of droughts popped-up. In this section some suggestions for further research are given.

- In this research drought propagation was investigated with one definition for al variables (Q_r, h^* and Q_s). This might not be the best solution and therefore further research is needed to investigate the characteristics of droughts and propagation with different drought definitions for the different variables.
- The sequent peak algorithm was also applied to the groundwater depth. In further research it should be investigated whether the sequent peak algorithm is an appropriate definition for the groundwater depth.
- In order to achieve a better set of drought definitions the threshold level method can be applied with other criteria (t_c and d_{min}). Also the use of the ratio α can be studied (appendix B).
- Other pooling criteria (e.g. p_c) can be applied for the threshold level method, with characteristics d_{pool} and s_{pool} according to equation 4.3
- The threshold levels used in this research are arbitrary and do not have an operational meaning. To investigate drought in relation to e.g. shipping, extraction of water or agriculture a threshold level should be chosen below which activities are not possible anymore.
- During this research only drought duration and time lag between variables are investigated. Besides these characteristics deficit volume, minimum flow or depth, ratio d_{real}/d_{full} (d_{max}/d_{total}) and the number of peaks in deficit for one drought can be investigated (chapter 4).

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Appendix A: Duration curves

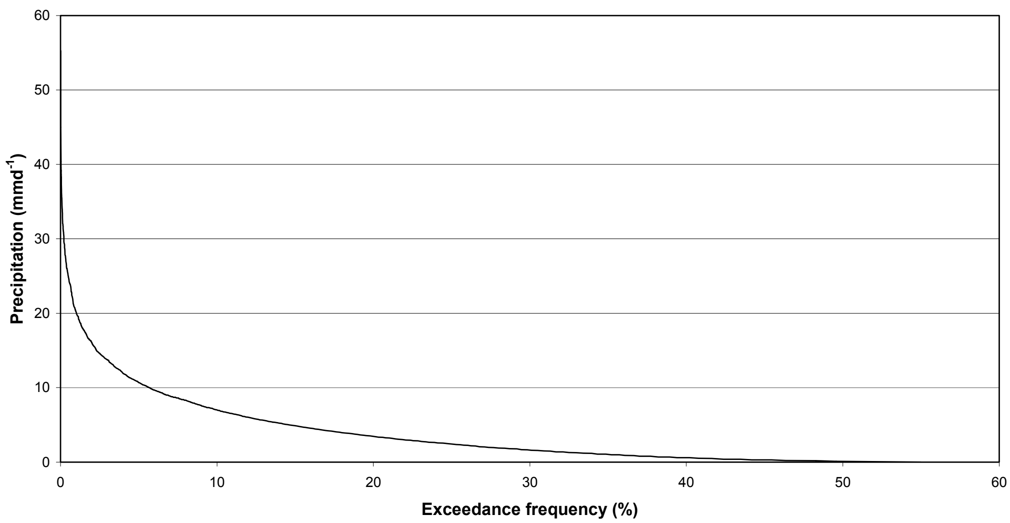


Figure A.1 Duration curve of daily precipitation averaged over the Poelsbeek and Bolscherbeek catchment.

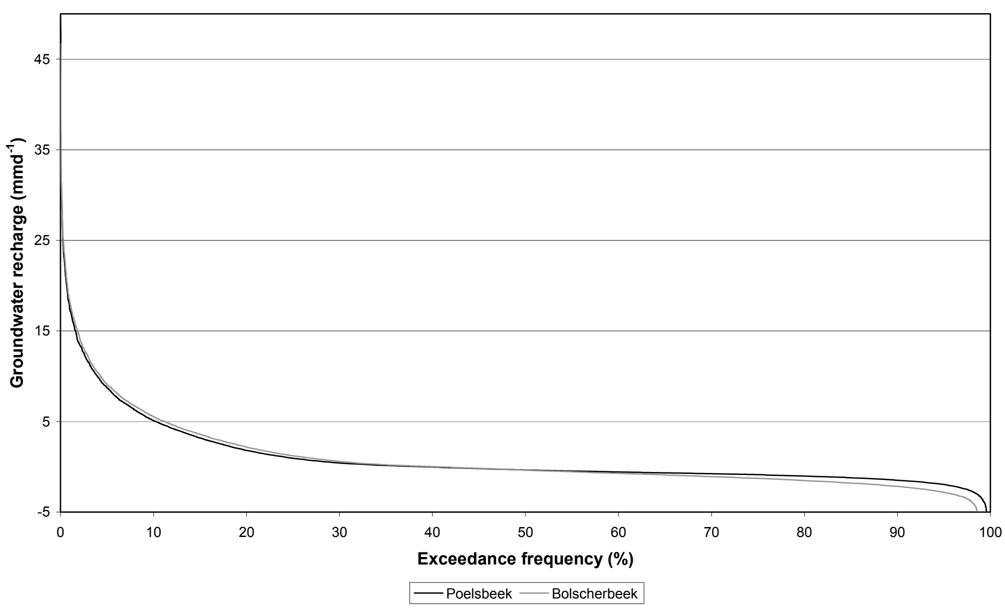


Figure A.2 Duration curves of groundwater recharge for two representative subregions in the Poelsbeek and Bolscherbeek catchment.

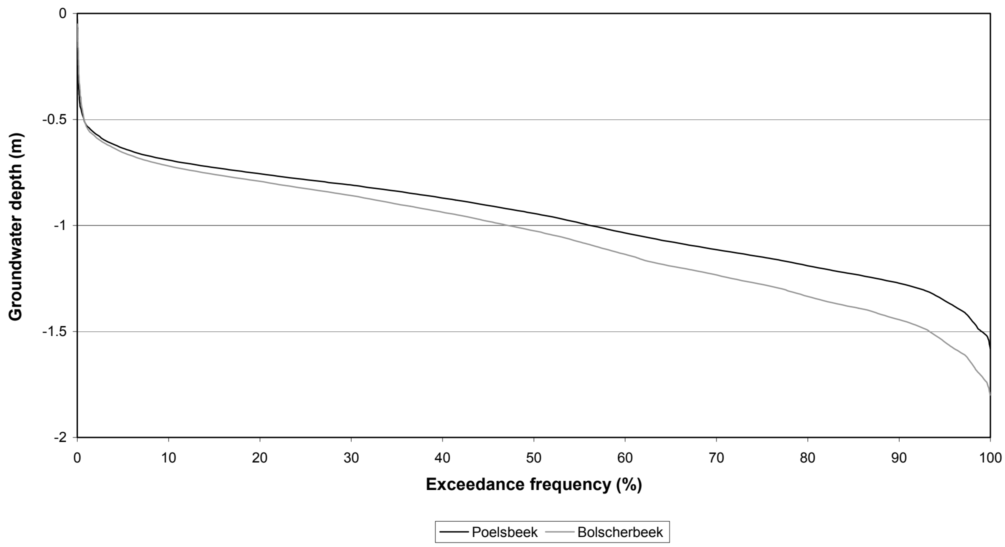


Figure A.3 Duration curves of groundwater depth for two representative nodes in the Poelsbeek and Bolscherbeek catchment.

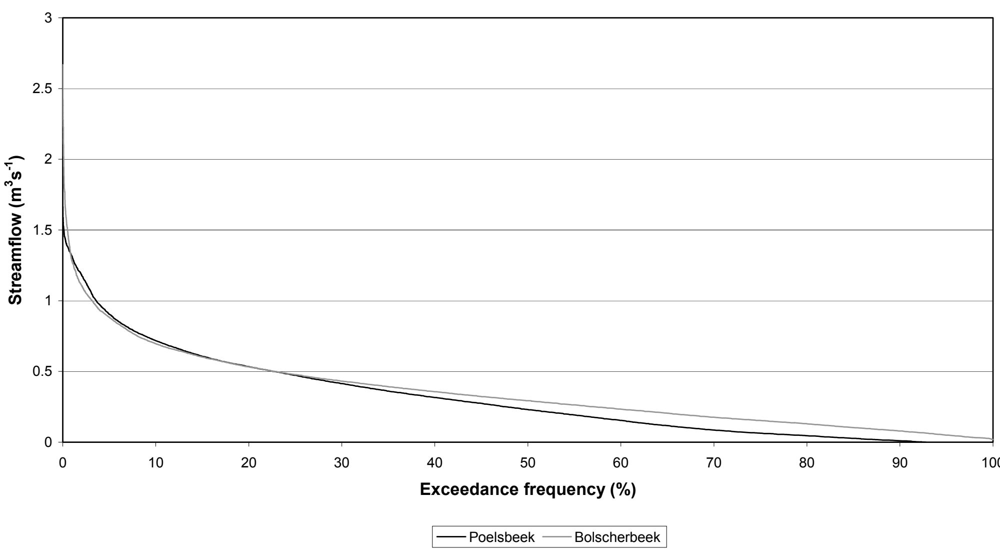


Figure A.4 Flow duration curves for the Poelsbeek and Bolscherbeek.

Appendix B: Programs

In this appendix follows a short description of the use of the programs *NIZOWKA* (threshold level method) and *R* (mainly used for SPA). It is assumed that the reader already has sufficient knowledge about *Excel*. In the subsection on *NIZOWKA* also recommendations are presented to improve *NIZOWKA*. In the subsection on *R* the use of the different programs is explained.

NIZOWKA

In this section only additional information to the software manual (Tallaksen *et al*., 2004) is given. Because *NIZOWKA* requires February 29 for leap years in the input file and the simulations done by *SIMGRO* does not provide these days, it is needed to add these to the time series and remove them from the output after using *NIZOWKA*. Removal is done in order to compare the characteristics obtained with *NIZOWKA* and the characteristics obtained with SPA. The procedure to do this is also described in this section.

Input

To work with *NIZOWKA* an appropriate input file is needed. According to Tallaksen *et al*. (2004) an example file is stored in the folder INPUT_PL and INPUT_GB of the program. Unfortunately these folders and the example file were not present. The input file is a text file with a number as name. The first column of the text file contains the name (number) of the file and the date (yyyy, mm, dd), all separated with a comma (figure B.1). The second column contains the data. The input file should contain a number of complete years (e.g. January 6, 1951 till January 5, 1999) and should also contain February 29 in leap years. If the input file is not available, in the correct format, it can keyed in or be generated by a program in any computer language. Here it was decided to use *R* (section 5.2 and next section). The resulting program (*input_NIZOWKA()*) can be found on the CD. After using this program, the data can be stored in *Excel*. Save the file as **.prn* file and rename this file as a **.txt* file. The input file should be put in a folder of the program *NIZOWKA* (e.g. INPUT_GB). Now the file is ready to be used by *NIZOWKA* (Tallaksen *et al*., 2004). *NIZOWKA* assumes the input data to be in m^3s^{-1}.

