Citation for published version:
Loots, I, Smithers, JC & Kjeldsen, T 2022, 'Quantifying the influence of urban development on runoff in South Africa', *Urban Water Journal*. https://doi.org/10.1080/1573062X.2022.2027472

DOI:
10.1080/1573062X.2022.2027472

Publication date:
2022

Document Version
Peer reviewed version

Quantifying the influence of urban development on runoff in South Africa

Ione Loots[a,b]*, J. C. Smithers[b] and T. R. Kjeldsen[b,c]

[a] *Department of Civil Engineering, University of Pretoria, Pretoria, South Africa;* [b] *Centre for Water Resources Research and School of Engineering, University of KwaZulu-Natal, Pietermaritzburg, South Africa;* [c] *Department of Architecture and Civil Engineering, University of Bath, Bath, United Kingdom*

*Ione Loots, Department of Civil Engineering, University of Pretoria, Pretoria, 0001, South Africa, ione.loots@up.ac.za, +27739204511, +27124205484

Quantifying the influence of urban development on runoff in South Africa

It is widely accepted that urban development results in larger flood peak discharges with faster catchment response times, larger total runoff volumes and lower base flow volumes. However, these effects have not previously been studied in the context of the specific characteristics of fast-growing urban areas in developing countries, which are generally unregulated. This study quantifies the effects of urban development on runoff, including: a) runoff volumes, b) base flow volumes and c) flood peaks from eight South African catchments using the Mann-Kendall test and Kendall's τ. Both total runoff and base flow volumes are found to increase with increased development levels and possible reasons for this are discussed. The flood peak analysis finds statistically insignificant trends in most catchments. However, there is an increasing trend in the catchment with the highest proportion of informal development. Recommendations are made for further investigation into reasons for the findings.

Keywords: Runoff; Urbanisation; Urban hydrology; Development impacts; Flood trends

Introduction

Globally, more people now reside in cities than ever before, with more than half of the world's population living in urban areas since 2005 (UNDP 2019). South Africa as a developing country is experiencing an especially high rate of increase in urban migration (StatsSA 2020; UNDP 2019) as people migrate to urban areas in search of employment and better service delivery (Geyer et al. 2012). This has led to significant development of both formal and informal settlements on the outskirts of cities. Thompson (2019) reported a 30% increase in total urban footprint at a national scale between 1990 and 2018.

The development associated with urbanisation could lead to significant impacts on hydrological responses of catchments. These responses need to be understood in order to implement sustainable water solutions. Although traditional urban drainage systems were designed with focus on design flood peaks, flood volumes, base flow volumes and catchment response times are required for the planning and design of all urban drainage systems (Ghodsi et al. 2020; Marvin 2018; Valizadeh, Shamseldin, and Wotherspoon 2019). This is especially applicable in a water-scarce country like South Africa, where proper planning and water sensitive urban design (WSUD) could provide opportunities to augment water supply to rapidly increasing urban populations (Fisher-Jeffes, Kirsty, and Armitage 2017; Fletcher, Andrieu, and Hamel 2013).

Since first suggested by Leopold (1968), it has become widely accepted that urban development can result in significant changes to the hydrological response from a catchment (Braud et al. 2013a; Gogate and Rawal 2015; Gorani 2019; Gumindoga et al. 2014; Jacobson 2011; Putro et al. 2016; Seidl et al. 2020; Shuster et al. 2005; Todeschini 2016). Wheater and Evans (2009) argue that as vegetated areas are replaced with impermeable areas, overland flow increases and infiltration reduces, leading to less attenuation in the system. In addition, the flow paths and velocities are altered, as runoff is generally collected by pipe networks and conveyed rapidly to streams. This combination is expected to result not only in larger and faster flood peak responses, but also smaller base flows and less groundwater recharge (Praskievicz and Chang 2009; Semadeni-Davies et al. 2008). The accepted impacts of urban development on runoff include, amongst others: increased flood frequency, increased peak flow and total flow volume, particularly for low-order floods (Aichele and Andresen 2013), decreased base flow (Braud et al. 2013a; Gogate and Rawal 2015; Jacobson 2011; Shuster et al. 2005; Smakhtin 2001) and decreased catchment response time (Chang 2007; Choi et al. 2015; Gallo et al. 2013; USEPA 2008).

However, some studies (Aichele and Andresen 2013; Brun and Band 2000; Burns et al. 2005; Chin and Gregory 2001; Fletcher, Andrieu, and Hamel 2013; Gallo et al. 2013; Miller and Hess 2017) suggest that not all aspects of storm water runoff are necessarily impacted by urban development as expected. The materials, and types of infrastructure used in some developments, as well as local topography and slope changes, could impact on the rate and flow pathways of storm water runoff (Fidal and Kjeldsen 2020; McGrane 2016).

A number of typical urban development characteristics found in developing countries could potentially cause different runoff responses to those expected in developed countries. The possibility of retention and attenuation in urban systems due to property boundary walls and/or the levelling of naturally sloping areas, combined with the potential effects of long-term blockages and poor maintenance of constructed water drainage and reticulation systems, which are typical in formal settlements in many developing countries, could substantially influence these parameters. In addition, the possible effects of informal settlements on runoff are not yet properly understood (Capps, Bentsen, and Ramirez 2016; Fell 2017; Parkinson, Tayler, and Mark 2007) and could prove to differ from the effects of more formal urban settlements, since the impermeable areas in these settlements are generally not connected to drainage systems (Gogate and Rawal 2015; Parkinson, Tayler, and Mark 2007; Sakijege 2013). The influence of development on drainage paths is closely linked to the influence of directly connected impervious areas (Lee and Heaney 2003; Miller et al. 2020; Redfern et al. 2016; Roy and Shuster 2009; Yao, Chen, and Wei 2015). However, drainage paths will not always be made more efficient by development, with various factors potentially causing flood attenuation and longer drainage paths (Rademeyer 2016). Van Vuuren (2012) noted that in many South African urban developments, solid boundary walls are often constructed around properties, causing temporal storage in the system.

