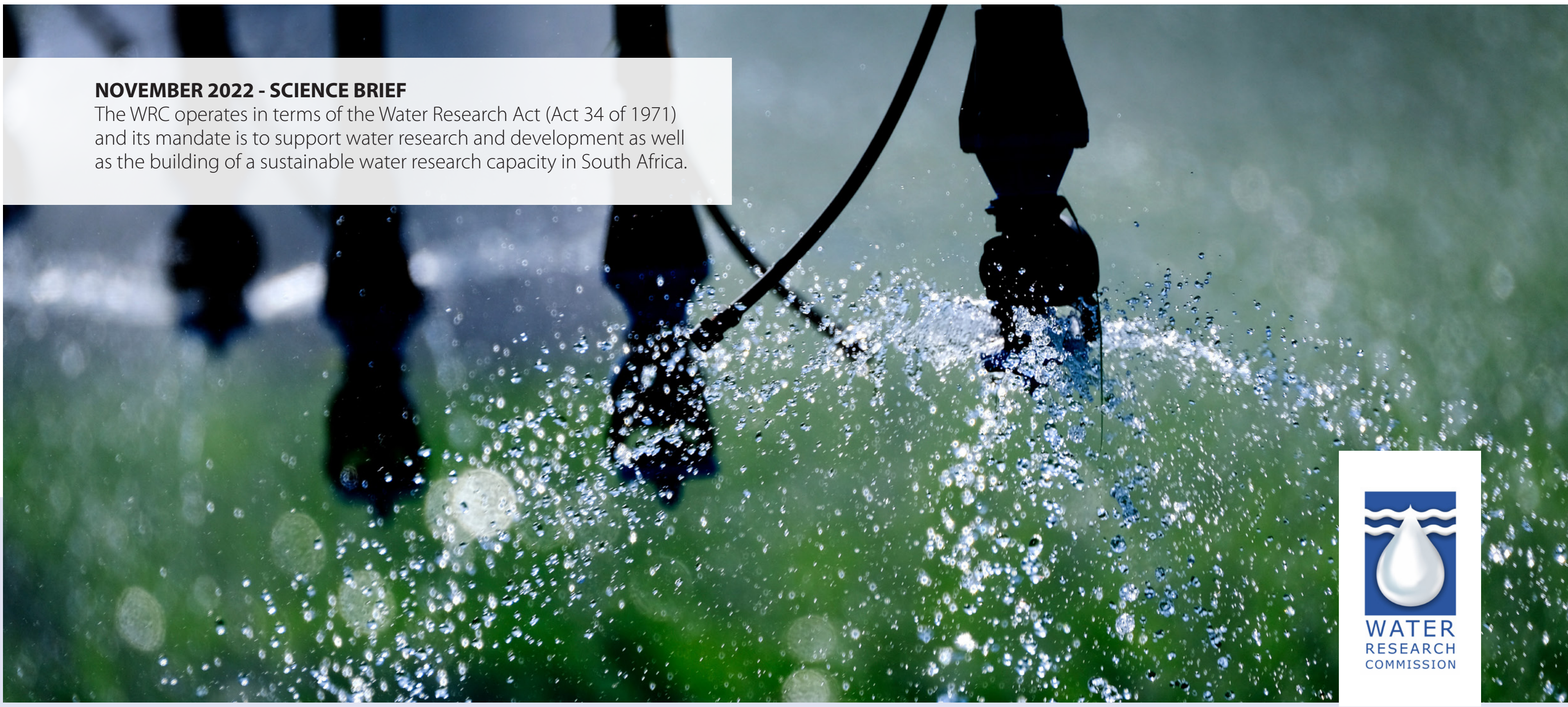

NOVEMBER 2022 - SCIENCE BRIEF
The WRC operates in terms of the Water Research Act (Act 34 of 1971) and its mandate is to support water research and development as well as the building of a sustainable water research capacity in South Africa.

A GIS-based approach to calculate runoff volume (Q_r) and peak runoff rate (P_r)

Luxon Nhamo, Sylvester Mpandeli, Samkelisiwe Hlophe-Ginindza, Mpho Kapari

Apart from their use in agricultural water management, runoff volume (Q_r) and peak runoff rate (Pr) are essential for estimating sediment yield (Y), sediment delivery ratio (SDR) and non-point source (NPS) pollution. Runoff is a complex, dynamic and nonlinear process, influenced by multiple interconnected physical factors. However, modelling runoff requires extensive spatial information on basins and flood risk areas. Geographic Information Systems (GIS) and Remote Sensing come equipped with tools that facilitate the modelling of complex spatial interactions, including those that interact in a runoff. This study uses the National Resources Conservation Society (NRCS) curve number (CN) method to estimate Q_r in a GIS environment, in the Olifants River Basin (Limpopo). The NRCS method is preferred in modelling Q_r as it can be applied at any spatial scale. Rainfall data collected for 10 years was used to estimate the mean annual Qr. The CN method results were then compared with those derived from a Water Research Commission (WRC) funded project, which used a locally developed model.