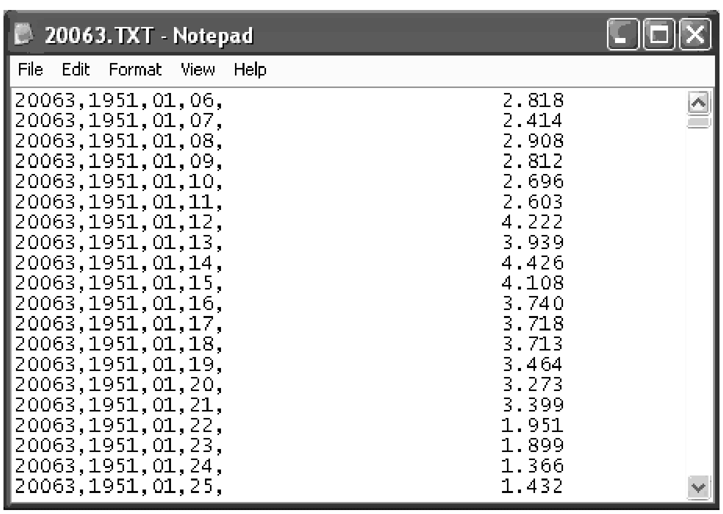


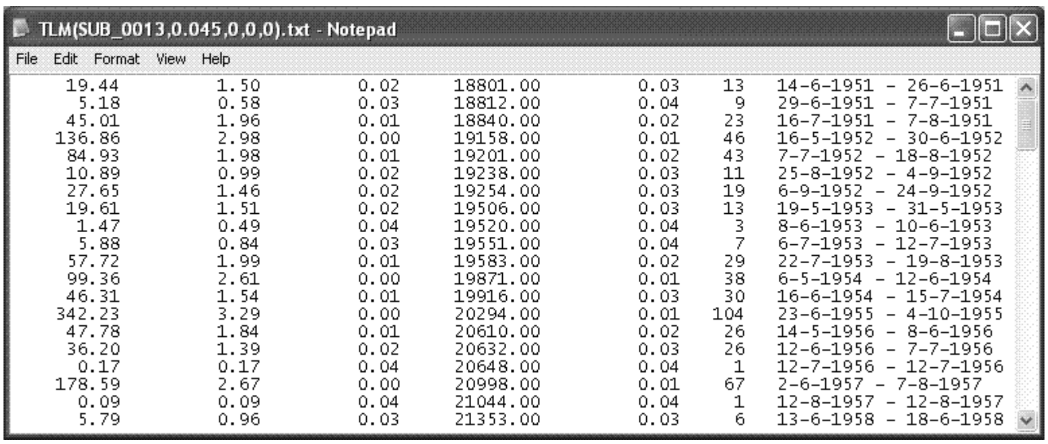
Figure B.1 Example of an input file for NIZOWKA. *The first column is produced with* NIZOWKA()*; the second is added in* Excel.

Drought characteristics

After computing a file with drought characteristics by *NIZOWKA*, the file can be saved as a text file. When saving the file with drought characteristics, the order of the characteristics slightly changes from the order on the screen. The order of characteristics in the saved text file is given in table B.1 and figure B.2. The 29th of February should be removed; this can be done with the program *remove_leap()*.

Table B.1 Content of NIZOWKA *output of drought characteristics, saved in a text file. Example of an output in figure B.2.*

Column	Quantity	Dimension	Description	Explanation
1	s	1000x m^3	Deficit volume	
2	$s\tau_{full}^{-1}$	1000x m^3	Average drought deficit	
3	Q_{min}	m^3s^{-1}	Minimum runoff	
4		d	Day of minimum runoff	Shown as a day number, starting with 1 at 1-1-1900, *Excel* uses this notation
5	$\overline{Q}$	m^3s^{-1}	Average drought runoff	
6	τ_{real}	d	Real duration	Total duration when the discharge is equal to or lower then the threshold
7			Starting day	Shown as a date (dd-mm-yyyy)
8			End day	Shown as a date (dd-mm-yyyy)



19.44	1.50	0.02	18801.00	0.03	13	14-6-1951 - 26-6-1951
5.18	0.58	0.03	18812.00	0.04	9	29-6-1951 - 7-7-1951
45.01	1.96	0.01	18840.00	0.02	23	16-7-1951 - 7-8-1951
136.86	2.98	0.00	19158.00	0.01	46	16-5-1952 - 30-6-1952
84.93	1.98	0.01	19201.00	0.02	43	7-7-1952 - 18-8-1952
10.89	0.99	0.02	19238.00	0.03	11	25-8-1952 - 4-9-1952
27.65	1.46	0.02	19254.00	0.03	19	6-9-1952 - 24-9-1952
19.61	1.51	0.02	19506.00	0.03	13	19-5-1953 - 31-5-1953
1.47	0.49	0.04	19520.00	0.04	3	8-6-1953 - 10-6-1953
5.88	0.84	0.03	19551.00	0.04	7	6-7-1953 - 12-7-1953
57.72	1.99	0.01	19583.00	0.02	29	22-7-1953 - 19-8-1953
99.36	2.61	0.00	19871.00	0.01	38	6-5-1954 - 12-6-1954
46.31	1.54	0.01	19916.00	0.03	30	16-6-1954 - 15-7-1954
342.23	3.29	0.00	20294.00	0.01	104	23-6-1955 - 4-10-1955
47.78	1.84	0.01	20610.00	0.02	26	14-5-1956 - 8-6-1956
36.20	1.39	0.02	20632.00	0.03	26	12-6-1956 - 7-7-1956
0.17	0.17	0.04	20648.00	0.04	1	12-7-1956 - 12-7-1956
178.59	2.67	0.00	20998.00	0.01	67	2-6-1957 - 7-8-1957
0.09	0.09	0.04	21044.00	0.04	1	12-8-1957 - 12-8-1957
5.79	0.96	0.03	21353.00	0.03	6	13-6-1958 - 18-6-1958

Figure B.2 Example output in saved text file of drought characteristics in NIZOWKA.

Recommendations for improving NIZOWKA

During this study with *NIZOWKA* items were encountered which were not present in *NIZOWKA* and which would be practical for the analysis of drought to incorporate also in *NIZOWKA*. Also a few difficulties arose. Below a list is presented with recommendations to extend and improve *NIZOWKA*.

- Provide also an option with which a time series of deficit volumes can be created (to replace *deficit_TLM()*).
- Extend *NIZOWKA* with the pooling criteria p_c (Zelenhasić and Salvai, 1987 and section 4.1).
- Extend *NIZOWKA* with the pooling criteria and characteristics according to Madsen and Rosbjerg (1995; in Tallaksen *et al.*, 1997).
- Provide an example input file (it should be there according to the help function, but it was not there) or show how this should look like.

R

This section deals with how to work with *R* and how to use the programs. All programs can be found on the CD as text file and in **.RData* files. For each program a table is available with a description of the input arguments and some information about the output file.
The statistical program *R* can be obtained freely from the website of the *R* project: http://www.r-project.org/index.html (last visited June 2005). Before using *R* and running the programs developed in this study, it is important to put, if an input file is needed, the input file in the same folder as the program. All programs in this study produce an output file. To create this file it is required to load an extra package in *R*, this can be done by choosing *Packages* in the menu bar, then *Load package…* and taking the package *MASS*. After loading the *MASS*-package, the program can be copied in *R*. The program can be run by typing in the name of the program, e.g. *SPA()*, and typing between the brackets the input arguments separated by a comma, e.g. *SPA("NOD_0154",11,-1.11,1951,1)*. Input arguments being no numbers should be placed between quotation marks.

input_NIZOWKA()

Table B.2 Input arguments for NIZOWKA(days,startyear,filename).

Input argument	Description
days	Number of days for which an input file for *NIZOWKA* should be made.
startyear	The starting year which the input file should have.
filename	The name for the input file (number of gauging station), this should be a number.

The output is a text file with one column, containing the name of the input file for *NIZOWKA* and the dates, separated by comma's (first column in figure B.1).

remove_leap()

Table B.3 Input arguments for remove_leap(dataset,output).

Input argument	Description
dataset	The name of the dataset, in which only the dates are stored in the first column, this file does not have a header in the first row. The dates are copied from the output file of *NIZOWKA*.
output	The name of the output file.

The output file is a text file with a column of dates. This column can be copied back in the output file of *NIZOWKA*.

SPA()

Table B.4 Input arguments for SPA(SIM,k,Q0,startyear,startday).

Input argument	Description
SIM	The name of the input file, without **.txt*. This file can contain more columns with data and the first row contains a header with information about the data.
k	The column in which the data of interest is stored.
Q0	The value of the threshold level, in the same dimensions as the data.
startyear	The year in which the data starts.
startday	The first day of the dataset, if this is for example February 10, it should be 41.

*Table B.5 Explanation for the output file of SPA(*SIM,k,Q0,startyear,startday*).*

Column number	Description
1	The first day of the drought (dd-mm-yyyy).
2	Drought duration (d_{max}).
3	Total drought duration (d_{total}).
4	The maximum deficit volume (m^3, supposed that the input is in m^3d^{-1}).
5	The day of the maximum deficit volume (dd-mm-yyyy).

The output is a text file.

deficits_TLM()

Table B.6 Input arguments for deficits_TLM(SIM,k,Q0,sep,minor).

Input argument	Description
SIM	The name of the input file, without **.txt*. This file can contain more columns with data and the first row contains a header with information about the data.
k	The column in which the data of interest is stored.
Q0	The value of the threshold level, in the same dimensions as the data.
sep	The pooling criterion, t_i, in days.
minor	The drought removing criterion, d_{min}, in days.

The output is a text file containing one column with results.

dates()

Table B.7 Input arguments for dates(days,startyear).

Input argument	Description
days	The length of the data vector
startyear	The first year

The output is a text file containing one column with dates.

Appendix C: Average drought characteristics

Table C.1 Average and standard deviation of the real and total duration for droughts in the Poelsbeek and Bolscherbeek, defined with different drought definitions.

