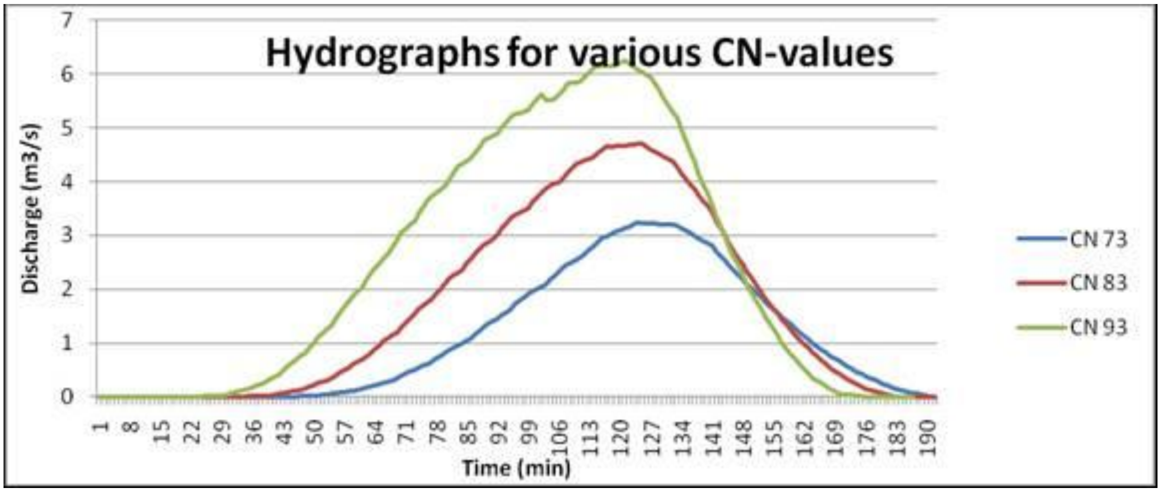
Sensitivity analysis of the Curve Number method

For the assessment of hydrological impacts of hill slope revegetation in the Baviaanskloof, South Africa.

Thesis report

BSc International Land and Water management



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Thesis report

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Summary

Hydrological modeling is used to give a simplified representation of actual hydrological systems (Brooks *et al.*, 1997). With the models insight in various hydrological relations in specific areas can be gained. For this thesis research hydrological modeling is used to investigate the sensitivity of CN-values, the most important parameter for the Curve Number method.

The Curve Number method has been identified as a feasible method to examine the effects of revegetation on water balances for the case study in the Baviaanskloof (Sommeijer, 2010). This method is simple, easy to understand and apply, and useful for ungauged watersheds (Boonstra, 1994).

This thesis report is a follow-up of the internship report *'Tentative assessment of hydrological impacts of hill slope revegetation in the Baviaanskloof'* (Sommeijer, 2010). A sub catchment within the Baviaanskloof, South Africa, was selected as pilot area. For this sub catchment a weighted average CN-value of 83 was computed. This CN-value is used as starting point for the sensitivity analysis.

The sensitivity analysis is conducted with two methods, which both evaluate the effect of small variations in CN-values. The first method evaluates the effect on computed annual surface runoff, the second method on computed peak surface runoff. A range in CN-value of 73 to 93 is used for the evaluations.

Results show that especially for the computed average annual runoff CN-values are sensitivity, which is explained by the exponential relation between CN-value and surface runoff. For the computed weighted average CN-values of 73, 83 and 93 the average annual discharge shows big differences. In comparison to a CN-value of 83, a CN-value of 73 only generates one third of the direct runoff, whereas a CN-value of 93 generates a threefold of the runoff.

In peak discharges differences between the three CN-values are apparent as well. For a CN-value of 83 on the degraded and replanted areas a peak of 4,7 m^3/s direct surface runoff is generated in the sub catchment. For CN-values 73 and 93 this is just over 30% less respectively more. Differences in starting moment of surface runoff are also visible; the higher the CN-value, the earlier the surface runoff starts. Differences in peak discharge are lower for varying CN-values than is the case for average annual surface runoff. Therefore sensitivity is lower as well.