Background

Surface runoff is important for recharging surface waterbodies and aquifers, and therefore its quantification is essential for managing both portable and agricultural water uses (Weatherl et al., 2021). Apart from being important for recharging waterbodies, as runoff water flows within a basin it also collects agrochemicals from cultivated land and toxic metals from urban areas, and oils from tarred roads polluting aquatic ecosystems (Cheng et al., 2022). Therefore, estimating runoff at the basin scale is important for quantifying the sediments emitted from river basins (sediment yield (Y)) and sediment delivery ratio (*SDR*) into waterbodies (Maltsev et al., 2022). Thus, measuring Q_r is equally important in quantifying non-point source (*NPS*) pollution. Furthermore, quantifying runoff gives indications on the opportunities to harvest surface runoff within a basin (Song et al., 2022). However, as indicated, the runoff process is complex, dynamic and nonlinear, which is determined by many interrelated physical factors (Shao et al., 2022). Therefore, modelling and estimating runoff and its consequences require extensive spatial information on basins and flood risk areas.

Quantifying runoff is equally complex as it is interlinked with many hydrological factors. Geographic Information Systems

(GIS) tools have become important in runoff modelling as they facilitate runoff estimation as are capable of handling a large amount of data (Manchado et al., 2021). Notably, GIS has become an important tool to identify areas that are prone to flooding and inundation and to indicate areas where runoff can effectively be dammed (Manchado et al., 2021). The use of GIS facilitates the visualisation of the modelled results for enhanced strategic decision-making.

This study evaluates the runoff volume *(Q_r)* and peak runoff rate *(P_r)* of the Upper Olifants River basin, which is part of the Limpopo River Basin, a transboundary river basin (Figure 1). The Upper Olifants River basin was chosen as the Olifants River is one of the most polluted rivers in South Africa due to several human-induced stressors present in the basin (Dabrowski and De Klerk, 2013). The basin is of strategic economic importance to South Africa, especially in the sectors of mining, agriculture, industry, and power generation. These sectors rely heavily on a variety of goods and services that they derive from the aquatic ecosystems in the area to sustain their processes (Cai et al., 2017; Nhamo et al., 2020). However, these activities have resulted in the rivers within the basin being heavily polluted causing the death of aquatic organisms. The basin covers an area of approximately 7 000 km^2, with a mean annual precipitation of about 689 mm. It has an average altitude of about 1 588 m.