There is therefore a need to quantify the effects of urban development on flow, including: a) runoff volumes, b) base flow volumes and c) flood peaks in catchments with typical urban development types found in South African to facilitate applicable sustainable urban water design. This study investigates the effects using five gauged urban catchment areas in the City of Tshwane, South Africa, as a pilot study, with three neighbouring gauged rural catchments included to confirm whether changes in runoff characteristics can be attributed to urban growth. The Mann-Kendall test and Kendall's τ are used to assess the statistical significance of temporal trends in selected runoff characteristics, in particular correlation between increasing urban development and: a) runoff volumes, b) base flow volumes and c) flood peak magnitude.

Site selection and data collation

Study areas

Five gauged catchments monitored by the Department of Water and Sanitation (DWS) (A2H027, A2H029, A2H054, A2H055, A2H063) with reliable flow records and at least 15% developed urban area (URBEXT) as of 2018 were selected for use in this study. All five catchments are located within the City of Tshwane Metropolitan Municipality (CoT), South Africa (Figure 1) ***[Figure 1 near here]***. Hydrological data from an additional three neighbouring gauged catchments (A2H030, B2H004, B2H007) which had less than 5% developed urban area as of 2018 were included in the study. The contrasting results from the urban and less developed catchments were used to determine whether trends in hydrological responses found in the urban catchment areas could be related to increasing developed urban area. Table 1 provides a summary of the eight study area catchments ***[Table 1 near here]***.

Figure 1. Locations of the study areas, including catchment boundaries and urban land-use classifications

Table 1. Study area information

Land use data

A series of historical land use data was extracted from applicable sources for all the catchments. Topographical maps with a scale of 1:50 000 were used to delineate the extent of development for the years 1965 or 1969, as well as 1975, 1995 and 2001 (Surveyor General 1965, 1969, 1975, 1979, 1995, 2001). The South African National Land Cover (SANLC) data sets were used for the identification of urban areas in 1990 (Geoterraimage 2015b), 2013 (Geoterraimage 2015a) and 2018 (Geoterraimage 2019). The 1990 and 2013 SANLC data sets contain 72 land use classes and the 2018 set contains 73 classes. All formal residential, industrial and commercial and classes, as well as roads, were classified as formal urban areas (URB_{Formal}). All informal residential and village classes were classified as informal urban areas ($URB_{Informal}$). All natural, agricultural and mining land uses were considered as rural area (RURAL). Since smallholdings are expected to have similar runoff characteristics to rural areas these areas were considered RURAL for the purposes of this study. URB_{Formal} and $URB_{Informal}$ were combined to calculate the total extent of urban development (URBEXT). The topographical maps do not differentiate between different land uses, but do indicate areas with urban development, industrial buildings, and buildings in rural areas. URB_{Formal} and $URB_{Informal}$ were differentiated with reference to aerial photographs obtained from National Geo-spatial Information (NGI). All urban and industrial areas were measured to estimate the URBEXT of each catchment for each available map. Linear interpolation was applied to estimate URBEXT for periods between map dates. Where discrepancies were found between the topographical maps, SANLC data and photographs, the photographs took precedence. The URB_{Formal}, $URB_{Informal}$ and RURAL area, as percentages of each catchment for each available historical data set, are summarised in Table 2 ***[Table 2 near here]***.

Table 2. Temporal evolution of URBEXT (%) for each of the eight test catchments

Observed records of rainfall and runoff

Observed and infilled daily rainfall depths from 1903 and up to August 2000 for 17 stations in or around the study catchment areas were extracted from the database collated by Lynch (Lynch 2003). Rainfall data for the remainder of the study period was obtained from the South African Weather Services (SAWS). The locations of the rainfall stations in and around Tshwane are shown in Figure 1. Annual rainfall statistics were calculated for each station showing that all the stations have median annual precipitation values ranging between 650 mm and 750 mm, with similar upper and lower quartile values, but with inter-annual variability in annual rainfall totals observed across all stations. Apparent inconsistencies in the data was checked. Since no data flags were indicated at any of the outliers, the data was accepted as correct. The median, lower and upper quartiles, as well as 5th and 95th percentile values are indicated in Figure 2 ***[Figure 2 near here]***.

Figure 2: Annual total rainfall depths (mm) from 1960 to 2020

Daily and monthly rainfall catchment rainfall for each catchment were estimated from the gauged data using Thiessen polygons. Since the rainfall stations used in this study have similar median annual precipitation, and since there are no major topographical or meteorological differences between different sections of any catchments in the study area, this widely-used method to estimate catchment rainfall from gauged values for urban hydrological studies (Blume, Zehe, and Bronstert 2007; Miller and Hess 2017) was deemed acceptable.