The reliability of the Curve Number method is debatable for the specific case study, because of the sensitivity for variation in the CN-values. Besides, computed CN-values for the study area are rough estimates, rather than accurate values. The results of modeling need to be seen more as an estimation, in which it can be a guide in decision making, rather than a detailed prediction.

Contents

1. Introduction

1.1 Hydrological modeling

Hydrological modeling is used to give a simplified representation of actual hydrological systems. These representations enable to study the functioning of watersheds and their response to various inputs (Brooks *et al.*, 1997). With the models insight in various hydrological relations in specific areas can be gained. For this thesis research hydrological modeling is used to investigate the sensitivity of CN-values, the most important parameter for the Curve Number method.

1.2 Curve Number method for peak discharge calculations

The Curve Number method has been identified as a feasible method to examine the effects of revegetation on water balances for the case study in the Baviaanskloof (Sommeijer, 2010). This method is simple, easy to understand and apply, and useful for ungauged watersheds. "The Curve Number is a dimensionless parameter indicating the runoff response characteristic of a drainage basin. This parameter is related to land use, land treatment, hydrological soil group and antecedent soil moisture condition" (Boonstra, 1994). Literature provides CN-values for various combinations of all relevant parameters (table 2.1 in Mishra and Singh, 2003). Based on values obtained from literature CN-values for the study area are estimated. By the use of the Curve Number method for a specific area, the excess rainfall and direct runoff can be estimated for a certain (sequence of) rainfall event(s).

1.3 Use of Curve Number method in the Baviaanskloof

This thesis report is a follow-up of the internship report *'Tentative assessment of hydrological impacts of hill slope revegetation in the Baviaanskloof'* (Sommeijer, 2010). For this research a sub catchment within the Baviaanskloof, South Africa, was selected as pilot area. On several fields within this area rainfall simulations, with two rainfall intensities, were conducted on (replanted) Spekboom and on bare soil. The relative effect of revegetation was derived from the results. Simultaneously, all model parameters for the Curve Number method were collected. The weighted average CN-value value based on literature and available maps and data was compared to the Curve Number method which was calculated from the rainfall simulations tests. New weighted average CN-values were computed to run the model for several scenarios and simulate the annual direct runoff. Results of this study show that hill slope revegetation can have tremendous effects on the hydrology of the area. On short term revegetation can lead to a runoff reduction of 30% on annual base. On the long term, revegetation has the potential to reduce runoff with as much as 86% compared to the current situation.

1.4 Research questions and objectives

In literature the CN-value is described as the most sensitive parameter of the model (Kousari *et al.*, 2010). In the sense that small variations in this CN-value can lead to big differences in the calculated direct surface runoff. In literature there is also quite some debate about the accuracy of the standard Curve Number method as applied for the *'Tentative assessment of hydrological impacts of hill slope revegetation in the Baviaanskloof'* (Sommeijer, 2010). The research question is therefore the following:

- To what extent is the Curve Number method reliable in the assessment of hydrological impacts of hill slope revegetation in the Baviaanskloof?

The corresponding objectives are:

- To investigate the effects of variations of CN-values on direct runoff.
- To get an impression of the accuracy of the Curve Number method.

2. Theory of the Curve Number method

The Curve Number method is based on a few principles and its corresponding equations; the water balance equation and two hypotheses. The water balance equation is as follows (Boonstra, 1994; Mishra and Singh, 2003):

$P = I_a + F + Q$ Equation 2.1

Where:
P = total rainfall (mm)
I_a = initial abstraction (mm)
F = amount of actual infiltration (mm)
Q = actual amount of direct surface runoff (mm)

The first fundamental hypothesis states that the ratio of the actual amount of direct surface runoff to the total rainfall equals to the ratio of the amount of actual infiltration to the amount of potential maximum retention (S). This latter parameter is related to soil properties, antecedent moisture condition, land use and vegetation and slope properties. “This proportionality equation enables partitioning (or dividing) (P-I_a) into surface water (Q) and subsurface water (F) for given watershed characteristics (S).” (Boonstra, 1994; Mishra and Singh, 2003)

$Q / (P - I_a) = F / S$ Equation 2.2

Where:
S = potential maximum retention (mm)

The combination of equation 2.1 and 2.2 results in:

$Q = (P - I_a)^2 / (P - I_a + S)$ Equation 2.3

The second hypothesis “relates the initial abstraction to the potential maximum retention” (Mishra and Singh, 2003).