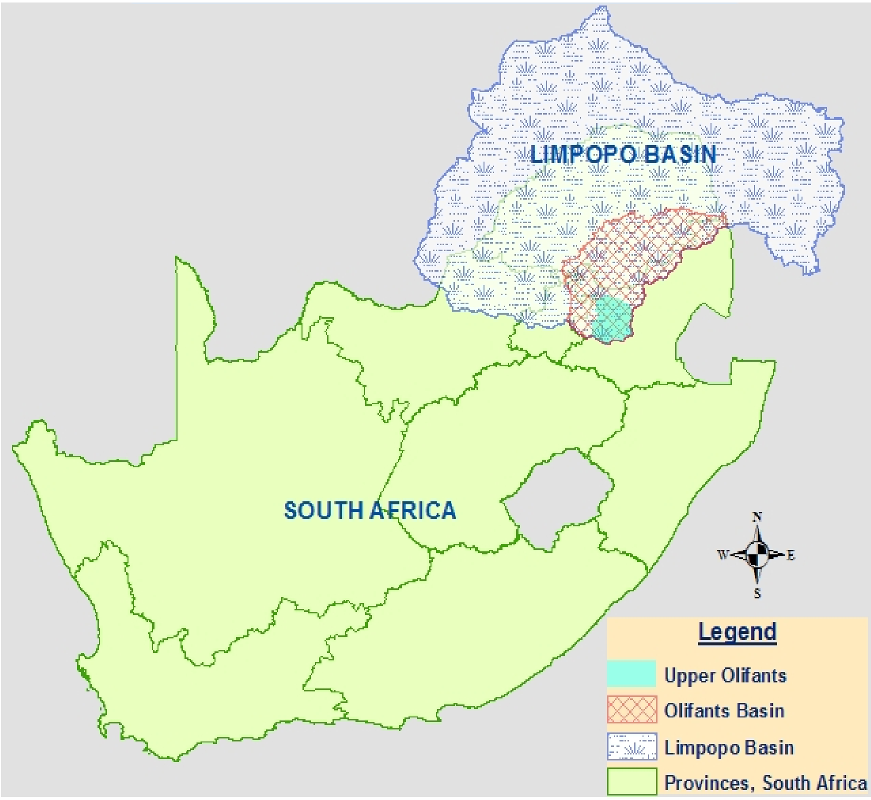

Figure 1. Location of the Upper River Basin

Estimating Runoff Volume (Qr)

The runoff volume of a rainfall event is equal to the product of the effective precipitation depth and the land surface area on which the rainfall occurred (i.e. the drainage basin area) (Blume et al., 2007). Q_r has been calculated using the curve number (*CN*) and the initial soil humidity (or antecedent humidity) method in which direct surface runoff *(Q)* has to be calculated first (Williams and LaSeur, 1976). *Q* is water that flows over the ground surface or through the ground directly into water bodies (streams, rivers, dams, or lakes) after a rainfall event.

The mean inter-annual daily precipitation with a return period of 10 (T_{10}) years was used to calculate the average daily Q_r. A return period refers to an estimated time for a rainfall event of a given magnitude to repeat itself. For example, the return period for a 24-hour rainfall total of 57.9 mm in the Upper Olifants is 10 years. This means that, on average, 57.9 mm of rainfall over 24 hours occurs in the basin every 10 years. Therefore, a mean inter-annual daily precipitation of 57.9 mm, with a T_{10}, means that this precipitation event has a recurrence period of 10 years (a 10-year cycle). Rainfall patterns often have inter-annual as well as inter-decadal time scale variations (Mann and Park, 1994). Thus, Q_r values calculated from rainfall data below a period of 10 or more years can be misleading.

Calculation of Direct Runoff (Q)

The *CN* method was developed by the United States National Resources Conservation Service (NRCS), formerly the Soil Conservation Service (SCS) (Mockus, 1964). The method is based on direct estimation of runoff from soil characteristics, soil use and vegetation cover and antecedent humidity conditions. The CN is a parameter used to estimate the maximum possible retention (S) of the soil in the area of interest. The NRCS derived the following Equation to calculate Q (Mockus, 1964).

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad (1)$$

where,
Q is the direct runoff (mm)
P is the storm amount (or the maximum daily annual precipitation, or of the particular calculation according to each case (in the present work, T_{10})) (mm)
S is the maximum retention capacity calculated as the difference between the maximum potential infiltration or the difference between *P* and *Q* (mm)

Equation 1 indicates that *P* and *Q* are functions of the maximum retention capacity of the basin, a variable that mainly depends on the soil and landuse characteristics.

The *CN* method is used to obtain the *S*, as expressed by Equation 2 (Mockus, 1964):

$$CN = \frac{1000}{S + 10} \qquad (2)$$

from where,

$$S = 254\left(\frac{100}{CN} - 1\right), \text{ in mm} \qquad (3)$$

This method enables the calculation of *Q* produced by a *P* over a complex soil-vegetation surface identified by the *CN*.

Estimating the Composite Curve Number (CN)

The maximum infiltration capacity (*S*) is obtained by using the *CN* of the basin (Equation 3) (Satheeshkumar et al., 2017). A ***CN***, a dimensionless runoff coefficient that is a function of vegetation cover and soil type of an area, was developed for small basins (≈ 25 Km²) with homogenous soil type and landuse because under such conditions it is easier to calculate the *CN* (Mockus, 1964). The Upper Olifants, however, is a large basin with varying soil and landuse types and making it complex to estimate the *CN* manually. The *CN* for different landuse categories was tabulated by the NRCS (Mockus, 1964). The landuse categories of the Upper Olifants are indicated in Figure 2.