The available instantaneous flow data for each catchment was obtained from DWS for each station. Prior to December 2003 the stations recorded water levels at intervals determined by relative water levels between measurements. The loggers recorded every 15 minutes during periods when changes in river stage were detected, and did not record when the stage levels were not changing. Post December 2003 the stations recorded water levels at intervals determined by relative water levels between measurements, but at an average of 20-minute time intervals. Periods of missing flow data were manually inspected and infilled using representative base flow for the relevant period if no rain was measured. Any gaps in the flow data during periods with rainfall were removed, both from the flow – and rainfall datasets and not included in the analyses. The annual runoff per area, divided by representative rainfall depth for one urban catchment (A2H054) and one rural catchment (B2H004) are shown in Figure 3 as illustration. ***[Figure 3 near here]***. Visual inspection of the representative curves over the study period shows generally higher relative flow rates in the urban catchment than rural catchment. Visual inspection of the other six catchments show similar trends. Since the trends could not be quantified through visual inspection alone, changes in: a) runoff volumes, b) base flow volumes and c) flood peaks needed to be analysed statistically. Statistical trend analysis and results are described in the following section.

Figure 3. Examples of annual runoff volume per area, divided by representative rainfall depth for (a) A2H054 and (b) B2H004

Trend analysis and results

Firstly, the statistical significance of temporal trends in rainfall data needed to be assessed in order to establish if climatological non-stationarity could influence trends in the runoff responses. Next, the statistical significance of temporal trends in: a) runoff volumes, b) base flow volumes, and c) flood peak magnitude was investigated. The widely used non-parametric Mann-Kendall test (Ahmad et al. 2015; Atif, Iqbal, and Mahboob 2018; Brandes, Cavallo, and Nilson 2005; Coch and Mediero 2015; Coen et al. 2020; Gocic and Trajkovic 2013; Requena et al. 2017) was used to test a null-hypothesis of no association between two variables. In this study the co-evolution of time and the selected runoff characteristics were studied. Correlation between URBEXT and a) runoff volumes, b) base flow volumes and c) flood peaks was also assessed using Kendall's τ, with the magnitude of the Kendall τ-value between 0 and 1 giving an indication of the monotonic association between the two variables, with higher values indicating stronger association (Gocic and Trajkovic 2013; Helsel et al. 2020; Pohlert 2020). The sign of the τ-value is in indication of positive or negative correlation (Helsel et al. 2020). The statistical significance was assessed at the 95% confidence level, therefore, any p-value smaller than 0.05 would indicate statistical significance. Where results were significant at the 1% confidence level, this was also reported.

Stationarity of rainfall data

Since non-stationarity of rainfall data could influence runoff responses, the possible existence of temporal trends in daily, monthly and annual rainfall were analysed using the Man-Kendall test. The daily rainfall depth analysis was performed using the annual maximum series (AMS). Time series of both the annual maximum daily rainfall depth and annual rainfall depth analysis were run considering the South African hydrological year that runs from October to September. The monthly rainfall depth analysis was performed using a seasonal Mann-Kendall test with a 12-month period in order to account for seasonality (Helsel et al. 2020; Hirsch and Slack 1984). In this test, monthly seasons were applied in order to compare January data only with January, etc. (Helsel et al. 2020).

The results in Table 3 show that a significant trend was detected in one of the 17 stations at the 5% ($p<0.05$) significance level at a daily scale and two stations at the 1% ($p<0.01$) significance level ***[Table 3 near here]***. Of the three stations with statistically significant trends, Stations 0477071 3 and 0477494 W showed the strongest association. Both these stations are in the southern region of the study area and were only used in the analysis for Catchment B2H007. Therefore, all subsequent analysis of B2H007 had to consider the increasing trend of extreme daily rainfall in this catchment. Considering the monthly analysis, four stations showed trends at the 5% significance level and one station at the 1% significance level. All five stations with statistically significant trends at a monthly scale showed decreasing trends. The low Kendall τ-values at a monthly scale indicate weak association due to significant variability of the rainfall data. Only two stations showed statistically significant increasing trends at the 5% significance level at an annual aggregation. The relatively low Kendall τ-values for these stations are indicative of relatively weak trends, despite being statistically significant (Helsel et al.

2020; Van den Berg 2020). Therefore, the notion of non-stationarity of rainfall data was disregarded in further trend analysis, for all catchments but B2H007, where non-stationarity of extreme daily rainfall could not be excluded.

Table 3. Rainfall depth statistical test results

Flow volumes

Two approaches were followed to meet Objective a). Firstly, ratios between runoff and rainfall (Q/P) were estimated by comparing the cumulative total annual runoff volumes with the estimated cumulative annual representative catchment rainfall volumes to obtain annual Q_{sum}/P_{sum} ratio values, as percentages. The Q_{sum}/P_{sum} percentages were compared with URBEXT and it was confirmed that catchments with lower URBEXT tend to have lower Q_{sum}/P_{sum} percentages, as shown in Figure 4 ***[Figure 4 near here]***.

Figure 4. The relationship between cumulative annual Q/P and URBEXT for each of the eight test catchments

For the second part of the Q/P analysis, the significance of trends in annual Q/P with time and with URBEXT were assessed (Table 4) ***[Table 4 near here]***. This was achieved through comparison of total annual runoff volumes with the estimated annual representative catchment rainfall volumes. The annual Q/P ratios in Figure 5 depict the influence of catchment development on flow volume ***[Figure 5 near here]***. With p-values significantly lower than 0.01 for most of the urban catchments, the results in

Table 4 show that strong trends exist in the temporal Q/P ratios as well as the URBEXT Q/P ratios for the urban catchments. The high Kendall's τ-values for A2H027, A2H054 and A2H055 are indicative of particularly strong association. None of the undeveloped catchments showed statistically significant results, with A2H030 indicating a negative trend (Figure 5). This analysis indicates an increase in total flow volumes follows from an increase in urbanisation.