$I_a = \lambda S$ Equation 2.4

For practical reasons the existing SCS-CN method assumes λ to be 0,2. This results in:

$I_a = 0{,}2\ S$ Equation 2.5

The combination of equation 2.3 and 2.5 results in the following rainfall – runoff relation:

$Q = (P - 0{,}2S)^2 / (P + 0{,}8S)$ for $P > 0{,}2\ S$ Equation 2.6

Parameter S can theoretically vary from zero to infinity. Therefore it has been converted into a non-dimensional quantity, the curve number (CN), with a more appealing range from 0 to 100 (equation 2.7). The CN-value is 0 in case of a highly permeable, flat-lying soil, where all water infiltrates and no direct runoff occurs. A CN-value of 100 indicates an area, where all rainfall is turned into direct runoff and no water infiltrates, such as paved areas. In practical situations, however, the CN mainly varies between 40 and 98. The CN-value can be obtained from tables in literature where physical properties of the area, land use and treatment, hydrological soil group and antecedent soil moisture condition, are combined. The Curve Number method was initially developed for cultivated, flat-lying areas in the USA. Slopes were therefore initially not included. However, since the method has been globally adopted new conversion tables have been set up that do include slope and different land use types. (Boonstra, 1994; Mishra and Singh, 2003)

$S = (1000 / CN) - 10$ Equation 2.7

A unit hydrograph is used to obtain the time distribution of runoff. The time-discharge curve is simplified by approaching the calculation with a triangle. The area of the triangle is equal to the area under the original curve, and the peak of the triangle coincides with the peak of the curve. This approach leads to the following relation: (Boonstra, 1994; Meindertsma, und.)

$Q = (q_p * T_b) / 2$ Equation 2.8

Where:
Q = total discharge volume (m^3)
q_p = unit peak discharge (m^3/h)
T_b = time of base (h)

The time of base is empirically related to the time to peak (T_p (h)):

$T_b = 2{,}67\ T_p$ Equation 2.9

The time to peak is related to both the lag time (T_L (h)) and the unit time of the unit hydrograph (D (h)), which is $0{,}2T_c$ (time of concentration (h)) in optimal situations.

$T_p = T_L - 0{,}5\ D$ Equation 2.10

The lag time is defined as "the time between the moment at which half of the rainfall excess has precipitated". It can be estimated for $50 < CN < 95$ with the following relation:

$T_L = (L^{0,8} (1000 / CN - 9)^{0,7}) / (735 \sqrt{s})$ Equation 2.11

Where:
L = the length of the longest travel path for water (m)
s = average slope of the catchment (%)

The time of concentration and lag time are also empirically related:

$Tc = 1{,}67\ TL$ Equation 2.12

3. Material and Methods

3.1 Baviaanskloof and sub catchment under study

The Baviaanskloof, South Africa, is a biodiversity hotspot and recognized as a World Heritage Site. It is a 75 km long East-West orientated valley between the Baviaanskloof Mountain range in the North and the Kouga Mountains in the South. (figure 3.1)

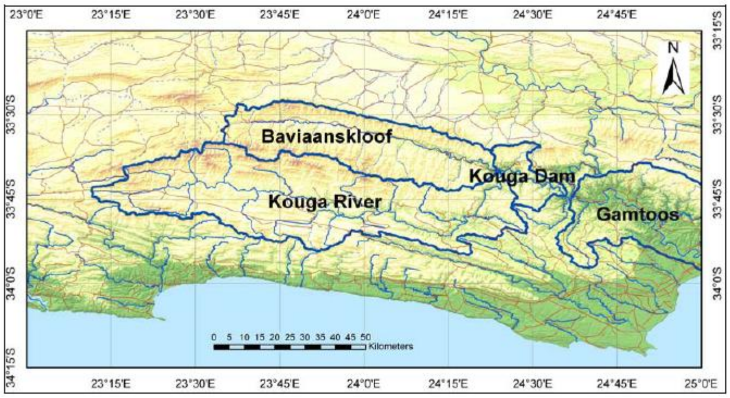

Figure 3.1: Baviaanskloof and location of surrounding catchments.(Jansen, 2008)