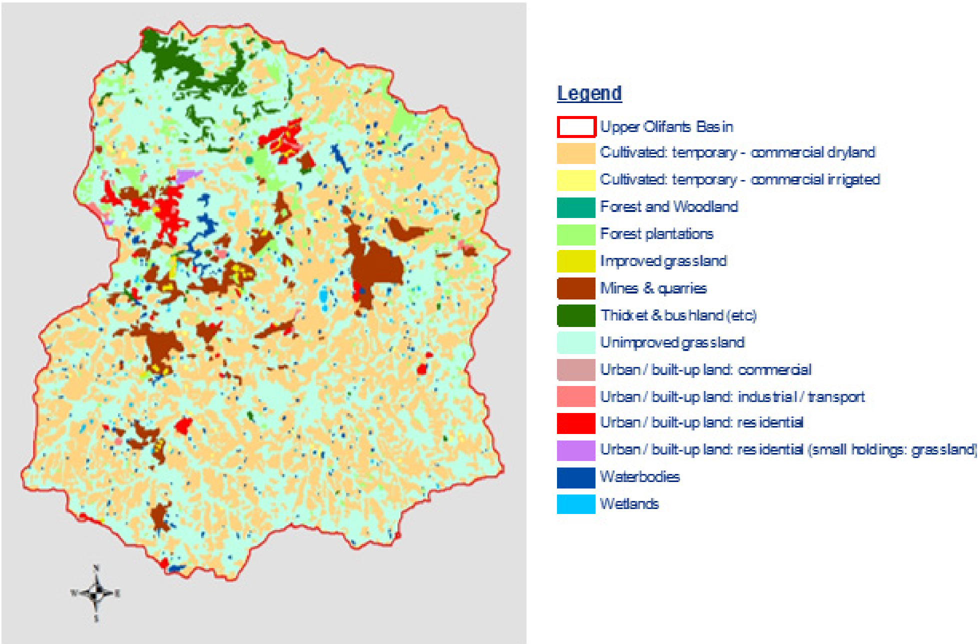

Figure 2. Landuse/cover for the Upper Olifants Basin

The soil types are shown in Figure 3. These soil types are categorised according to their hydrological soil groups (A, B, C, and D). The hydrological soil groups for the Upper Olifants are shown in Table 1 (Russell et al., 2010).

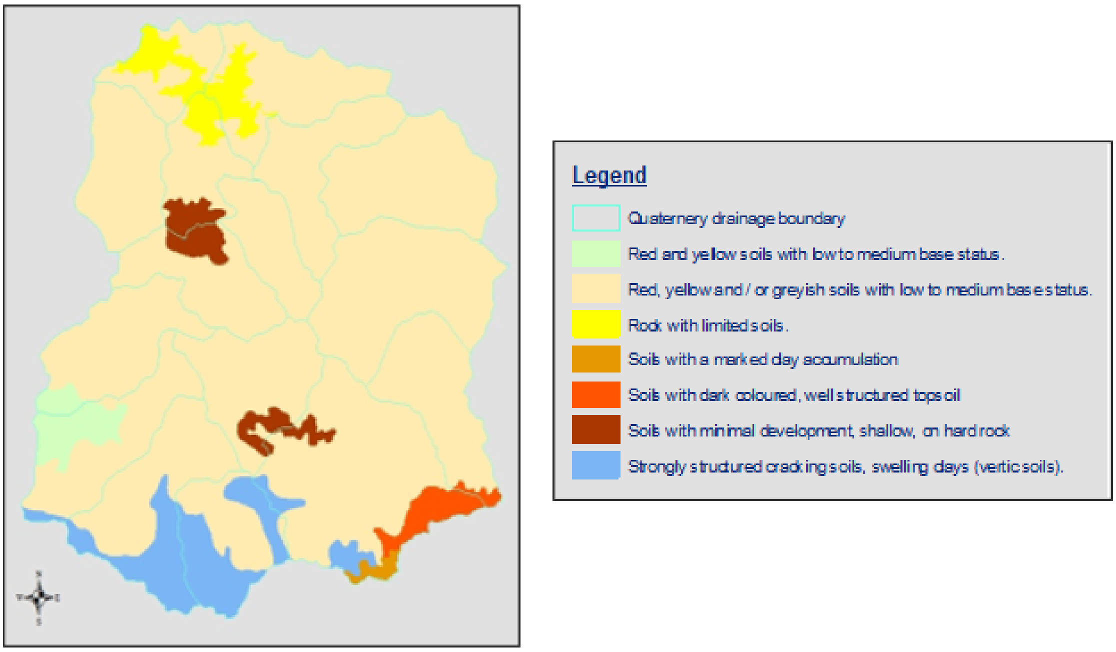

Figure 3. Soil types with the Upper Olifants Basin

Table 1. Soil groups of the Upper Olifants Basin

Description	Hydrologic Soil Group
Rock with limited soils.	D
Red, yellow and/or greyish soils with low to medium base status.	B
Red and yellow soils with low to medium base status.	B
Soils with minimal development, usually shallow, on hard or weathering rock, with or without intermittent diverse soils. Lime rare or absent in the landscape.	C
Soils with dark coloured, well-structured topsoil and high base status (melanic soils). In addition, one or more of vertic and red structured soils may be present.	A
Soils with a marked clay accumulation, strongly structured and a non-reddish colour. They may occur associated with one or more of vertic, melanic and plinthic soils.	A