Table 4. τ values for trends in annual Q/P ratios over time and with URBEXT

Figure 5. Co-evolution of annual Q/P and URBEXT over time for each of the eight test catchments

Base flow volumes

For Objective b), trends in base flow were studied for the eight catchment areas. Various methods could be used to separate the surface runoff and base flow in the primary flow data (Arnold et al. 1995; Chapman 1999; Gericke and Smithers 2017; Lyne and Hollick 1979; Smakhtin 2001). For the purposes of this study, the base flow was separated from the instantaneous flow data and extracted at 30-minute intervals using the HYBASE application in the HYDSTRA/TS data management system developed by KISTERS (Pty) Ltd (formerly Hydsys (Pty) Ltd, Hydstra (Pty) Ltd). This tool applies recursive digital filtering as first proposed by Lyne and Hollick (1979). This methodology was also adopted for other studies in South Africa (Gericke and Smithers 2017; Hughes, Hannart, and Watkins 2003; Smakhtin and Watkins 1997). Smakhtin and Watkins (1997) established that α-parameters of between 0.995 and 0.997 were applicable for most catchments in South Africa and Hughes, Hannart, and Watkins (2003) found a β-parameter of 0.5 to be acceptable. Gericke and Smithers (2017) found that catchments with sub-daily flow measurements produced better results when an α-parameter 0.997 was applied. Since all the data sets for this study had sub-daily measurements from 2003, a fixed α-parameter of 0.997 and β-parameter of 0.5 was used to separate the base flow from the primary flow time series. It is important to note that the base flow separation did not consider catchment response to precipitation directly, but considered all base flow at the catchment outlet.

In order to compare results, the base flow rates are shown in Figure 6 as a percentage of the 1-year recurrence interval event estimated as the median of the annual maximum series (AMS) ***[Figure 6 near here]***. From this figure it is clear that the three catchments with the highest percentages or URBEXT (A2H054, A2H055 and A2H063) have the lowest base flows relative to the AMS. Increasing trends are visible in A2H027 and A2H029 at this scale.

The Mann-Kendall tests for base flow were done by comparing annual base flow volumes, calculated by summing the 30-minute interval extracted base flow data over a hydrological year, with time and with increased URBEXT. The results showed statistically significant trends at the 1% significance level for four of the urban catchments (A2H027, A2H029, A2H054 and A2H055), and at the 5% significance level for the catchment with the highest percentage of URBEXT (A2H063). The Kendall τ-values indicated the strongest association for catchments A2H027 and A2H055 (Table 5) ***[Table 5 near here]***.

Figure 6. Trends in observed base flow rates expressed as percentage of the 1-year RI flood peak

Table 5. Statistical test results for base flow

Flood peaks

For Objective c), the flood peaks were assessed in two ways: i) for the AMS and ii) for all flood peak points in the instantaneous flow data above the 1-year recurrence interval threshold, estimated as the median of the AMS (PoT). The trend over time in the data for each catchment was compared using the Mann-Kendall test. In addition, the trends in peak discharge with increasing URBEXT as assessed. The three catchments with longer data sets (A2H027, A2H029 and A2H030) experienced a number of high peaks before 1982. This influenced the results of both sets of analysis, but especially the PoT analysis. Therefore, both sets of analysis were run twice: first with flood peaks before 1982 included, and then with only flood peaks after 1982. The AMS is shown as a percentage of the 1-year recurrence interval flood peak for each catchment in Figure 7, with linear regression curves shown to identify trends. Of significance are the slopes of the AMS linear regression curves for A2H029, at 0.010 when considering the entire data period and 0.023 when considering the data set from 1982; and A2H063 with dataset starting in 1985, at 0.004. The slope of the PoT linear regression curves for A2H027, at -0.013 considering the entire data period and -0.009 for the data set from 1982, are also noteworthy ***[Figure 7 near here]***.

The Mann-Kendall statistical test results for trends between peak discharges over time and with URBEXT are shown in Table 6. These results show that for the peak discharge analysis, A2H029 and A2H063 have the highest Kendall's τ-values, with trends significant at the 1% ($p<0.01$) level. For A2H029 these trends are evident when considering either the full data period, or the shorter period from 1982. For the PoT analysis, only A2H027 shows a trend at the 1% ($p<0.01$) significance level, and A2H029 at the 5% significance level, and in both cases only for the analysis considering the full data period. Both are negative trends. ***[Table 6 near here]***

Figure 7. Trends in observed peak flow rates, expressed as a percentage of the 1-year RI flood peak, and URBEXT over time

Table 6. Statistical test results for flood peaks

Discussion

Flow volumes

The results of the flow volume analysis indicate that an increase in total flow volumes follows from an increase in urbanisation. Q_{sum}/P_{sum} ratios range between just above 0 and 5% in undeveloped catchments, between 3.5% and 8% at 10% URBEXT, approximately 11% at 50% URBEXT, between 12% and 14% at 60% URBEXT and between 8% and 23% at 70% URBEXT. The significant Q_{sum}/P_{sum} increase in A2H063 despite minimal increase in URBEXT could possibly be attributed to densification of urban areas in the catchment. Different Q_{sum}/P_{sum} ratios in catchments with similar percentages of URBEXT could be caused by different development densities in formal and informal residential areas in South Africa. The imperviousness of different South African urban land use types needs to be quantified in order to analyse this further. Kendall τ-values are the highest in the catchments with the highest degrees of temporal change in URBEXT. The increase in total runoff with increased urbanisation is consistent with findings of most other studies (Konrad 2003; Putro et al. 2016).