Pressure on natural resources, especially water resources, negatively influences the area as well as the rural livelihoods. Average annual rainfall is relatively low, approximately 300 mm, and highly erratic. Due to factors as the current land use, slope and soil characteristics most of this rainfall is turned into direct runoff and transported overland while a minor quantity infiltrates and contributes to the base flow. As a result, the water is flowing relatively rapidly out of the area, causing water shortage during the dry periods. Furthermore, the direct runoff causes (increased) stream bank and hill slope erosion. (Jansen, 2008)

Over the last century the total surface of the main vegetation type in the area, Spekboom thicket (Lat. *Portucalaria afra*), has reduced from 1.400.000 ha to 200.000 ha in 2009 (Mills *et al*, 2009). This is mainly due to overstocking. The degraded fields are no longer protected by vegetation and therefore highly vulnerable to surface runoff and erosion. Active intervention is required as severely degraded thicket is unable to recover naturally (Mills *et al*, 2009). Revegetation improves soil cover which leads to a reduction of direct runoff and erosion. Furthermore the water retention in the area is increased and the base flow can partly be restored.

Sommeijer 2010, identified criteria for the selection of a sub catchment as study area. Though the Piniese kloof catchment is relatively small (1,5 km^2) in comparison to surrounding catchments, the area of thicket cover is equal to that of the larger catchments. The larger sub catchments generally have a larger part covered with Fynbos. Since the focus of this study is mainly on Spekboom thicket, the area of Fynbos cover is considered unimportant for the selection. In the Piniese kloof Spekboom thicket is present in various stages. There are some plots of recently replanted Spekboom (January/February 2010), some plots have been replanted two years ago and fully grown native Spekboom is also present. Degraded thicket is also present in the catchment as a reference point of the hydrologic impacts of replanting. Figure 3.2 shows the location of the sub catchment within the area as well as the types of ground cover of the sub catchment. (Sommeijer, 2010)

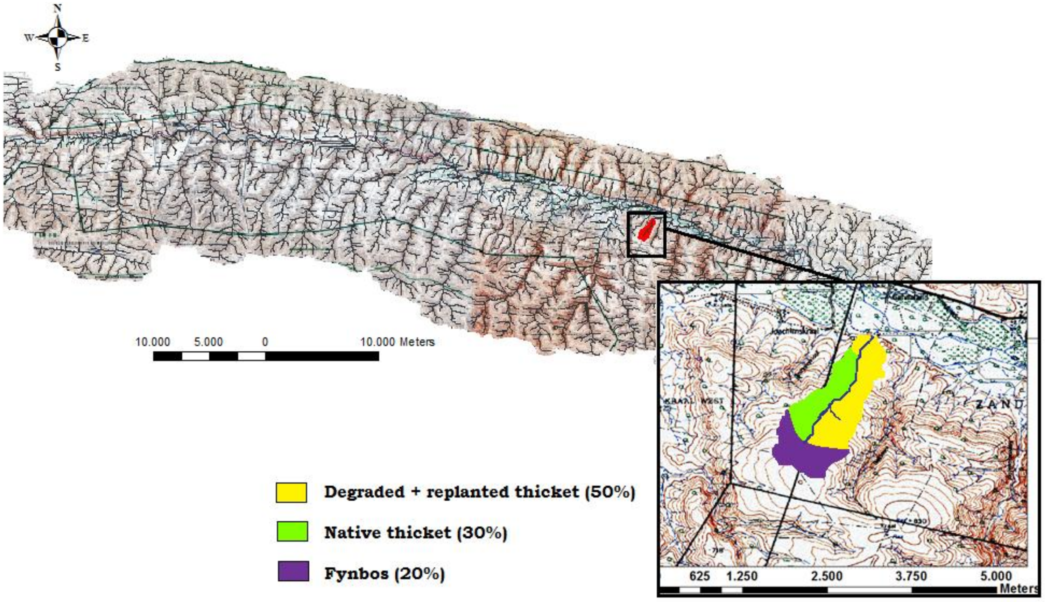

Figure 3.2: Location of sub catchment within Baviaanskloof. The colored areas mark the different types of ground cover and in which percentage they occur.