				Drought durations (d)					
				Poelsbeek			Bolscherbeek		
				Q_r	h^*	Q_s	Q_r	h^*	Q_s
TLM_0_0	80%	Real duration	Average	23.1	45.0	30.4	22.1	48.2	6.5
			Standard deviation	26.1	54.2	43.7	27.1	58.3	6.8
		Full duration	Average	23.1	45.0	30.4	22.1	48.2	6.5
			Standard deviation	26.1	54.2	43.7	27.1	58.3	6.8
	90%	Real duration	Average	14.8	32.5	22.8	13.0	33.5	6.5
			Standard deviation	14.8	47.0	28.5	15.0	48.2	7.0
		Full duration	Average	14.8	32.5	22.8	13.0	33.5	6.5
			Standard deviation	15.8	47.0	28.5	15.0	48.2	7.0
	95%	Real duration	Average	10.0	46.3	-	9.4	44.4	7.5
			Standard deviation	10.0	48.8	-	10.4	46.4	7.8
		Full duration	Average	10.0	46.3	-	9.4	44.4	7.5
			Standard deviation	10.0	48.8	-	10.4	46.4	7.8
TLM_3_0	80%	Real duration	Average	26.0	54.7	33.2	26.0	51.6	15.3
			Standard deviation	26.9	59.2	45.3	28.1	59.2	17.9
		Full duration	Average	26.2	54.9	33.4	26.3	51.7	17.3
			Standard deviation	27.0	59.4	45.3	28.2	59.2	20.6
	90%	Real duration	Average	17.6	36.4	29.6	16.2	36.8	12.3
			Standard deviation	14.8	49.4	38.5	15.8	50.1	14.4
		Full duration	Average	17.8	36.5	29.7	16.6	37.0	13.8
			Standard deviation	16.3	49.4	38.5	15.9	50.1	16.3
	95%	Real duration	Average	11.8	51.4	-	11.1	49.3	11.1
			Standard deviation	10.3	50.1	-	10.7	46.9	10.6
		Full duration	Average	12.1	51.6	-	11.4	49.5	12.0
			Standard deviation	10.4	50.4	-	10.6	47.2	11.4
TLM_0_5	80%	Real duration	Average	31.0	55.8	41.1	31.4	61.8	11.6
			Standard deviation	26.4	55.7	47.1	28.3	59.9	7.8
		Full duration	Average	31.0	55.8	41.1	31.4	61.8	11.6
			Standard deviation	26.4	55.7	47.1	28.3	59.9	7.8
	90%	Real duration	Average	21.7	41.7	39.6	20.7	34.1	12.1
			Standard deviation	14.8	50.2	40.3	15.4	51.6	7.4
		Full duration	Average	21.7	41.7	39.0	20.7	34.1	12.1
			Standard deviation	15.8	50.2	40.3	15.4	51.6	7.4
	95%	Real duration	Average	16.4	48.6	-	16.3	51.8	12.9
			Standard deviation	9.5	49.0	-	10.3	46.6	8.0
		Full duration	Average	16.4	48.6	-	16.3	51.8	12.9
			Standard deviation	9.5	49.0	-	10.3	35.6	8.0

Table C.1 Cont'd.

				Drought durations (d)					
				Poelsbeek			Bolscherbeek		
				Q_r	h^*	Q_s	Q_r	h^*	Q_s
TLM_3_5	**80%**	**Real duration**	Average	32.3	62.0	42.8	33.2	64.0	23.0
			Standard deviation	26.8	59.7	48.0	28.4	60.2	18.6
		Full duration	Average	32.5	62.2	43.0	33.5	64.1	26.1
			Standard deviation	26.9	59.9	48.0	28.3	60.1	21.4
	90%	**Real duration**	Average	22.0	44.9	40.5	21.9	45.4	19.4
			Standard deviation	14.8	52.0	40.6	15.4	52.7	15.4
		Full duration	Average	22.2	45.0	40.6	22.3	45.5	21.8
			Standard deviation	15.8	51.9	40.6	15.4	52.7	17.4
	95%	**Real duration**	Average	16.8	51.4	-	15.7	52.0	16.5
			Standard deviation	9.5	50.1	-	10.3	46.9	10.0
		Full duration	Average	17.1	51.6	-	16.0	52.2	17.9
			Standard deviation	9.6	50.4	-	10.1	47.2	10.6
TLM_MA	**80%**	**Real duration**	Average	34.5	63.4	46.3	36.2	67.5	16.2
			Standard deviation	27.9	58.9	49.7	28.5	60.7	17.8
		Full duration	Average	34.5	63.4	46.3	36.2	67.5	16.2
			Standard deviation	27.9	59.7	49.7	28.5	60.7	17.8
	90%	**Real duration**	Average	22.4	45.9	40.0	21.2	50.9	13.1
			Standard deviation	16.8	53.3	41.7	16.0	56.7	12.8
		Full duration	Average	22.4	45.9	40.0	21.2	50.9	13.1
			Standard deviation	16.8	53.3	41.7	15.7	56.7	12.8
	95%	**Real duration**	Average	17.8	55.7	-	17.4	49.9	9.5
			Standard deviation	11.0	51.2	-	11.6	47.7	9.3
		Full duration	Average	17.8	55.7	-	17.4	49.9	9.5
			Standard deviation	3.5	51.2	-	11.6	47.7	9.3
SPA	**80%**	**Real duration**	Average	35.0	74.4	47.2	37.0	72.1	14.8
			Standard deviation	38.6	84.1	52.0	40.2	84.4	29.8
		Full duration	Average	53.2	118.4	68.1	57.5	115.7	19.8
			Standard deviation	53.9	143.5	73.9	58.8	144.0	42.7
	90%	**Real duration**	Average	17.9	48.5	39.8	20.6	46.3	9.7
			Standard deviation	17.2	55.9	45.7	19.6	56.1	16.2
		Full duration	Average	30.0	77.7	51.1	32.9	73.8	11.4
			Standard deviation	30.6	86.9	58.0	33.4	88.2	21.2
	95%	**Real duration**	Average	13.1	53.8	-	12.2	48.7	8.1
			Standard deviation	11.2	50.3	-	11.8	47.5	8.6
		Full duration	Average	22.0	81.1	-	21.8	74.1	9.0
			Standard deviation	21.0	74.4	-	22.8	70.6	10.9

Appendix C: Average drought characteristics

Table C.2 Average and standard deviation of the <u>deficit volume</u> of droughts in the Poelsbeek and Bolscherbeek, defined with different drought definitions.

Maximum deficit volume								
			Poelsbeek			Bolscherbeek		
			Q_r (mm)	***h**** (md)	***Q_s*** (mm)	***Q_r*** (mm)	***h**** (md)	***Q_s*** (mm)
TLM_0_0	**80%**	Average	8.8	4.8	2.0	10.9	6.7	1.3
		Standard deviation	12.0	9.8	3.6	16.3	12.9	1.4
	90%	Average	3.6	3.1	0.3	4.4	3.9	0.7
		Standard deviation	5.4	7.1	0.5	7.1	8.5	1.1
	95%	Average	2.0	3.7	-	2.7	3.9	0.4
		Standard deviation	3.4	5.8	-	4.7	6.0	0.6
TLM_3_0	**80%**	Average	9.9	5.8	2.1	12.9	7.2	3.0
		Standard deviation	12.3	10.7	3.7	17.0	13.2	4.9
	90%	Average	4.3	3.4	0.5	5.5	4.3	1.3
		Standard deviation	5.7	7.5	0.8	7.6	8.8	2.2
	95%	Average	2.4	4.1	-	3.2	4.3	0.6
		Standard deviation	3.6	5.9	-	5.0	6.2	0.8
TLM_0_5	**80%**	Average	11.9	6.0	2.7	15.8	8.6	0.6
		Standard deviation	12.6	10.7	4.0	17.6	14.1	0.7
	90%	Average	5.6	4.0	0.7	7.3	5.1	1.4
		Standard deviation	5.9	7.9	0.8	8.1	9.4	1.4
	95%	Average	3.6	3.9	-	5.0	4.6	0.7
		Standard deviation	4.0	5.8	-	5.6	6.3	0.8
TLM_3_5	**80%**	Average	12.4	6.6	2.8	16.6	9.0	4.6
		Standard deviation	12.7	11.2	4.1	17.7	14.3	5.6
	90%	Average	5.5	4.3	0.7	7.6	5.3	2.1
		Standard deviation	2.4	8.1	0.8	8.1	9.6	2.6
	95%	Average	3.6	4.1	-	4.6	4.6	0.9
		Standard deviation	4.0	5.9	-	5.5	6.3	0.9
TLM_MA	**80%**	Average	12.4	6.9	2.9	17.1	9.5	2.6
		Standard deviation	12.9	11.3	4.2	17.7	14.6	4.3
	90%	Average	5.2	4.6	0.7	6.6	6.2	1.2
		Standard deviation	5.9	8.4	0.9	8.1	10.2	1.7
	95%	Average	3.3	4.5	-	4.5	4.5	0.5
		Standard deviation	4.0	6.1	-	5.6	6.3	0.7
SPA	**80%**	Average	12.2	7.8	3.0	16.8	9.8	2.2
		Standard deviation	13.7	3.5	4.2	19.4	15.4	5.5
	90%	Average	4.5	4.9	0.7	6.3	5.7	0.8
		Standard deviation	5.8	8.5	0.9	8.2	9.9	1.6
	95%	Average	2.5	4.6	-	3.5	4.6	0.4
		Standard deviation	3.7	6.1	-	5.2	6.3	0.7

Table C.3 Average and standard deviation of <u>minimum runoff/groundwater depth</u> for droughts in the Poelsbeek and Bolscherbeek, defined with different drought definitions.

Minimum runoff/groundwater depth								
			Poelsbeek			**Bolscherbeek**		
			Q_r (mm)	h^* (m)	Q_s (m^3s^{-1})	Q_r (mm)	h^* (m)	Q_s (m^3s^{-1})
TLM_0_0	**80%**	Average	-0.7	-1.3	0.0	-0.9	-1.4	0.1
		Standard deviation	0.4	0.1	0.0	0.5	0.1	0.0
	90%	Average	-0.8	-1.3	0.0	-1.2	-1.5	0.1
		Standard deviation	0.3	0.1	0.0	0.3	0.1	0.0
	95%	Average	-1.0	-1.4	-	-1.3	-1.6	0.0
		Standard deviation	0.2	0.1	-	0.3	0.1	0.0
TLM_3_0	**80%**	Average	-0.7	-1.3	0.0	-1.0	-1.5	0.1
		Standard deviation	0.4	0.1	0.0	0.5	0.1	0.0
	90%	Average	-0.9	-1.3	0.0	-1.2	-1.5	0.1
		Standard deviation	0.3	0.1	0.0	0.3	0.1	0.0
	95%	Average	-1.0	-1.4	-	-1.4	-1.6	0.0
		Standard deviation	0.2	0.1	-	0.3	0.1	0.0
TLM_0_5	**80%**	Average	-0.8	-1.3	0.0	-1.1	-1.5	0.1
		Standard deviation	0.4	0.1	0.0	0.4	0.1	0.0
	90%	Average	-1.0	-1.4	0.0	-1.3	-1.5	0.0
		Standard deviation	0.3	0.1	0.0	0.3	0.1	0.0
	95%	Average	-1.1	-1.4	-	-1.5	-1.7	0.0
		Standard deviation	0.3	0.1	-	0.3	0.1	0.0
TLM_3_5	**80%**	Average	-0.8	-1.3	0.0	-1.1	-1.5	0.1
		Standard deviation	0.4	0.1	0.0	0.4	0.1	0.0
	90%	Average	-1.0	-1.4	0.0	-1.4	-1.5	0.0
		Standard deviation	0.3	0.1	0.0	0.3	0.1	0.0
	95%	Average	-1.1	-1.4	-	-1.5	-1.7	0.0
		Standard deviation	8.0	0.1	-	0.3	0.1	0.0
TLM_MA	**80%**	Average	-0.7	-1.3	0.0	-1.0	-1.5	0.1
		Standard deviation	0.3	0.1	0.0	0.4	0.1	0.0
	90%	Average	-0.8	-1.4	0.0	-1.2	-1.5	0.1
		Standard deviation	0.2	0.1	0.0	0.3	0.1	0.0
	95%	Average	-1.0	-1.4	-	-1.4	-1.6	0.0
		Standard deviation	0.2	0.1	-	0.3	0.1	0.0

Table C.4 Number of droughts of different drought definition for the threshold levels of 80%, 90% and 95%, for the Poelsbeek and Bolscherbeek.