Adapted from Russell et al, 2009

As a function of soil and landuse, *CN*s estimation requires mapping of the soil and landuse within the basin and the specification of unique soil types and unique landuse categories, requiring handling of large quantities of data. The use of GIS simplified the calculation of the composite *CNs* for the *UO* basin.

The basic Equation to calculate composite *CN* is:

$$CN = \frac{\sum_{i=1}^{n} CN_i A_i}{A} \qquad (4)$$

where, *CN,* the compound curve number (runoff coefficient) of the basin, *A,* the basin area (Km^2), CN_i, the curve number of each uniform plot of land within the basin and A_i, the area of each uniform plot within the watershed (Km^2)

The procedure to calculate composite *CN*s in a GIS setting using Equation 4 (Savvidou et al., 2018) is:

- Define and map the basin boundaries for which the *CNs* will be calculated
- Map the soil types and landuse for the basins
- Convert the soil types to the hydrologic soil groups as shown in Table 5
- Overlay the landuse and hydrologic soil group maps, identify each unique landuse-soil group polygon and determine the area of each polygon
- Assign a *CN* to each unique polygon using the information in Table 1
- Overlay the basin boundary map on the landuse-soil group polygons
- Calculate the *CN* for each drainage basin by area-weighting the landuse-soil group polygons within the basin boundaries.

With the required datasets, calculating *CN*s is achieved by using the Raster Calculator in ArcGIS. The composite *CN*s calculated for the UO basin are indicated in table 2. The *CN*s are a variable for calculating the maximum infiltration (*S*), which is calculated using Equation 3 giving values shown in Table 2.

Table 2. CN, S and P values for the Upper Olifants basin

Quaternary basin ID	Area (Km^2	CN	S (mm)	T_{10} (mm)	Q (m)
B11A	946.2	75	84.7	57.9	0.097
B11B	435.6	80	63.5	50.9	0.079
B11C	385.7	68	119.5	56.8	0.115
B11D	551.1	77	75.9	43.4	0.079
B11E	466.8	75	84.7	52.3	0.092
B11F	428.5	74	89.2	50.7	0.093
B11G	368.0	78	71.6	50.2	0.083
B11H	246.2	75	84.7	52.2	0.092
B11J	269.5	66	130.8	46.9	0.114
B11K	378.5	72	98.8	46.6	0.094
B11L	241.9	68	119.5	45.9	0.106
B12A	405.7	72	98.8	57.8	0.104
B12B	659.1	66	130.8	49.2	0.116
B12C	529.5	60	169.3	49.4	0.140
B12D	362.6	71	103.7	52.7	0.102
B12E	436.1	80	63.5	52.1	0.081

Equation 1 also requires calculating precipitation *(P)* in order to estimate *Q*. A T_{10} has been used to calculate the average inter-annual daily *P* because the final objective is to estimate average *Y*, *SDR* and *NPS* pollution. The average inter-annual daily *P* with a T_{10} was calculated using precipitation data from 1990 to 1999 for gauging stations in each quaternary basin. The T_{10} values for the sub-basins are shown in Table 2. With the *S* and *P* values, *Q* is calculated using Equation 1 and the results are also shown in Table 2.

Estimating Peak Runoff Rate (P_r)

Another important hydrological modelling process is the peak runoff rate (P_r), which is the maximum runoff rate at a given point resulting from a storm event (Savvidou et al., 2018). Using the obtained *Q* values the P_r for a particular control point is calculated using Equation 5, which is a unit hydrograph method. This method is preferred because it takes into consideration the physical and hydrological conditions of the basin.

Unit Hydrograph method

A unit hydrograph (or storm hydrograph) is any graph that shows the rate of water flow (river, canal, etc.) as a function of time at a determined section (Walega et al., 2020). A storm hydrograph can be described as an integral expression describing the physiographic and climatic characteristics which control the relationships between precipitation and runoff in a basin (Walega et al., 2020).