Within the sub catchment five plots with Spekboom thicket in various stages of revegetation and degradation are defined. Sommeijer 2010 conducted two series of rainfall simulations with different intensities on these plots. She observed a distinct difference in runoff between Spekboom and the reference simulations on bare soil. On the plots with the smaller Spekboom, replanted within the last two years, a reduction in CN-value is indicated of 5% on average with an average reduction of 30% in annual direct runoff. The biggest differences however, are visible in the native Spekboom, with an average reduction in CN-value of 30%, with this CN-value average annual direct runoff can be reduced over 80%.

A weighted CN-value of 83 is calculated for the pilot area, based on literature and with the use of available DEM, landtype and vegetation maps and ArcGIS. The values for the Spekboom thicket, which covers the pilot area for 80%, range from 73 to 86. This range is comparable to the range resulting from the rainfall simulations.

Results of this study show that hill slope revegetation can have tremendous effects on the hydrology of the area. On short term revegetation can lead to a runoff reduction, but especially on the long term revegetation has the potential to reduce direct runoff tremendously.

3.2 Sensitivity analysis

The sensitivity analysis will be conducted with two methods. Both methods will evaluate the effect of small variations in CN-values. The first method evaluates the effect on computed annual surface runoff, the second method on computed peak surface runoff. A range in CN-value of 73 to 93 is used for the evaluations. Both methods are below described in more detail.

3.2.1 Effect of variations in CN-value on computed annual surface runoff

Based on a weighted CN-value of the sub catchment and on daily rainfall data annual direct surface runoff can be computed. Over the range of 73 to 93 in CN-value the annual direct surface runoff is computed for each individual CN-value. Rainfall records of the weather station at the police station (Studtis POL 32093) will be used as the input for rainfall in the model. This weather station has the most continuous sequence of data for the Baviaanskloof of the last years (1994-2009). With the computed average annual direct runoff the effect of (small) variations in the CN-values can be investigated. This will give an indication of the sensitivity of the CN-value to small errors.

3.2.2 Effect of variations in CN-value on computed peak surface runoff

The peak discharge is usually used for dimension calculations of dams, river width and other structures. The peak surface runoff can be calculated based on catchment characteristics and a design rainfall event.

The sub catchment of 1,5 km^2 can roughly be divided into three parts. Approximately 20% of the area is covered with Renoster Sandolienveld (figure 3.2), part of the Fynbos biome, which is rewarded with a CN-value of 76 (Sommeijer 2010). Native thicket with a CN-value of 73 takes up about 30% of the area. The remaining 50% of the area is degraded thicket at some places intermixed with replanted Spekboom. It is this area that has a ranging CN-value of 73 to 93. Other characteristics required for the computation of peak surface runoff are the length of the longest travel path for water and the average slope of the catchment. These are 2200m and 19% respectively.

Only daily rainfall data of this area is available. Over the 16 years of which this data is available only in 4 years the annual maximum daily rainfall exceeded 50 mm. In case such an amount of rainfall precipitates in the Baviaanskloof it is often with heavy, but short thunderstorms. Therefore the design rainfall for this research is assumed to be 50 mm in 2 hours.

4. Results

4.1 Effect of variations in CN-value on annual surface runoff

The average annual direct surface runoff is computed for CN-values over the range of 73 to 93. These results are plotted against the CN-value (figure 4.1). The figure shows a straight line, with the average annual runoff on a logarithmic scale, on which all data points fit almost perfectly. The straight line indicates the exponential relation between CN-value and runoff. This means that the higher the CN-value becomes, the bigger the difference in runoff with a variation of 1 in CN-value. This automatically implies that high CN-value are more sensitive than low CN-values in giving errors in runoff.

For the case study in the Baviaanskloof, the computed CN-value of 83 is relatively high. This means that small variations in CN-value can lead to big differences in calculated runoff. Table 4.1 shows the differences in runoff compared to the CN-value of 83. The average annual runoff with a CN-value of 73 is only one third of the direct runoff with a CN-value of 83. A CN-value of ten points higher even leads to a bigger difference. A CN-value of 93 triples the amount of direct surface runoff in comparison to a CN-value of 83.