Base flow volumes

The results of the base flow analysis indicate that the largely urbanised catchments tend to have lower relative base flow volumes than rural catchments, however, statistical analysis found that base flow tends to increase with an increase in URBEXT. The increasing base flow trends are contrary to findings in most other catchments (Braud et al. 2013a; Gogate and Rawal 2015; Jacobson 2011; Shuster et al. 2005; Smakhtin 2001). Some activities associated with urbanisation, including inter-catchment transfers and wastewater flow, may well change the net impact on hydrological responses (Brandes, Cavallo, and Nilson 2005; Meyer 2005; Schutte and Schulze 2017; Whitney et al. 2015). Although the specific causes of the base flow trends cannot be determined from the data collated for this study, it should be noted that South Africa is a water-scarce country with developmental hubs far away from natural water sources. The country therefore has a number of potable water transfer schemes that supply water to urban regions through long piped distribution networks. It is postulated that the water transferred into the catchments may contribute to baseflow through pipe bursts, pipe leaks, garden irrigation, swimming pool backwashing and other activities. As shown in Figure 6 the sudden increase in base flows in A2H027, A2H029, A2H054 and A2H055 do not correlate exactly with change in URBEXT, nor do the start of the changes occur at the same time in all catchments. The effect of water transfer into the catchments is potentially combined with aging, poorly maintained, or poorly installed infrastructure leading to leakage of potable water and waste water into the river systems. A wastewater treatment plant upstream of A2H027 could also contribute to increased base flow in this catchment.

The reasons for this phenomenon need to be further investigated and quantified, since it is expected that this phenomenon will occur in other South African urban areas, as well as urban areas in other water-scarce countries. Base flow, whether naturally occurring or due to urban activities and infrastructure failure, needs to be incorporated into hydrological models and drainage system design, especially when lower-order flood events are of significance. It is therefore recommended that the changes in surface runoff be investigated further by considering Q/P to base flow trends.

It should be noted that this study only considered URBEXT using land use data. In order to incorporate possible effects into design of sustainable urban water systems in developing countries, distinction between effects in formal and informal settlements, as well as impervious percentage and directly connected impervious areas within urban land use classes needs to be investigated and quantified.

Flood peaks

The flood peak analysis delivered different results depending on whether the AMS or the PoT data set was considered. The AMS analysis delivered statistically significant increasing trends with the strongest association for the catchment with the highest proportion of informal development (A2H029), followed by the catchment with the highest percentage of formal development and total URBEXT (A2H063). Of the two, the linear regression line for A2H029 shows a steeper slope than A2H063, with A2H063 also showing little variation from the linear regression line. The characteristics of the informal development might influence rainfall-runoff responses in this catchment differently to characteristics in the catchments with more formal development. This observation needs to be investigated further.

Despite the AMS analysis for A2H027 not showing a statistically significant trend, the PoT analysis for the entire data period showed a negative trend of statistical significance. Of interest is the different results for A2H029 when considering AMS or PoT, with the AMS showing positive trends and the PoT showing the opposite trend. This could be attributed to the 1967 hydrological year that experienced above-average rainfall, both in annual totals and in events above the AMS.

Both the AMS and PoT results also showed the potential significance of data set length, where the exclusion of the period between 1962 and 1982 from the data set for A2H029 resulted in an increase of the Kendall τ-values between the AMS and both time and URBEXT. Although the AMS results in A2H027 and A2H030 did not show statistical significance, and only showed weak association with low Kendall's τ-values, it is still interesting to note the changes from negative to positive trends. For the PoT analysis the Kendall τ-values and p-values decreased for A2H027 with a shorter data set. The question could therefore be raised what influence a longer data set would have had on trends in the other catchments.

The AMS results for A2H029 and A2H063 are similar to results of most studies in other urbanising catchments (Konrad 2003; Lee and Heaney 2003; Putro et al. 2016; Todeschini 2016), however, the fact that the trend in A2H063 is relatively flat, and the fact that three of the urbanised catchments did not show trends in the AMS, brings into question whether formal South African urban development causes increased flood peaks. This observation has previously been made in other international studies (Aichele and Andresen 2013; Burns et al. 2005; Miller and Hess 2017). The causes of the negative trends in A2H027 also need to be investigated further. Possible causes could be drainage path inefficiency and ponding between dwellings. The causes need to be investigated and verified in other catchments.

It is widely accepted that connectivity of impervious areas plays a major role in runoff response (Lee and Heaney 2003; Miller et al. 2020; Redfern et al. 2016; Roy and

Shuster 2009; Yao, Chen, and Wei 2015). However, since A2H029 is the catchment with the largest proportion of informal development, this assertion might not be applicable in certain South African informal developments. Therefore, it is imperative that the types of urban development, total impervious areas and impervious area connectivity of this catchment need to be quantified and compared with the results from the other catchments in this study in order to further investigate this unexpected result.

It should be noted that the flood peaks in B2H007 did not show a statistically significant increasing trend, despite the increase in extreme rainfall events in this catchment. This could be due to the hydrological processes in this rural catchment that dampen the effect of extreme rainfall events.

Conclusions and recommendations

The aims of this study were achieved using the Mann-Kendall method and Kendall's τ-value to test for trends over time and with urban development in a) flood volumes, b) base flow and c) flood peaks. Five urban catchment areas and three undeveloped catchment areas were used as case studies and trends in urban and rural catchments were compared.

It was established that strong increasing trends exist in the urban catchments in the temporal Q/P ratios and base flows, as well as between Q/P ratios and URBEXT and base flow and URBEXT. Despite the strong correlation for Q/P ratios and base flows, the magnitudes of flood peaks do not seem to be affected to the same extent by degree of urban development, with statistically insignificant changes in most catchments, negative trends evident in some catchments and an unexpected positive trend in the catchment the catchment where development commenced most recently and unregulated.