The triangular hydrograph developed by the U.S. Bureau of Reclamation (USBR) is used in this study (USBR, 1987). This particular hydrograph takes into consideration the peak time (T_p), lag time, (T_L), concentration time (T_c), duration of the shower (T_r) (24 hours), and the base time (T_b) of a rain event (USBR, 1987). Once the value of the T_b is obtained, quantifying P_r in m^3/sec is calculated through Equation 5 (Mockus, 1964).

$$P_r = \frac{AQ}{1.8T_b} \qquad (5)$$

where P_r is the peak runoff rate, *A* is the area of the basin (Km^2), *Q* is the direct runoff (mm), and T_b is base time (hrs.)

The P_r values of the basin are calculated as functions of precipitation and runoff as shown in Table 5. The P_r values for the Upper Olifants are shown in Figure 4. The results are based on precipitation data for a T_{10}. These variables, including time events of a particular storm event for the Upper Olifants, are shown in table 5.

Table.3. Peak Runoff values for the Upper Olifants Basin

Basin	T_{10} (mm)	S (mm)	CN	Q (m)	Height (m)	Length (Km)	Area (100000 m^2)	T_c (hrs)	T_p (hrs)	T_r (hrs)	T_b (hrs)	P_r (m^3/sec)	Q_r (m^3/a)
B11A	57.9	84.7	75	0.09672	1658.26	37.65	9462	3.2	13.9	24	37.2	1365.4	92 000 000
B11B	50.9	63.5	80	0.07947	1596.70	47.27	4356	4.2	14.5	24	38.8	495.7	35 000 000
B11C	56.8	119.5	68	0.11467	1618.42	28.47	3857	2.4	13.4	24	35.8	685.8	44 000 000
B11D	43.4	75.9	77	0.07905	1598.72	21.06	5511	1.7	13.0	24	34.7	696.9	44 000 000
B11E	52.3	84.7	75	0.09165	1600.21	52.09	4668	4.8	14.9	24	39.7	598.8	43 000 000
B11F	50.7	89.2	74	0.09268	1572.13	39.42	4285	3.6	14.1	24	37.7	584.7	40 000 000
B11G	50.2	71.6	78	0.08295	1567.40	25.25	368	2.1	13.3	24	35.4	478.4	31 000 000
B11H	52.2	84.7	75	0.09156	1563.34	28.53	2462	2.4	13.4	24	35.9	348.9	23 000 000
B11J	46.9	130.8	66	0.11384	1480.69	55.13	2695	5.2	15.1	24	40.4	421.6	31 000 000
B11K	46.6	98.8	72	0.09449	1491.77	28.42	3785	2.5	13.5	24	36.0	551.2	36 000 000
B11L	45.9	119.5	68	0.10616	1390.68	32.55	2419	2.9	13.8	24	36.7	388.4	26 000 000
B12A	57.8	98.8	72	0.10406	1680.03	65.34	4057	6.2	15.7	24	42.0	559.1	42 000 000
B12B	49.2	130.8	66	0.11546	1630.50	33.02	6591	2.8	13.7	24	36.5	1156.8	76 000 000
B12C	49.4	169.3	60	0.14035	1634.63	31.81	5295	2.7	13.6	24	36.4	1135.6	74 000 000
B12D	52.7	103.7	71	0.10237	1558.88	35.48	3626	3.1	13.8	24	36.9	558.3	37 000 000
B12E	52.1	63.5	80	0.08060	1495.75	48.31	4361	4.4	14.6	24	39.0	500.2	35 000 000