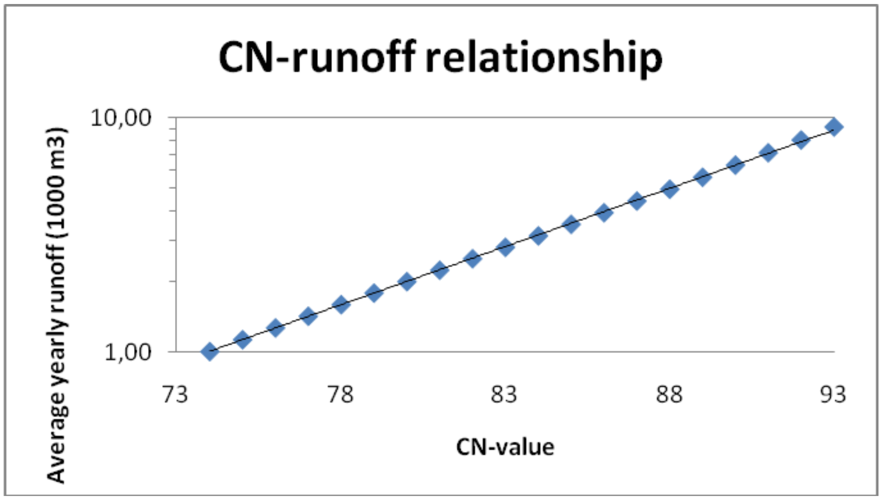

Figure 4.1: CN-runoff relation with CN-value range 73 – 93.

Table 4.1: Average annual runoff corresponding to various CN-values and their difference with CN-value 83.

Average annual runoff			
CN	**Average annual runoff (1000m^3)**	**Difference with CN 83 (1000m^3)**	**Difference with CN 83 (%)**
73	0,9	-1,9	-68
83	2,8	0,0	0
93	9,1	6,3	224

4.2 Effect of variations in CN-value on peak surface runoff

Hydrographs with a design rainfall event of 50 mm in 2 hours are computed for various CN-values. The CN-values vary for the degraded and replanted thicket area; namely 73, 83 and 93. As expected the peak discharge is the highest with CN-value 93 for the degraded and replanted area and the lowest with CN-value 73. In both cases the difference with CN-value 83 is just over 30%. The results are displayed in figure 4.2 and table 4.2. A difference of 30% is quite high and therefore it can be concluded that also in this case the CN-values are sensitive to errors.

The graph (figure 4.2) shows that direct surface runoff with a higher CN-value is discharged faster than that with a lower CN-value. For higher CN-values the direct surface runoff starts earlier and stops sooner after the start of the rainfall event as well. In the worst scenario (CN-value 93) the runoff starts after approximately 24 minutes and after 176 minutes all excess rainfall is discharged. For the best scenario (CN-value 73) these moments occur after respectively after 44 and 191 minutes. For all three scenario's the peak discharge occurs at approximately the same moment; between 120 and 125 minutes after the start of the rainfall event. The moment of peak discharge is therefore not sensitive to changes in CN-value, but the moment of the beginning of runoff is.