		Number of droughts					
		Poelsbeek			Bolscherbeek		
		Q_r	h^*	Q_s	Q_r	h^*	Q_s
TLM_0_0	**80%**	152	79	116	159	75	541
	90%	119	56	81	135	55	276
	95%	88	20	0	94	20	118
TLM_3_0	**80%**	135	65	106	135	70	229
	90%	100	50	60	108	50	145
	95%	74	18	0	79	18	80
TLM_0_5	**80%**	111	63	84	109	58	250
	90%	77	43	44	80	42	119
	95%	48	19	0	49	17	59
TLM_3_5	**80%**	107	57	81	104	56	145
	90%	78	40	43	77	40	84
	95%	48	18	0	53	17	50
TLM_MA	**80%**	101	54	74	95	52	166
	90%	74.0	37	42	78	34	80
	95%	46	16	0	46	17	45
SPA	**80%**	105	46	74	100	49	235
	90%	96	35	44	91	37	181
	95%	70	16	0	71	17	104

Appendix D: Drought deficit graphs for the period 1951-1998

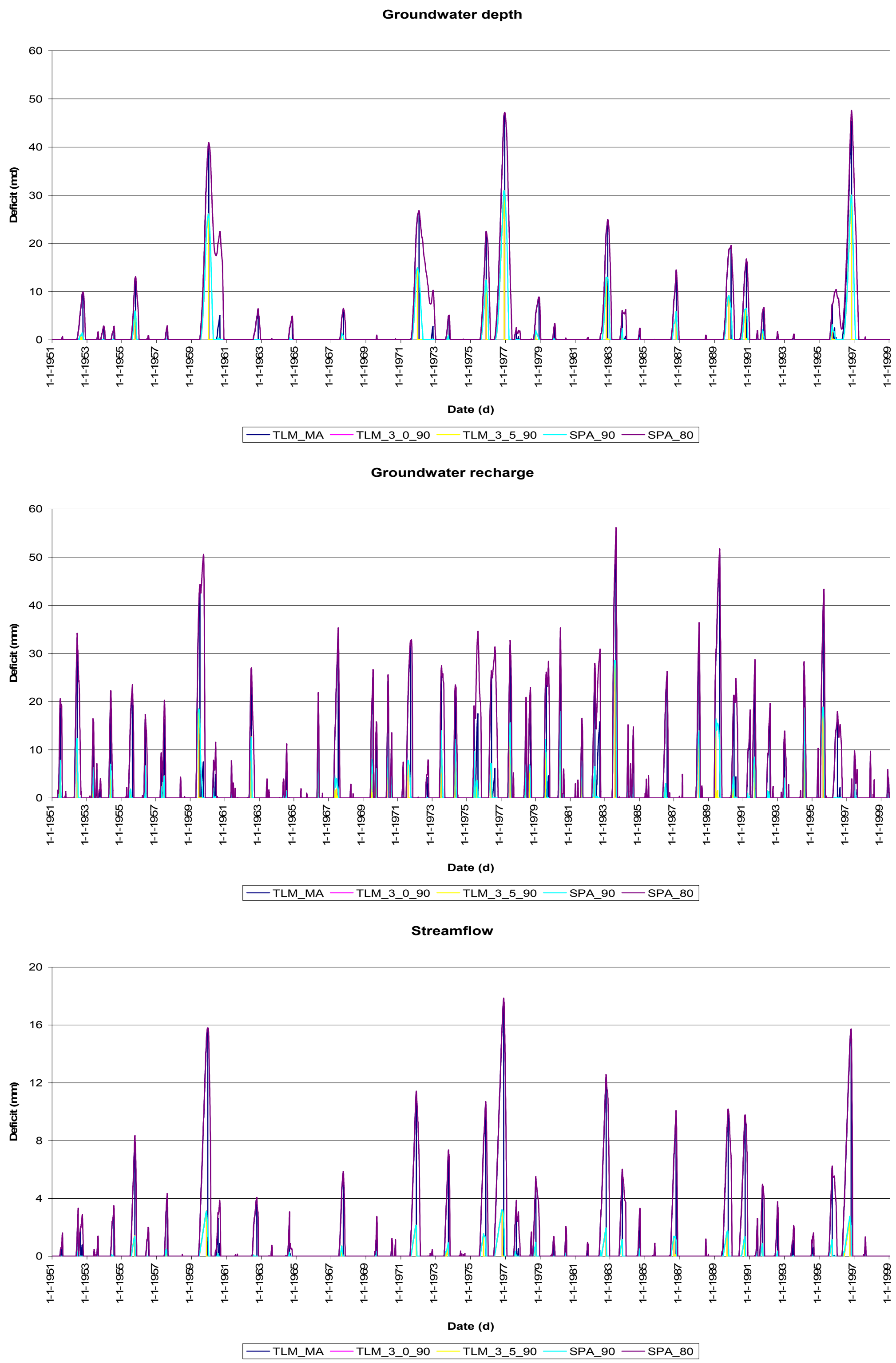


Figure D.1 Deficits in groundwater depth, groundwater recharge and streamflow for the five selected drought definitions, the highest peaks represent major droughts in groundwater depth, groundwater recharge or streamflow.

Appendix E: Drought characteristics for three major droughts

Table E.1 Drought characteristics for TLM_MA_80, for the Poelsbeek, in the years 1959, 1976 and 1996.

TLM_MA_80									
							Starting difference		
		start date	end date	τ_{real} (d)	τ_{full} (d)	s (mm or md)	Q_r-h^* (d)	h^*-Q_s (d)	Q_r-Q_s (d)
1959	Q_{r}_1	29-4-1959	25-7-1959	88	88	44.65	45	-18	27
	Q_{r}_2	14-8-1959	8-10-1959	56	56	7.98			
	h^*	13-6-1959	27-12-1959	198	198	40.87			
	Q_s	26-5-1959	12-12-1959	201	201	15.74			
1976	Q_{r}_1	6-4-1976	8-6-1976	64	64	26.49	36	-15	21
	Q_{r}_2	2-7-1976	23-8-1976	53	53	6.55			
	h^*	12-5-1976	17-12-1976	220	220	47.13			
	Q_s	27-4-1976	27-11-1976	215	215	17.76			
1996	Q_{r}_1	11-3-1996	22-6-1996	104	104	18.39	38	0	38
	Q_{r}_2	22-7-1996	14-8-1996	24	24	2.35			
	h^*	18-4-1996	7-11-1996	204	204	45.32			
	Q_s	18-4-1996	27-10-1996	193	193	15.66			

Table E.2 Drought characteristics for TLM_3_0_90 and TLM_3_5_90, in the Poelsbeek, for the years 1959, 1976 and 1996.

TLM_3_0_90 and TLM_3_5_90									
							Starting difference		
		start date	end date	τ_{real} (d)	τ_{full} (d)	s (mm or md)	Q_r-h^* (d)	h^*-Q_s (d)	Q_r-Q_s (d)
1959	Q_r	1-5-1959	1-7-1959	62	62	18.53	61	-23	38
	h^*	1-7-1959	21-12-1959	174	174	26.11			
	Q_s	8-6-1959	8-11-1959	154	154	3.13			
1976	Q_r	10-4-1976	29-5-1976	50	50	7.20	50	-15	35
	h^*	30-5-1976	4-12-1976	189	189	30.96			
	Q_s	15-5-1976	23-10-1976	162	162	3.21			
1996	Q_r	27-4-1996	1-5-1996	5	5	0.13	10	0	10
	h^*	7-5-1996	3-11-1996	181	181	30.05			
	Q_{s}_1	7-5-1996	25-5-1996	19	19	0.30			
	Q_{s}_2	2-6-1996	2-10-1996	123	123	2.53			

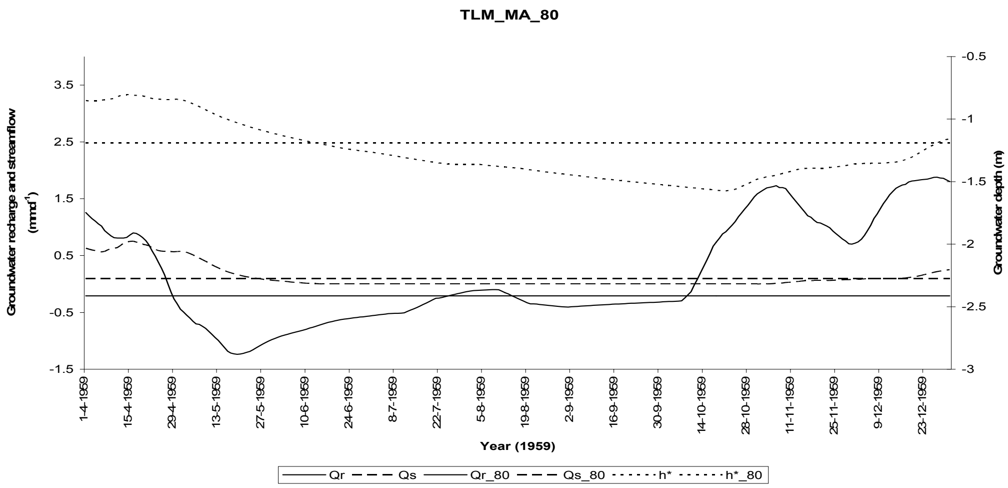
Table E.3 Drought characteristics for SPA_90, for the Poelsbeek, in the years 1959, 1976 and 1996.