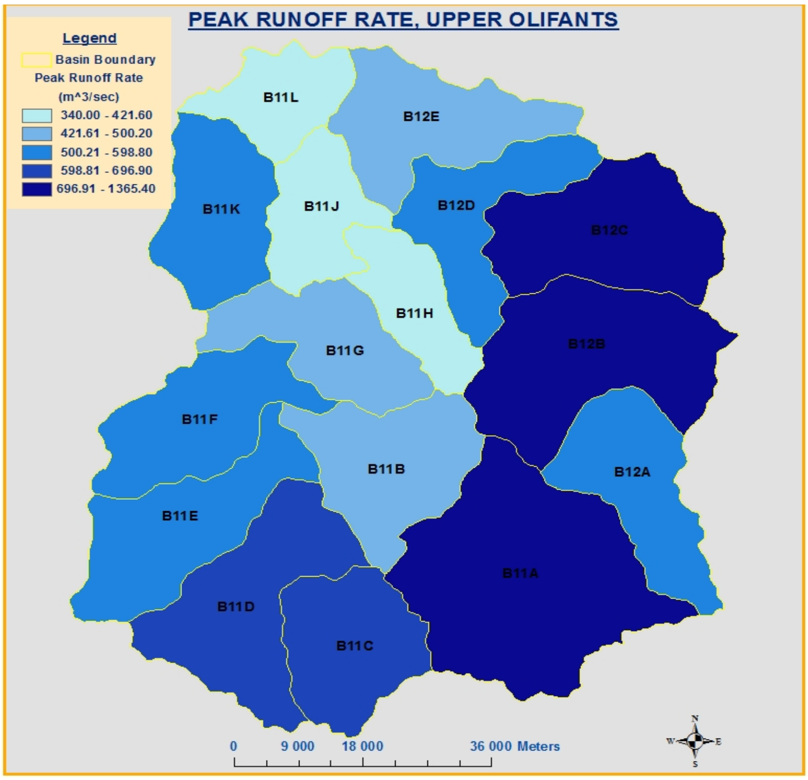

Figure 4. Peak runoff rates within the Upper Olifants Basin

The *P* values for every 24 hours for T_{10}, and the *S* values are then used to calculate *Q* using Equation 1. However, there is a need to calculate the Q_r in m^3 to use the data to estimate *Y*, *SDR* and *NPS* pollution. As a result, *Q* (mm) values are converted to metres (m) and then multiplied by the basin area (m^2) to obtain the Q_r in m^3. The Q_r values for the basins are indicated in table 3 and shown spatially on Map 5.

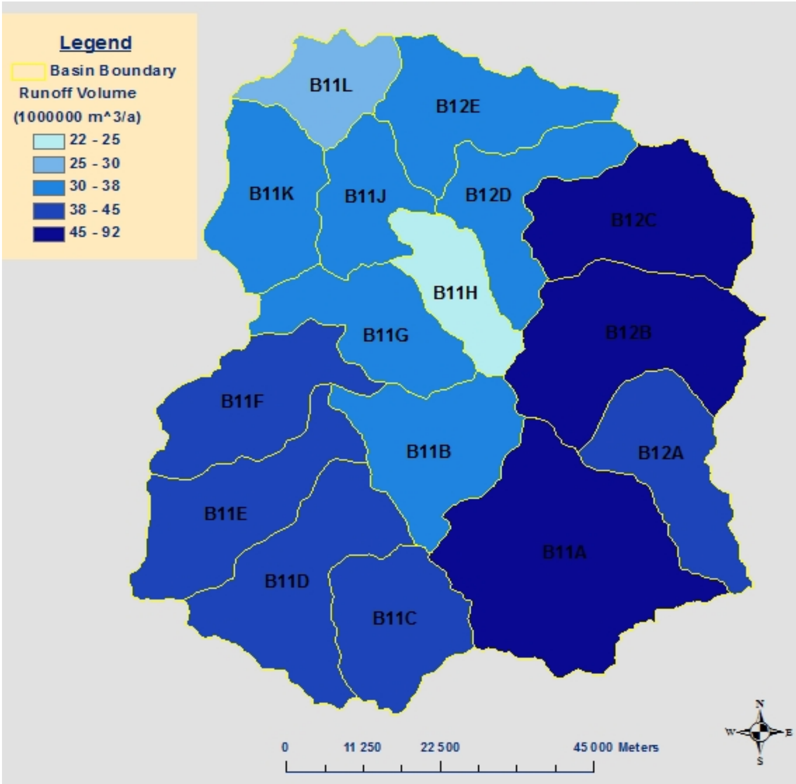

Figure 5. Annual runoff volume of the Upper Olifants Basin

Discussion and conclusions

Table 4 shows the mean annual runoff (MAR) obtained from the *CN* method for a T_{10}, and those obtained from a Water Research Commission study. In the WR90 study by the WRC, considerable effort was made to calibrate and validate a deterministic model to synthesize natural flow conditions (Midgley and Pitman, 1969; Russell et al., 2010). The model used, the Water Resources Simulation Model–90 (WRSM90), is a version of the Pitman Model. This is a monthly time-step rainfall-runoff model developed specifically for use in South Africa. Naturalized flow was derived for 17 of the gauging stations in the Upper Olifants Basin, but for different periods. Once calibrated, model parameters were regionalised and the model was used to generate 70-year sequences (HY1920-HY1989) of naturalized flow for each quaternary basin in the country (Midgley and Pitman, 1969; Russell et al., 2010). The WRC recently completed the naturalized flow series for all the quaternary basins using the same method which is the same data as shown in Table 4.