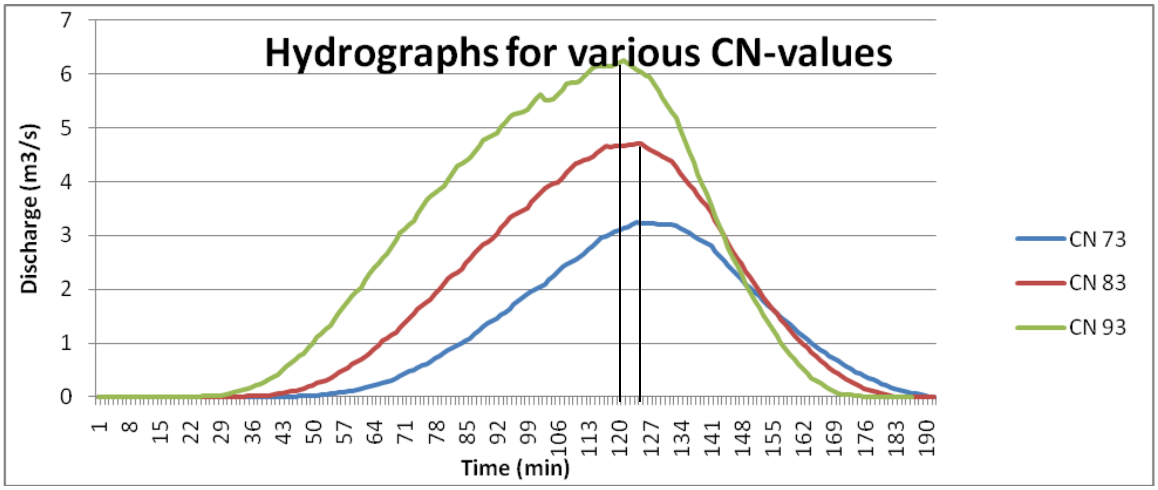

Figure 4.2: Hydrographs for CN-values 73, 83 and 93.

Table 4.2: Peak discharge corresponding to various CN-values and their difference with CN-value 83.

Peak discharge				
CN	Time (min)	Discharge (m^3/s)	Difference with CN 83 (m^3/s)	Difference with CN 83 (%)
73	125	3,2	-1,5	-31
83	125	4,7	0,0	0
93	121	6,3	1,5	33

5. Discussion

Although the Curve Number method is “well established in hydrologic engineering” there are some limitations and points of discussion (Ponce, 1996). For this research the Curve Number method shows some limitations as well. Below the most important ones will be discussed.

One the strengths of the Curve Number method is that it relies on only one parameter, the CN-value. This makes the method simple and easy to use and understand (Ponce *et al.,* 1996). Particularly for this reason the Curve Number method is considered feasible for the case study of the Baviaanskloof. The aim of this case study was to conduct a tentative assessment to get a first impression of rainfall-runoff relations in the area. It was therefore not necessary to conduct a very detailed research for which more input data is required. These data are only limited available, for instance discharge measurements and rainfall intensities for instance are not available for the area.

The fact the Curve Number method is based on only one parameter is besides a strength, a weakness as well. The fewer parameters a model is based on the more sensitive it is to errors in those parameters. In fact, the CN-value is the parameter with the largest influence on the direct runoff (Kousari *et al.,* 2010). Even though this parameter is based on multiple environmental characteristics, the calculation of direct surface runoff requires a combination of these characteristics into only one parameter. Based on assessment tables these combinations are made. For the Baviaanskloof no exclusive assessment tables are available and therefore CN-values are estimated.

A second weakness of the Curve Number method is that it levels out extremes in physical characteristics. Both methods in the sensitivity analysis for calculating effects of changes in CN-value use a weighted average for the entire sub catchment under study whereas the area is far from homogenous. Some parts in the area have very shallow soils and even bedrock exposed, while other parts have deeper soils and are covered with native Spekboom thicket vegetation. As Ponce (*et al.,* 1996) describe this limitation of the Curve Number method: “The Curve Number method describes average trends, which precludes it from being perfectly predictive”.

The Curve Number method as applied for the assessment of the average annual direct surface runoff contains no spatial and temporal expressions, which is a third limitation of the method. Therefore rainfall intensity and its distribution as well as the spatial and temporal variability of infiltration are not taken into consideration (Mishra and Singh, 2003; Ponce *et al.,* 1996). Especially for the Baviaanskloof this can be a limitation. Rainfall in this area is highly erratic, sometimes rainfall events occur as heavy thunderstorms, but in other occasions as a drizzle. This difference in rainfall intensity is of importance when computing the direct surface runoff. The rainfall intensity and duration which are used for the computation of the peak discharge are assumptions as this is not available for the area. These values might deviate significant from actual situations.