Increases in Q_{sum}/P_{sum} despite minimal URBEXT, as well as different Q_{sum}/P_{sum} ratios in catchments with similar percentages of URBEXT could possibly be attributed to densification of urban areas and different development densities in formal and informal residential areas in South Africa. The imperviousness of different South African urban land use types needs to be quantified in order to further analyse this.

Base flow, whether naturally occurring or due to urban activities and infrastructure failure, needs to be incorporated into hydrological models and drainage system design, especially when lower-order flood events are of significance. It is therefore recommended that the changes in surface runoff be investigated further by considering trends between Q/P ratios and base flow. The possible effects of water transfer into the catchments as development and population increases, combined with aging, poorly maintained, or poorly installed infrastructure leading to leakage of potable water and waste water into the river systems also need to be considered in order to understand the results from this study. It should be noted that this study only considered URBEXT using land use data. In order to incorporate possible effects into design of sustainable urban water systems in developing countries, distinction between effects in formal and informal settlements, as well as total imperviousness and impervious area connectivity within urban land use classes need to be investigated and quantified.

The fact that few statistically significant trends were found in the flood peak analysis, but significant trends in the flow volume and base flow analyses supports the argument for flood peak attenuation in urban areas in South Africa (Van Vuuren 2012). The analysis of flood peaks in urban catchments showed the potential significance of record length on the results, especially for PoT analysis, where years with more high flow events could significantly alter analysis results. Both A2H027 and A2H029 had higher Kendall τ-values and levels of significance for the PoT analysis considering the entire record length.

The catchment with the strongest association in the AMS analysis is A2H029, which is the catchment with the highest proportion of informal development. The causes for the trends in this catchment need to be investigated and verified in other catchments to confirm whether the trends are linked to the URBEXT, or possibly the types of development in the catchment, as well as the influence of total impervious area and impervious area connectivity.

Quantification of the effects of URBEXT on catchment response times was not considered in this paper, but this will also influence design decisions for sustainable urban drainage systems and therefore it is recommended that this be investigated in future studies.

Acknowledgement and Disclosure

Historical rainfall data was provided by the South African Weather Service (SAWS). The South African Department of Water and Sanitation (DWS) supplied all flow data and Ms. A Joubert separated base flow from the data sets. Her assistance is acknowledged with gratitude. The authors do not have competing interests to disclose.

References:

Ahmad, I, D Tang, T Wang, M Wang, and B Wagan. 2015. "Precipitation trends over time using Mann-Kendall and Spearman's rho tests in Swat River Basin, Pakistan." *Advances in Meteorology* 2015.

Aichele, Stephen S, and Jeffery A Andresen. 2013. "Spatial and temporal variations in land development and impervious surface creation in Oakland County, Michigan, 1945-2005." *Journal of Hydrology* 485:96-102. doi: http://dx.doi.org/10.1016/j.jhydrol.2012.12.049.

Arnold, J.G, P.M Allen, R Muttiah, and G Bernhardt. 1995. "Automated base flow separation and recession analysis techniques." *Groundwater* 33 (6):1010-8.

Atif, I, J Iqbal, and A Mahboob. 2018. "Investigating snow cover and hydrometeorological trends in constrasting hydrological regimes of the Upper Indus Basin." *Atmosphere* 9 (5).

Blume, T, E Zehe, and A Bronstert. 2007. "Rainfall—runoff response, event-based runoff coefficients and hydrograph separation." *Hydrological Sciences Journal* 52 (5):843-62. doi: 10.1623/hysj.52.5.843.

Brandes, D, G.J Cavallo, and M.L Nilson. 2005. "Base flow trends in urbanizing watersheds of the Delaware River basin." *Journal of hte American Water Resources Association* 41(6):1377-91.

Braud, I, P Breil, F Thollet, M Lagouy, F Branger, C Jacqueminet, S Kermadi, and K Michel. 2013a. "Evidence of the impact of urbanization on the hydrological regime of a medium-szed periurban catchment in France." *Journal of Hydrology* 485:5-23. doi: http://dx.doi.org/10.1016/j.jhydrol.2012.04.049.

Brun, S.E, and L.E Band. 2000. "Simulating runoff beahvior in an urbanizing watershed." *Computers, Environment and Urban Systems* 24:5-22.

Burns, D, T Vitvar, McDonnell, J, J Hassett, K Duncan, and C Kendall. 2005. "Effects of suburban development on runoff generation in the Croton River basin, New York, USA." *Journal of Hydrology* 311:266-81. doi: 10.1016/j.jhydrol.2005.01.022.

Capps, K.A, C.N Bentsen, and A Ramirez. 2016. "Poverty, urbanization, and environmental degradation: urban streams in the developing world." *Freshwater Science* 35 (1):429-35.

Chang, H. 2007. "Comparative streamflow characteristics in urbanizing basins in the Portland Metropolitan Area, Oregon, USA." *Hydrological Processes* 21:211-22. doi: 10.1002/hyp.6233.

Chapman, T. 1999. "A comparison of algorithms for stream flow recession and baseflow separation." *Hydrological Processes* 13:701-14.

Chin, A, and K.J Gregory. 2001. "Urbanization and adjustment of ephemeral stream channels." *Annals of the Association of American Geographers* 91(4):595-608.

Choi, W, K Nauth, J Choi, and S Becker. 2015. "Urbanization and rainfall-runoff relationships in the Milwaukee river basin." *The Professional Geographer* 68(1):14-25.