The Q_r results obtained using the rainfall data for 10 years are almost double the results used by the WRC. Rainfall patterns often have inter-annual as well as inter-decadal time scale variations, thus, values calculated from rainfall data below the recommended period of 10 or more years can be misleading. It is important to note that this is based on statistics, meaning that if one has 100 years of records, there should be 10 such rainfall events (an average of once every 10 years). And if one has 70 years of records there should be 7 such events.

Table 4. Runoff volumes in the Upper Olifants Basin

Basin	Area (km^2)	Mean Runoff (CN), (m^3/a)	Mean Runoff (WRC) (m^3/a)
B11A	946.2	92 000 000	36 800 000
B11B	435.6	35 000 000	15 750 000
B11C	385.7	44 000 000	12 770 000
B11D	551.1	44 000 000	16 580 000
B11E	466.8	43 000 000	15 050 000
B11F	428.5	40 000 000	14 680 000
B11G	368.0	31 000 000	13 190 000
B11H	246.2	23 000 000	8 920 000
B11J	269.5	31 000 000	13 110 000
B11K	378.5	36 000 000	17 390 000
B11L	241.9	26 000 000	11 590 000
B12A	405.7	42 000 000	10 630 000
B12B	659.1	76 000 000	18 460 000
B12C	529.5	74 000 000	15 800 000
B12D	362.6	37 000 000	13 810 000
B12E	436.1	35 000 000	22 900 000

The WRC method presents a challenge when doing a study of an international river basin like the Limpopo River Basin because it is only applicable in South Africa. Using a model that can be applied universally, like the *CN* method, enables to make an objective analysis of results obtained from areas in different countries. The *CN* runoff applied in this study is faster and less expensive than the traditional method of long-term data collection. The use of GIS-enabled the handling of the large quantities of data involved. Considering the levels of pollution in the Olifants River and the death of aquatic animals in the area, the Q_r results from the *CN* method seem to be consistent with what is taking place in the Olifants Water Management Area. The WRC results tend to underestimate the runoff volume. Bearing in mind that the Q_r data is used to estimate sediment delivery and non-point source (*NPS*) pollution, the use of the WRC runoff data will underestimate the level of pollution from runoff.

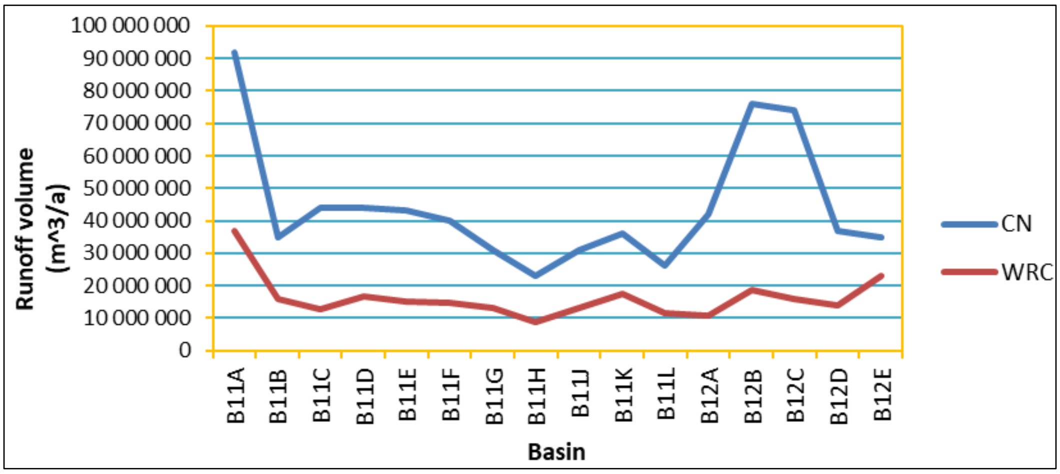

Figure 6. Comparisons between the CN and WRC derived runoff volumes in the Upper Olifants Basin

However, data from both models (WRC and CN) indicate that the area of the basin has a determinant influence on the Q_r. The trend of the data produced by the models shows that when the Q_r value for the *CN* method is high, that for the WRC method is also high and the process goes on like that successively (Figure 4). The graphs do not merge at any given time.

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