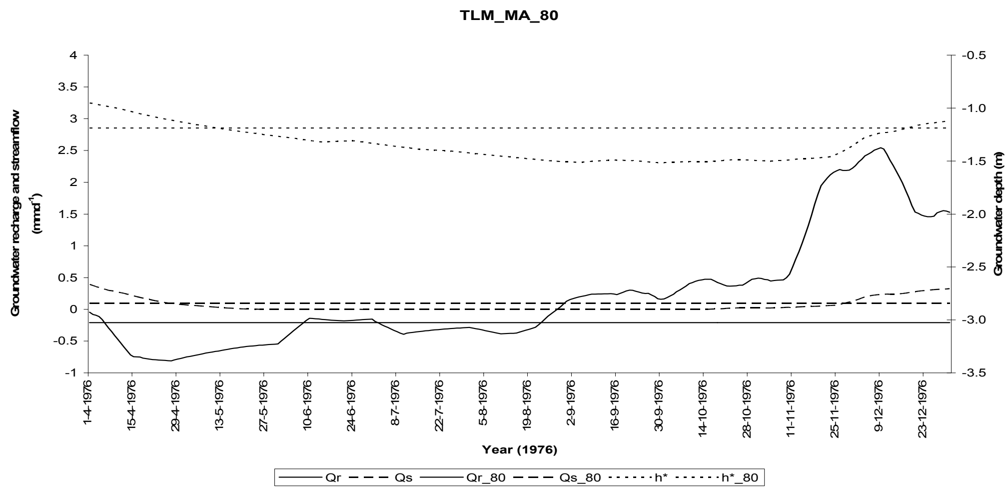
SPA_90							Starting difference		
		start date	**end date**	d_{max} **(d)**	d_{total} **(d)**	s **(mm or md)**	Q_r-h^* **(d)**	h^*-Q_s **(d)**	Q_r-Q_s **(d)**
1959	Q_r	1-5-1959	19-9-1959	62	142	18.54	64	-26	38
	h^*	4-7-1959	29-3-1960	170	270	26.11			
	Q_s	8-6-1959	24-12-1959	154	200	3.13			
1976	Q_r	10-4-1976	22-6-1976	50	74	7.20	54	-19	35
	h^*	3-6-1976	16-3-1977	185	287	30.96			
	Q_s	15-5-1976	11-12-1976	160	211	3.21			
1996	Q_r	27-4-1996	6-5-1996	5	10	0.13	12	-2	10
	h^*	9-5-1996	29-1-1997	179	266	30.05			
	Q_s	7-5-1996	7-11-1996	149	185	2.76			

Table E.4 Drought characteristics for SPA_80, for the Poelsbeek, in the years 1959, 1976 and 1996.

SPA_80							Starting difference		
		start date	**end date**	d_{max} **(d)**	d_{total} **(d)**	s **(mm or md)**	Q_r-h^* **(d)**	h^*-Q_s **(d)**	Q_r-Q_s **(d)**
1959	Q_r	1-5-1959	14-11-1959	164	198	50.64	44	-20	24
	h^*	14-6-1959	7-11-1960	194	513	40.94			
	Q_s	25-5-1959	14-2-1960	197	266	15.80			
1976	Q_r	9-4-1976	27-10-1976	138	202	31.40	34	-17	17
	h^*	13-5-1976	19-5-1977	218	372	47.21			
	Q_s	26-4-1976	31-1-1977	217	281	17.87			
1996	Q_r	12-3-1996	29-9-1996	102	202	17.98	-226	262	36
	h^*	30-7-1995	9-4-1997	465	620	47.62			
	Q_s	17-4-1996	3-12-1996	194	231	15.74			

Appendix F: Flow/groundwater depth and deficit graphs for three major droughts





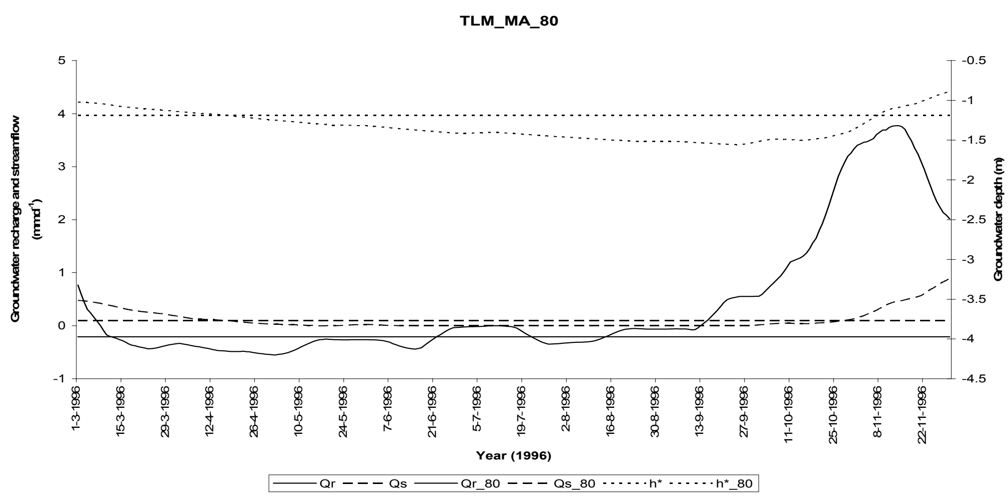


Figure F.1 Groundwater recharge, groundwater depth and streamflow, with moving average of 10 days, for the Poelsbeek in the years 1959, 1976 and 1996 and the corresponding threshold levels of 80%.

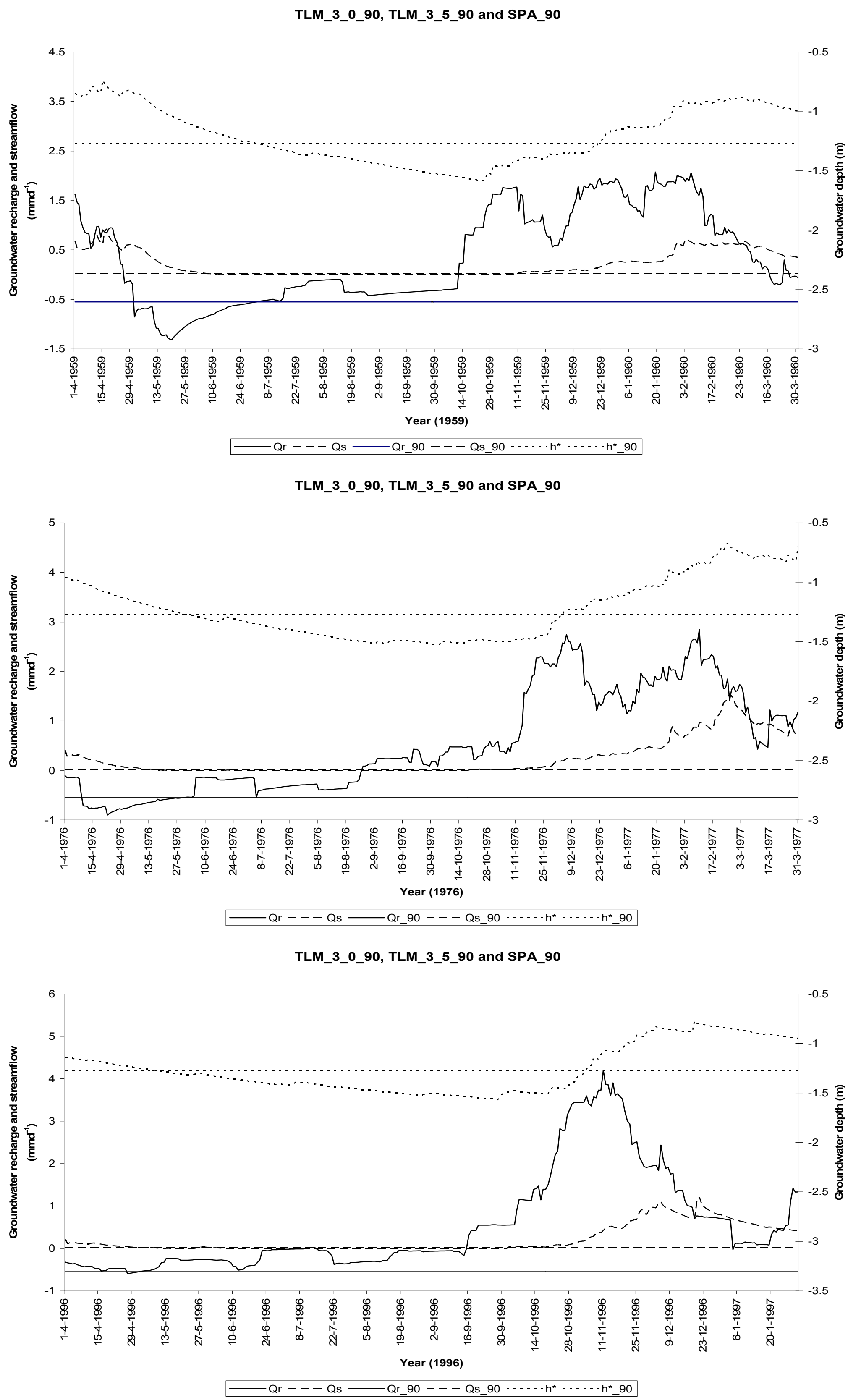
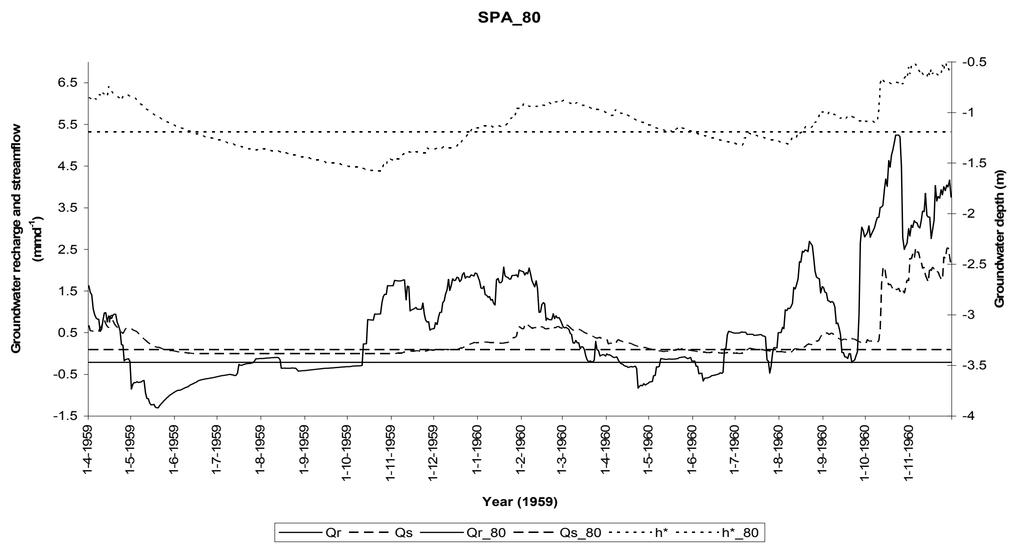
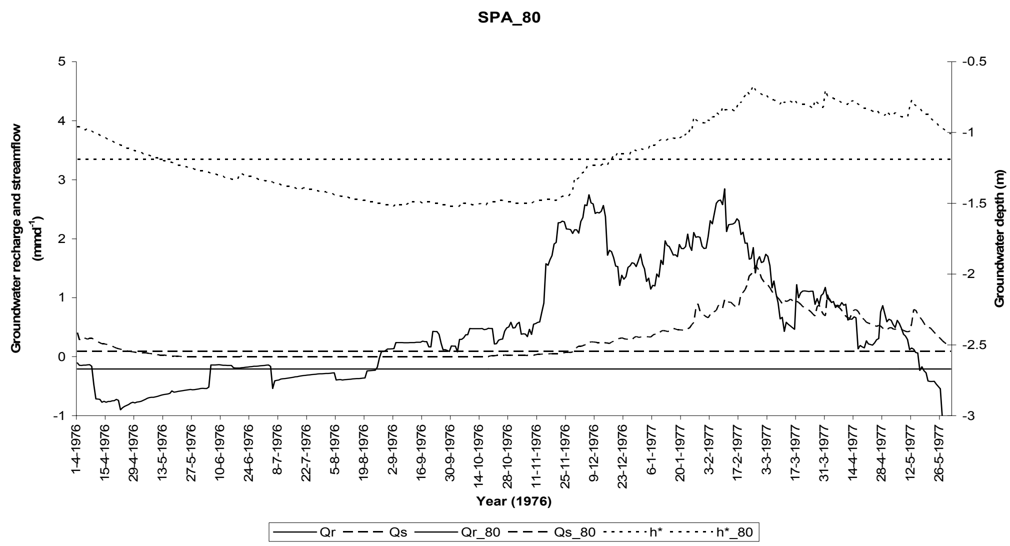


Figure F.2 Groundwater recharge, groundwater depth and streamflow, for the Poelsbeek in the years 1959, 1976 and 1996 and the corresponding threshold levels of 90%.