Coch, A, and L Mediero. 2015. "Trends in low flows in Spain in the period 1949-2009." *Hydrological Sciences Journal* 61 (3):568-84.

Coen, M. C, E Andrews, A Bigi, G Martucci, G Romaneus, F. P. A Vogt, and L Vuilleumier. 2020. "Effects of the prewhitening method, the time granularity, and the time segmentation on the Mann-Kendall trend detection and associated Sen's slope." *Atmospheric Measurement Techniques* 13:6945-64.

Fell, J. 2017. "An analysis of surface water from an informal settlement, Langrug, Franschhoek: down a slippery slope." University of Cape Town.

Fidal, J, and T.R. Kjeldsen. 2020. "Accounting for soil moisture in rainfall-runoff modelling of urban areas." *Journal of Hydrology* 589:125122. doi: 10.1016/j.jhydrol.2020.125122.

Fisher-Jeffes, L, C Kirsty, and N Armitage. 2017. "A water sensitive urban design framework for South Africa." *Town and Regional Planning* 71:1-10.

Fletcher, T. D., H. Andrieu, and P. Hamel. 2013. "Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art." *Advances in Water Resources* 51:261-79. doi: http://dx.doi.org/10.1016/j.advwatres.2012.09.001.

Gallo, Erika L, Paul D Brooks, Kathleen A Lohse, and Jean E.T McLain. 2013. "Land cover controls on summer discharge and runoff solution chemistry of semi-arid urban catchments." *Journal of Hydrology* 485:37-53.

Geoterraimage. 2015a. "2013 - 2014 South African National Land-Cover Dataset." In. Pretoria, South Africa: Department of Environmental Affairs.

———. 2015b. "1990 South African National Land-Cover Dataset." In. Pretoria, South Africa: Department of Environmental Affairs.

———. 2019. "2018 South African National Land-Cover Dataset." In. Pretoria, South Africa: Department of Environmental Affairs.

Gericke, O.J, and J.C Smithers. 2017. "Direct estimation of catchment response time parameters in medium to large catchments using observed streamflow data." *Hydrological Processes* 31 (5):1125-43.

Geyer, H. S. Jr, H.S. Geyer, D.J Du Plessis, and A Van Eeden. 2012. "Differential urbanisation trends in South Africa - regional and local equivalents." *Environment and Planning A* 44(12):2940-56.

Ghodsi, S.H, Z Zahmatkesh, E Goharian, R Kerachian, and Z Zhu. 2020. "Optimal design of low impact development practices in response to climate change." *Journal of Hydrology* 580:124266.

Gocic, M, and S Trajkovic. 2013. "Analysis of changes in meteorological variables using Mann-Kendall and Sen's slope estimator statistical tests in Serbia." *Global and Planetary Change* 100:172-82.

Gogate, N.G, and P.M Rawal. 2015. "Identification of potential stormwater recharge zones in dense urban context: a case study from Pune City." *International Journal of Environmental Resolution* 9(4):1259-68.

Gorani, G. 2019. "Assessing the impact of urbanisation on surface runoff peak flows in Bogota." Lund University.

Gumindoga, W, T Rientjies, M.D Shekede, D.T Rwasoka, I Nhapi, and A.T Haile. 2014. "Hydrological Impacts of Urbanization of Two Catchments in Harare, Zimbabwe." *Remote Sensing* 6:12544-74. doi: 10.3390/rs61212544.

Helsel, D.R, R.M Hirsch, K.R Ryberg, S.A Archfield, and E.J Gilroy. 2020. "Statistical Methods in Water Resources." In *Statistical methods in water resources: U.S. Geological Survey Techniques and Methods, book 4, chapter A3*, edited by G.A Norten. U.S. Geological Survey.

Hirsch, R.M, and J.R Slack. 1984. "A nonparametric tren test for seasonal data with serial dependence." *Water Resources Research* 20 (6):727-32.

Hughes, D. A, P Hannart, and D.A Watkins. 2003. "Continuous baseflow from time series of daily and monthly streamflow data." *Water SA* 29 (1):43-8.

Jacobson, C.R. 2011. "Identification and quantification of the hydrological impacts of imperviousness on urban catchments: a review." *Journal of Environmental Management* 92:1438-48. doi: 10.1016/j.jenvman.2011.01.018.

Konrad, Christopher P. 2003. "Effects of Development on Floods." In. Virginia, USA: US Geological Survey.

Lee, J.G, and J.P Heaney. 2003. "Estimation of urban imperviousness and its impacts on storm water systems." *Journal of Water Resources Planning and Management* 129(5):419-26.

Leopold, Luna B. 1968. "Hydrology for Urban Land Planning - A Guidebook on the Hydrologic Effects of Urban Land Use." In. Virginia, USA: US Geological Survey.

Lynch, S.D. 2003. "The development of an improved gridded database of annual, monthly and daily rainfall." In. Pretoria, RSA: Water Research Commission.

Lyne, V, and M Hollick. 1979. "Stochastic time-variable rainfall-runoff modelling." In *Hydrology and Water Resources Symposium*, 89-92. Perth: Institution of Engineers Australia.

Marvin, J.T. 2018. "Using Continuous Simulation to Analyse the Downstream Impacts of Stormwater Management Ponds in the Sawmill River Watershed." *Journal of Water Management Modeling* 26. doi: 10.14796/JWMM.C458.

McGrane, Scott J. 2016. "Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review." *Hydrological Sciences Journal* 61(13):2295-311.

Meyer, Scott C. 2005. "Analysis of base flow trends in urban streams, northeastern Illinois, USA." *Hydrogeology Journal* 13:871-85. doi: 10.1007/s10040-004-0383-8.