Another limitation of the Curve Number method is it is applicability. It is originally designed for agricultural sites, on which the model has proven to perform best. On sites as range land and forest however, the model is argued to perform fairly to poorly (Mishra and Singh, 2003). It can therefore be argued whether this method is considered this argument the best method to apply on this study area. In a case study in the Kardeh Watershed, Iran, errors between estimated and observed runoff rates and amounts were observed as well (Ebrahimian *et al.*, 2009). For this case study the Curve Number method had been applied as well, while less than 20% of the watershed was covered with agricultural land. One of the main conclusions of this research is however that “there is no enough reason that the Curve Number method should not be used for used for ungauged watersheds which do not have runoff records to produce runoff data for the purpose of management and conservations” (Ebrahimian *et al.*, 2009). Based on this conclusion there is no reason to assume that the Curve Number method performs poorly on the case study of the Baviaanskloof.

Due to the limitations mentioned above it is likely to have errors between estimated and observed runoff rates and amounts. This has been reason for researchers to search for variations on the Curve Number method with better results. Examples of these models are the Michel model, the Sahu model (and a simplified version), Storm event method and Rank-order method (Ali and Sharda, 2008; Sahu *et al.,* 2010). Even though variations of the Curve Number method have been adopted, the methods still mainly rely on the CN-value as the one and only important parameter. The performance of the adapted models in comparison to the standard Curve Number method is mainly case specific. Each of the models requires specific conditions under which it performs optimally. There is no model that performs best for all cases with varying environmental and rainfall characteristics. A detailed investigation in the optimal performance characteristics of these models is therefore required before the standard Curve Number method is replaced by another model.

Computed CN-values for the study area are rough estimates, rather than accurate values, as there are no exclusive assessment tables for the Baviaanskloof available. Kousari (*et al.,* 2010) who conducted a sensitivity analysis on the Curve Number method confirm that “very low changes in CN have an important effect on peak discharge”. Therefore, the reductions, respectively enlargements, in direct surface runoff as described for the ‘*Tentative assessment of hill slope revegetation in the Baviaanskloof*’ (Sommeijer, 2010) should therefore be seen as relative relations rather than absolute quantities. In order to minimize the errors in direct runoff detailed investigation is needed to compute accurate CN-values from which more accurate figures about direct surface runoff can be conducted.

6. Conclusion and Recommendations

Lower CN-values generate in general less direct surface runoff. It is therefore recommended to apply those soil and water conservation measures and techniques that reduce the CN-value as much as possible. This relation is also visible in both the analyses conducted for the investigation of the sensitivity analysis of the CN-values.

For the computed weighted average CN-values of 73, 83 and 93 the average annual discharge shows big differences. In comparison to a CN-value of 83, a CN-value of 73 only generates one third of the direct runoff, whereas a CN-value of 93 generates a threefold of the runoff. This implies that higher CN-values are more sensitive to errors, which can be explained by the exponential relation between CN-value and direct surface runoff. Small variations in CN-value can therefore lead to big differences in runoff.

As expected, differences in CN-value generate different hydrographs. For a CN-value of 83 on the degraded and replanted areas a peak of 4,7 m^3/s direct surface runoff is generated in the sub catchment. For CN-values 73 and 93 this is just over 30% less, respectively more. In the scenario with the highest value, CN-value 93, the direct surface runoff starts almost twice as soon after the start of the rainfall event in comparison to CN-value 73. The CN-value is not sensitive for the moment of peak discharge as this occurs for all three scenarios at approximately the same time. Changes in CN-value have lower effects on peak discharge than they have on annual surface runoff. The sensitivity of the CN-value in the situation of peak discharge is therefore lower than for average annual surface runoff. Nevertheless a decrease of in CN-value lowers the amount of peak discharge and lower peak discharges automatically imply less erosion.

Based on the results of both analyses it can be concluded that the CN-value is a sensitive parameter in the Curve Number method. Therefore the reliability of the Curve Number method in this case can be debatable, especially for the computation of quantitative figures of runoff and infiltration. The results of the Curve Number method need to be seen more as an estimation, in which it can be a guide in decision making, rather than a detailed prediction. For detailed planning, more detailed studies may be required. Also adaptations of the Curve Number method can be applied for better results.

In order to get more detailed information about the hydrological effects of hill slope revegetation the application of completely different hydrological models can be considered as well. It is recommended to select a model which considers temporal and spatial variations, requires more detailed input information and has a wider application area than merely agricultural sites. Eventually up scaling of theories and applications over the entire Baviaanskloof is required. Therefore more sub catchments should be taken under investigation.

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