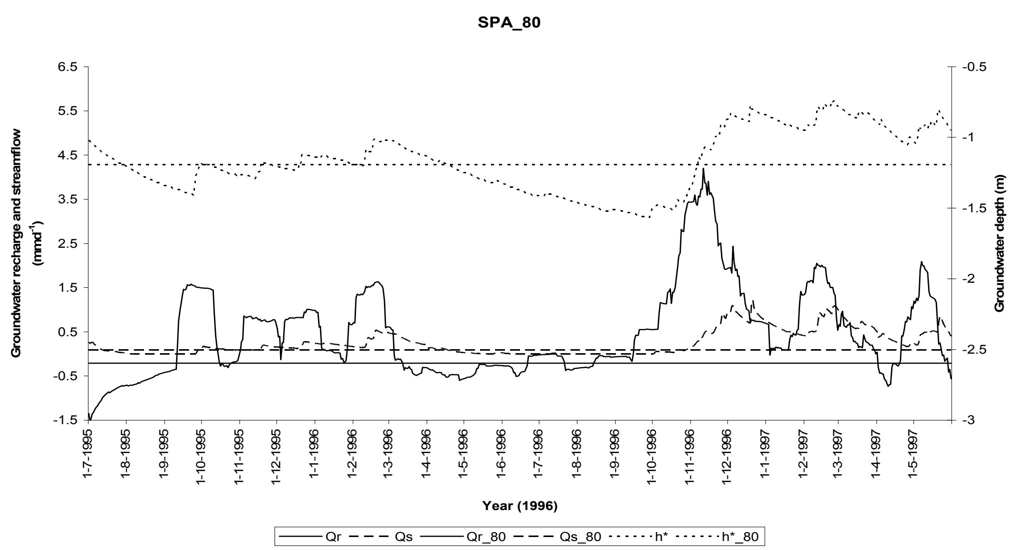


Figure F.3 Groundwater recharge, groundwater depth and streamflow, for the Poelsbeek in the years 1959, 1976 and 1996 and the corresponding threshold levels of 80%.

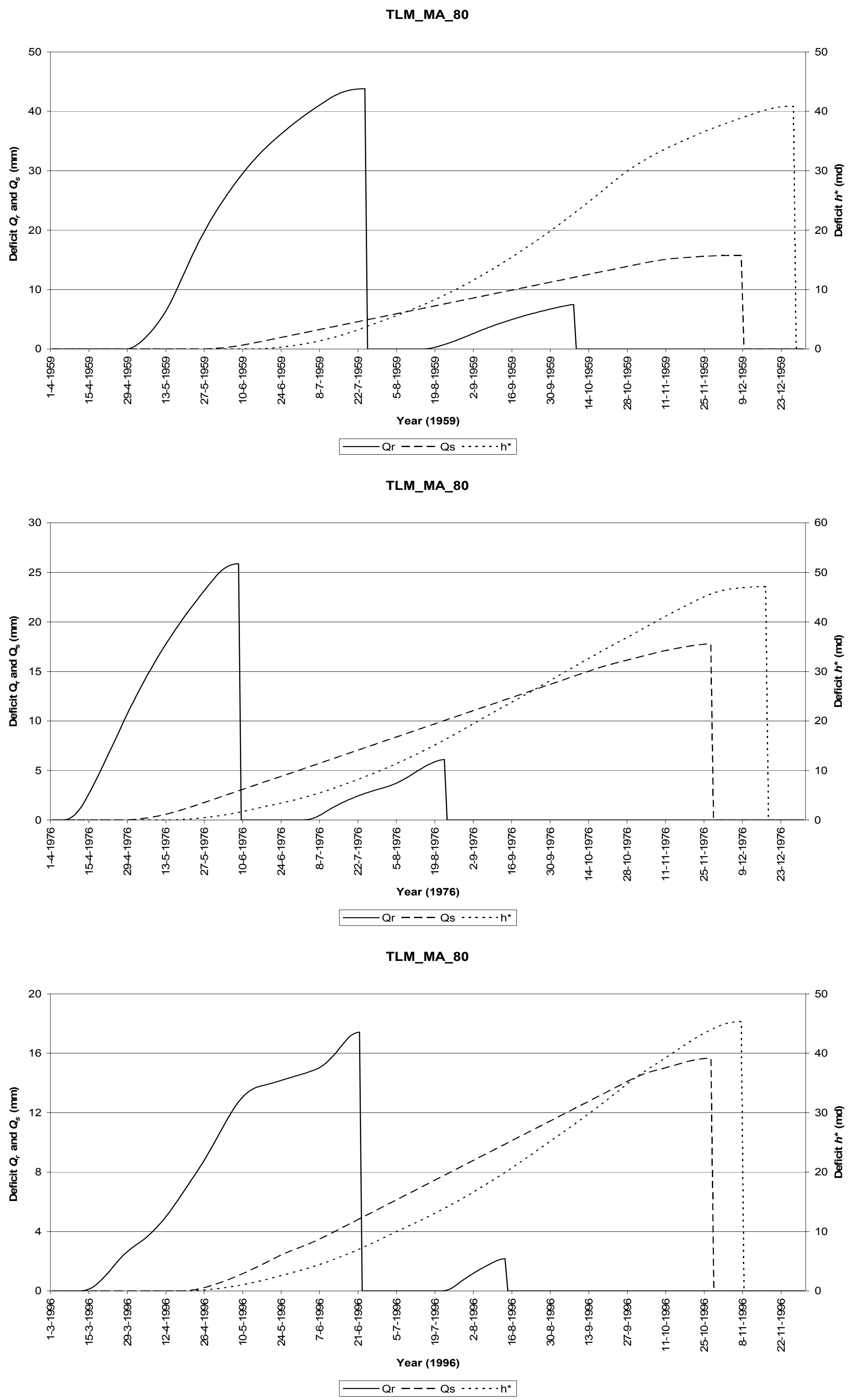
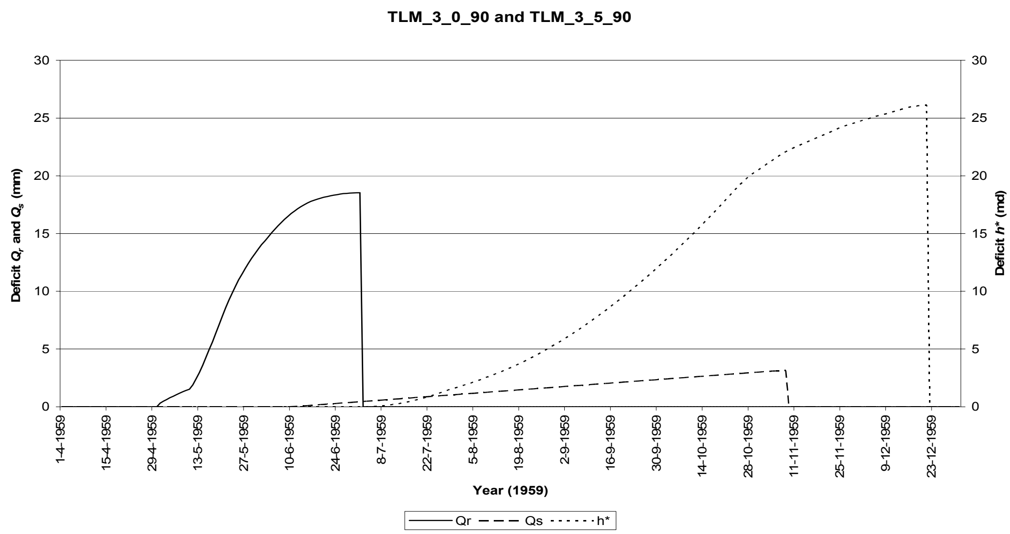
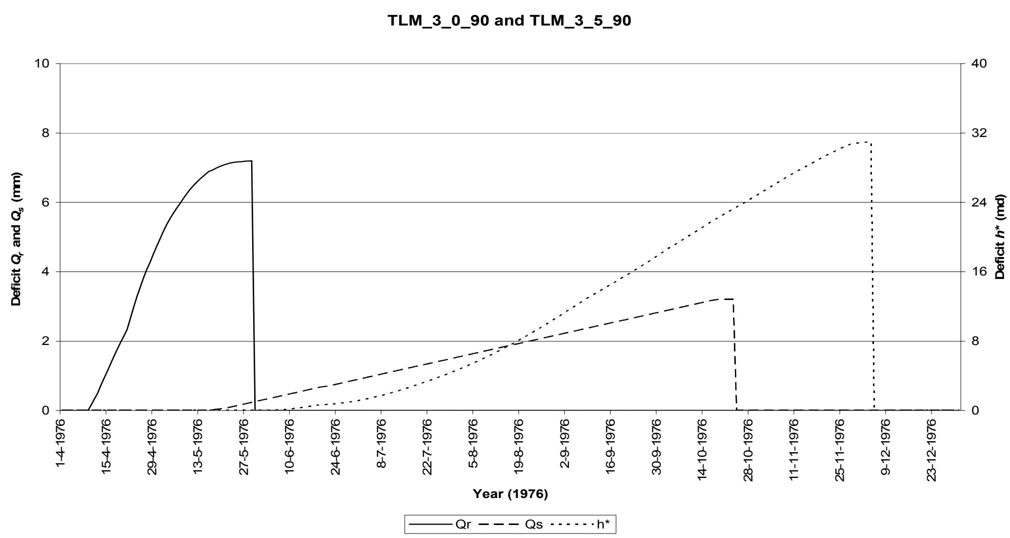


Figure F.4 Deficit volumes derived from groundwater recharge, depth and streamflow withTLM_MA_80, for the Poelsbeek, in the years 1959, 1976 and 1996.

Appendix F: Flow/groundwater depth and deficit graphs for three major droughts





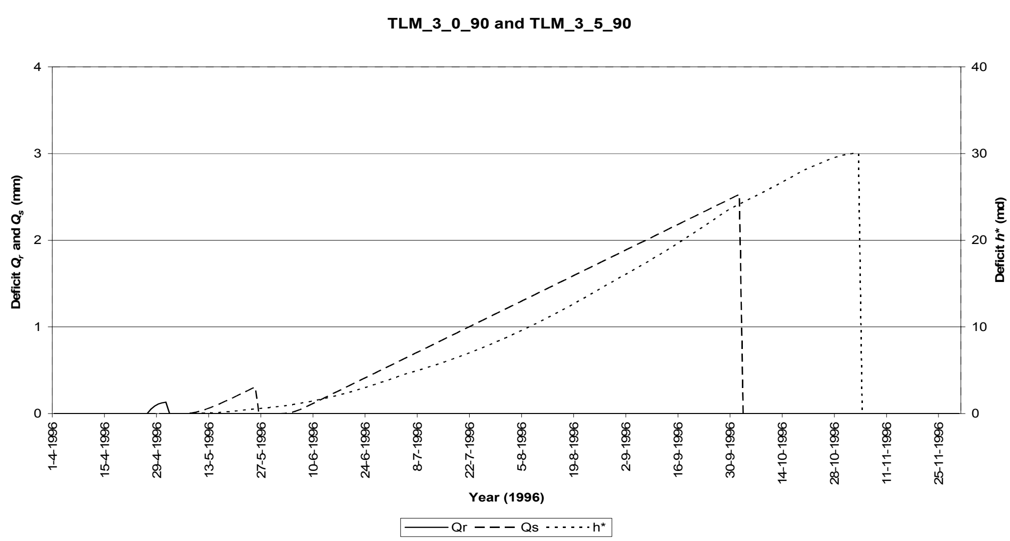


Figure F.5 Deficit volumes derived from groundwater recharge, depth and streamflow with TLM_3_0_90 and TLM_3_5_90 (these definitions give the same results for these major droughts), for the Poelsbeek, in the years 1959, 1976 and 1996.

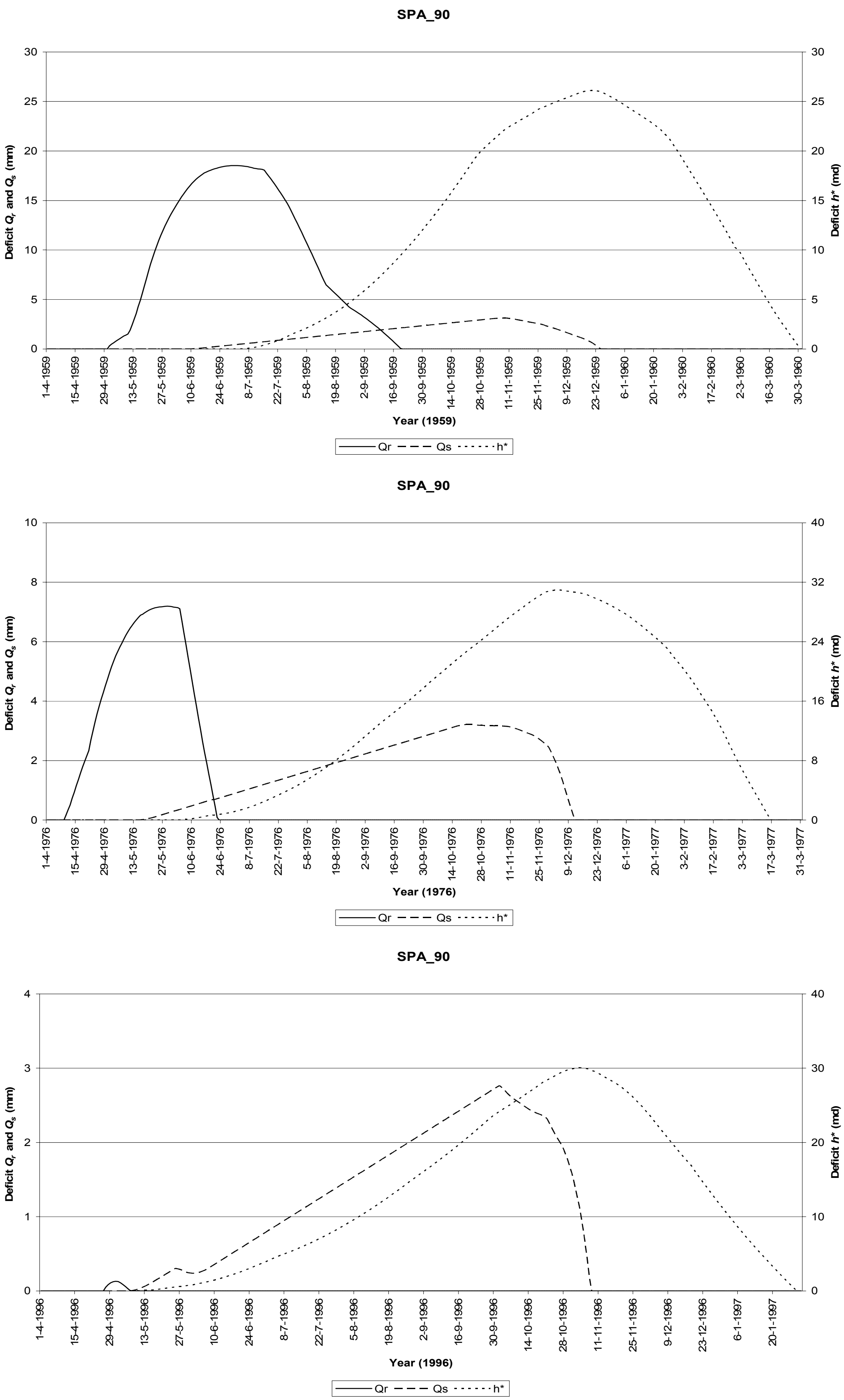


Figure F.6 Deficit volumes derived from groundwater recharge, depth and streamflow with SPA_90, for the Poelsbeek, in the years 1959, 1976 and 1996.

Appendix F: Flow/groundwater depth and deficit graphs for three major droughts

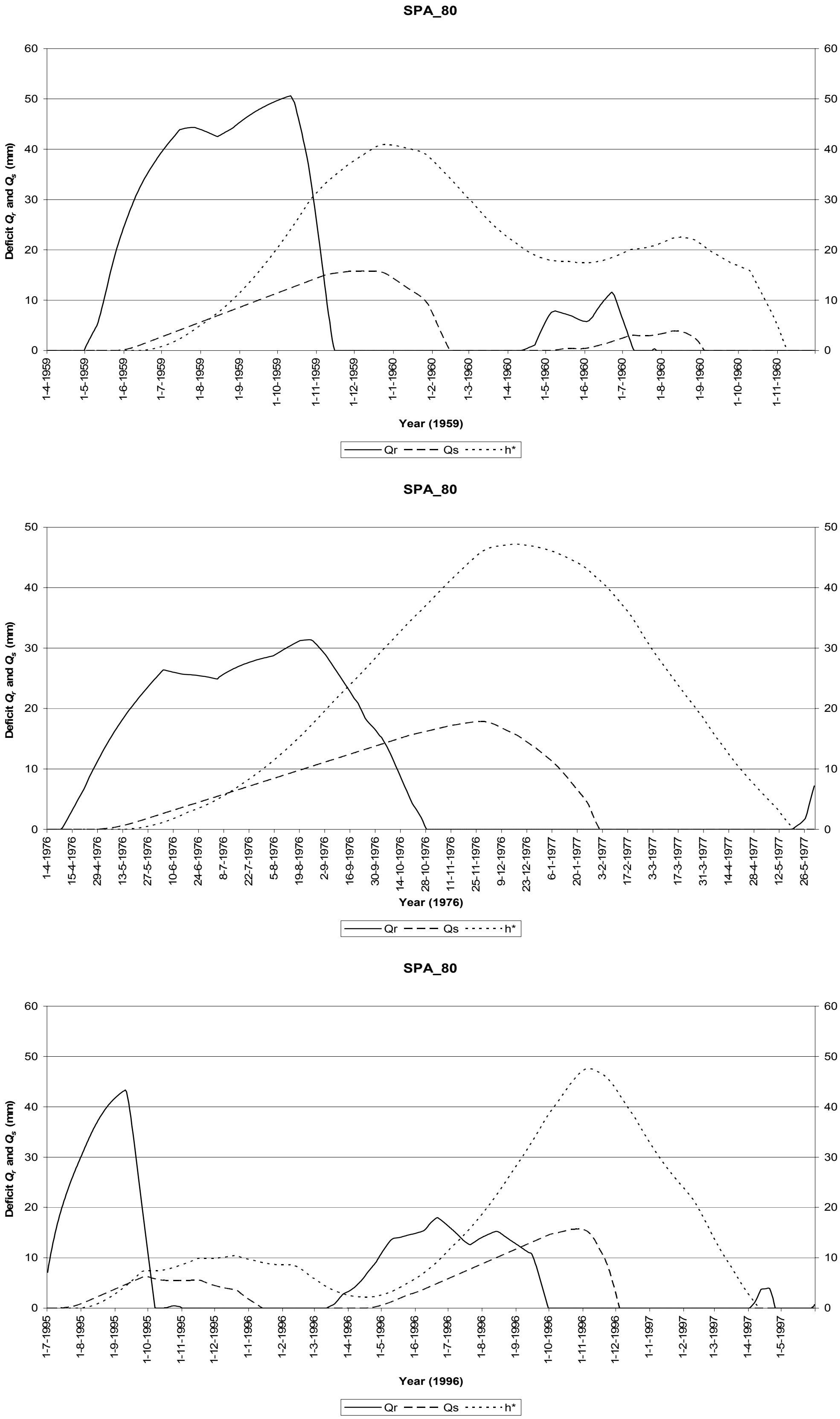


Figure F.7 Deficit volumes derived from groundwater recharge, depth and streamflow with SPA_80, for the Poelsbeek, in the years 1959, 1976 and 1996.

Appendix G: Droughts in the Bolscherbeek

Table G.1 Drought characteristics for TLM_MA_80, for the Bolscherbeek, in the year 1976.

TLM_MA_80								
						Starting difference		
	start date	end date	τ_{real} (d)	τ_{full} (d)	*s* (mm or md)	Q_r-h^* (d)	h^*-Q_s (d)	Q_r-Q_s (d)
Q_r	7-4-1976	23-8-1976	139	139	49.87	38	-32	6
h^*	15-5-1976	18-12-1976	218	218	57.74			
Q_s_1	13-4-1976	15-6-1976	64	64	11.86			
Q_s_2	25-6-1976	24-7-1976	30	30	6.92			
Q_s_3	26-7-1976	30-8-1976	36	36	11.96			
Q_s_4	2-9-1976	3-9-1976	2	2	0.05			
Q_s_5	9-9-1976	10-10-1976	32	32	5.00			
Q_s_6	8-10-1976	9-10-1976	2	2	0.01			
Q_s_7	11-10-1976	14-10-1976	4	4	0.26			
Q_s_8	24-10-1976	20-11-1976	28	28	2.56			

Table G.2 Drought characteristics for TLM_3_5_90, for the Bolscherbeek, in the year 1976.

TLM_3_5_90								
						Starting difference		
	start date	end date	τ_{real} (d)	τ_{full} (d)	*s* (mm or md)	Q_r-h^* (d)	h^*-Q_s (d)	Q_r-Q_s (d)
Q_r	10-4-1976	4-6-1976	56	56	11.87	56	-37	19
h^*	5-6-1976	4-12-1976	183	183	35.77			
Q_s_1	29-4-1976	17-6-1976	43	50	4.41			
Q_s_2	21-6-1976	31-8-1976	66	72	11.10			
Q_s_3	11-9-1976	29-9-1976	17	19	2.75			

Table G.3 Drought characteristics for SPA_90, for the Bolscherbeek, in the year 1976.

SPA_90								
						Starting difference		
	start date	end date	d_{max} (d)	d_{total} (d)	*s* (mm or md)	Q_r-h^* (d)	h^*-Q_s (d)	Q_r-Q_s (d)
Q_r	10-4-1976	16-7-1976	56	98	11.87	58	-38	20
h^*	7-6-1976	11-3-1977	180	278	35.77			
Q_s_1	2-4-1976	2-4-1976	1	1	0.04			
Q_s_2	30-4-1976	1-5-1976	2	2	0.02			
Q_s_3	4-5-1976	18-6-1976	45	46	2.43			
Q_s_4	21-6-1976	28-10-1976	72	130	7.56			

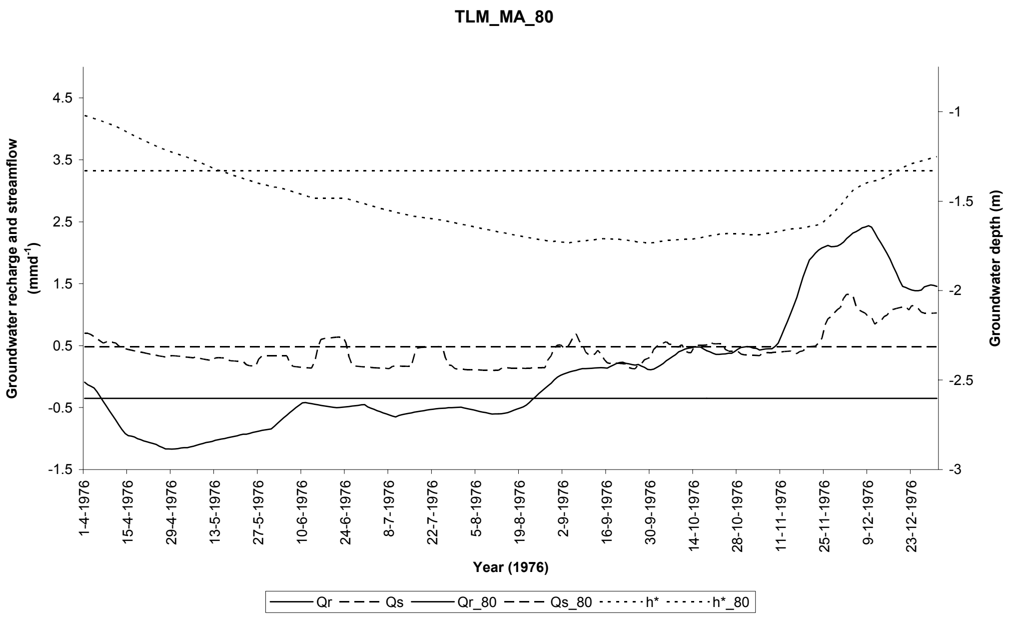


Figure G.1 Groundwater recharge, groundwater depth and streamflow, with moving average of 10 days, for the Bolscherbeek in the year, 1976 and the corresponding threshold levels of 80%.

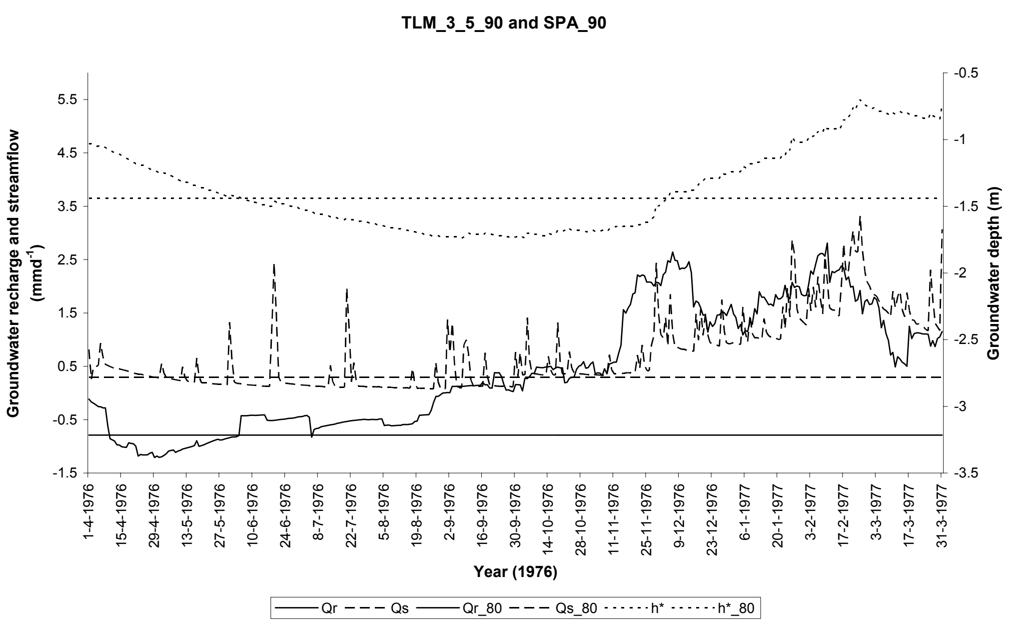


Figure G.2 Groundwater recharge, groundwater depth and streamflow, for the Bolscherbeek in the year 1976 and the corresponding threshold levels of 90%.

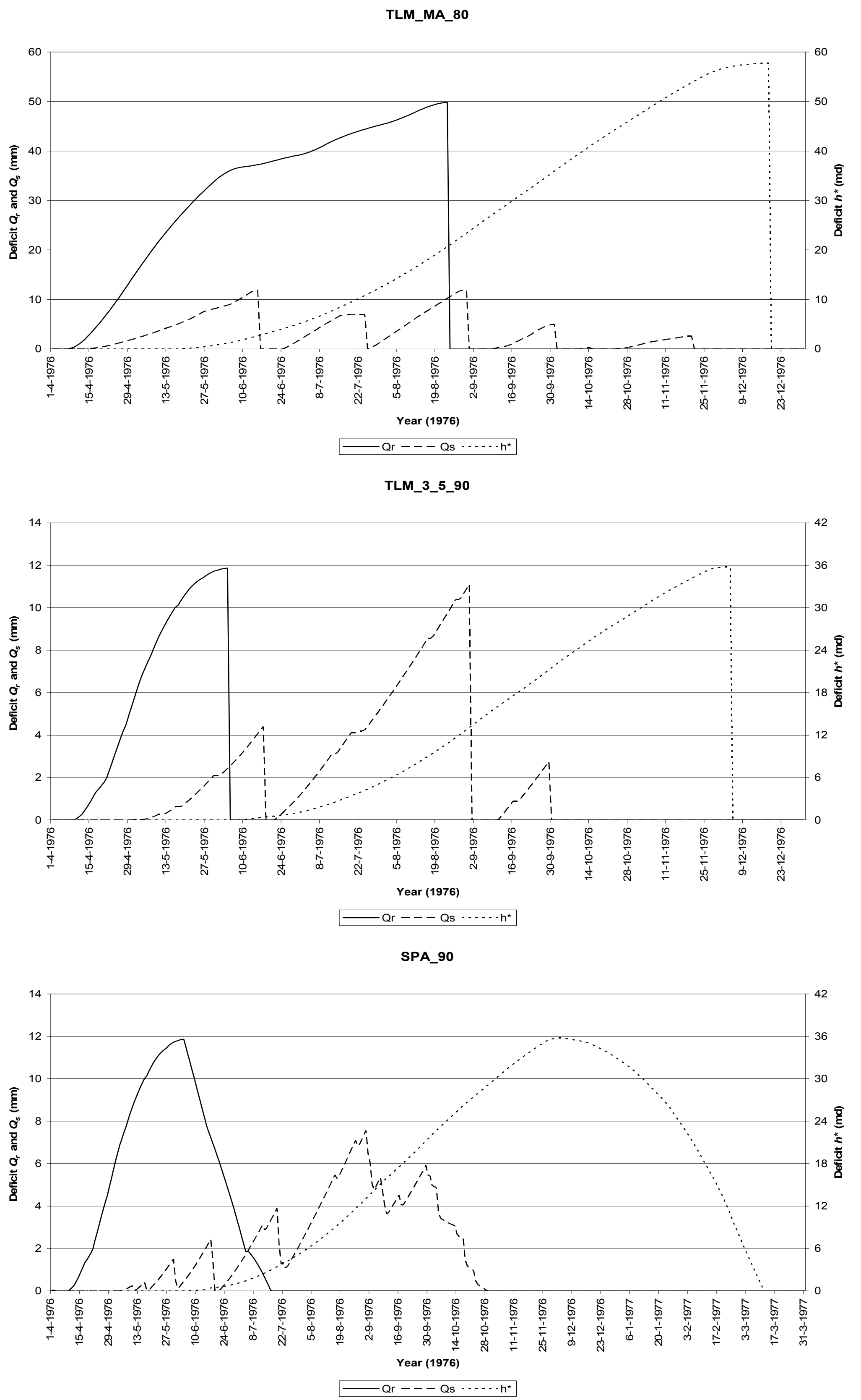


Figure G.3 Deficit in groundwater recharge, depth and streamflow with TLM_MA_80, TLM_3_5_90 and SPA_90 for the Bolscherbeek, in the year 1976.

Appendix H: Content of CD

- *NIZOWKA*; folder with installation file for *NIZOWKA*.
- *rw2010.exe*; installation file for *R*.
- *date.txt*
- *deficits_TLM.txt*
- *NIZOWKA.txt*
- *remove_leap.txt*
- *SPA.txt*
- *Programs_R.RData*; all programs (*R*), stored in **.RData* file.