Miller, J.D., and Tim Hess. 2017. "Urbanisation impacts on storm runoff along a rural-urban gradient." *Journal of Hydrology* 552:474-89.

Miller, J.D., L Stewart, Tim Hess, and Tim Brewer. 2020. "Evaluating landscape metrics for characterising hydrological response to storm events in urbanised catchments." *Urban Water Journal* 17 (3):247-58. doi: 10.1080/1573062X.2020.1760320.

Parkinson, J, K Tayler, and O Mark. 2007. "Planning and design of urban drainage systems in informal settlements in developing countries." *Urban Water Journal* 4(3):137-49.

Pohlert, T. 2020. "Non-parametric trend tests and change-point detection." In. CC BY-ND, 4.

Praskievicz, S, and H Chang. 2009. "A review of hydrological modelling of basin-scale climate change and urban development impacts." *Progress in Physical Geography* 33(5):650-71.

Putro, B., T.R. Kjeldsen, M.G. Hutchins, and J.D. Miller. 2016. "An empirical investigation of climate and land-use effects on water quantity and quality in two urbanising catchments in the southern United Kingdom." *Science of the Total Environment* 548-549:164-72.

Rademeyer, P. 2016. The Rational Method. Paper presented at the Three day short course in flood hydrology, Stellenbosch, South Africa.

Redfern, Thomas W, Neil Macdonald, T.R. Kjeldsen, J.D. Miller, and Nick Reynard. 2016. "Current understanding of hydrological processes on common urban surfaces." *Progress in Physical Geography* 40(5):699-713. doi: 10.1177/0309133316652819.

Requena, A.I, I Prosdocimi, T.R. Kjeldsen, and L Mediero. 2017. "A bivariate trend analysis to investigate the effect of increasing urbanisation on flood characteristics." *Hydrology Research* 48 (3):802-21.

Roy, Allison H, and William D Shuster. 2009. "Assessing impervious surface connectivity and applications for watershed management." *Journal of the American Water Resources Association* 45(1):198-209.

Sakijege, T. 2013. "Managing flood risks: lessons from Keko Machungwa informal settlement in Dar Es Salaam, Tanzania." *Indonesian Journal of Geography* 45 (1):1-14.

Schutte, S., and R.E Schulze. 2017. "Projected impacts of urbanisation on hydrological resource flows: A case study within the uMngeni Catchment, South Africa." *Journal of Environmental Management* 196:527-43.

Seidl, M, B Hadrich, L Palmier, G Petrucci, and N Nascimento. 2020. "Impact of urbanisation (trends) on runoff behaviour of Pampulha watersheds (Brazil)." *Environmental Science and Pollution Research* 27:14259-70. doi: https://doi.org/10.1007/s11356-019-06029-6.

Semadeni-Davies, A, C Hernebring, G Svensson, and L.G Gustafsson. 2008. "The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: Combined sewer system." *Journal of Hydrology* 350:100-13.

Shuster, W.D, J Bonta, H Thurston, E Warnemuende, and D.R Smith. 2005. "Impacts of impervious surface on watershed hydrology: a review." *Urban Water Journal* 2(4):263-75.

Smakhtin, V.U. 2001. "Low flow hydrology: a review." *Journal of Hydrology* 240:147-86.

Smakhtin, V.U, and D.A Watkins. 1997. "Low flow estimation in South Africa." In. Pretoria, South Africa: Water Research Commission.

StatsSA. 2020. "General Household Survey 2019." In. Pretoria, RSA: Statistics South Africa.

Surveyor General. 1965, 1969, 1975, 1979, 1995, 2001. "1:50 000 Cadastral Maps for 2528." In. Mowbray, RSA: Chief Directorate: Surveys and Land Information.

Thompson, M. 2019. "2018 South African National Land-Cover Change Assessments." In. Pretoria, RSA: Geoterraimage.

Todeschini, S. 2016. "Hydrologic and Environmental Impacts of Imperviousness in an Industrial Catchment of Northern Italy." *Journal of Hydrologic Engineering* 21 (7):05016013. doi: 10.1061/(ASCE)HE.1943-5584.0001348.

UNDP. 2019. "World Urbanization Prospects: The 2018 Revision." In. New York, USA: United Nations, Department of Economic and Social Affairs, Population Division.

USEPA. 2008. "Urbanization and Streams: Studies of Hydrological Impacts." In. Washington D.C., USA: United States Environmental Protection Agency.

Valizadeh, N, A.Y Shamseldin, and L Wotherspoon. 2019. "Quantification of the hydraulic dimension of stormwater management system resilience to flooding." *Water Resources Management* 33:4417-29. doi: 10.1007/s11269-019-02361-1.

Van den Berg, R.G. 2020. "Kendall's Tau - Simple Introduction." In *SPSS Tutorials*. The Netherlands: SPSS Help.

Van Vuuren, Stefanus J. 2012. "Influence of Catchment Development on Peak Urban Runoff." In. Pretoria, RSA: Water Research Commission.

Wheater, H, and E Evans. 2009. "Land use, water management and future flood risk." *Land Use Policy* 26:251-64.

Whitney, John W, Patrick A Glancy, Susan E Buckingham, and Arthur C Ehrenberg. 2015. "Effects of rapid urbanization on streamflow, erosion, and sedimentation in a desert stream in the American Southwest." *Anthropocene* 10:29-42.

Yao, Lei, Liding Chen, and Wei Wei. 2015. "Assessing the effectiveness of imperviousness on stormwater runoff in micro urban catchments by model simulation." *Hydrological Processes* 30(12):1836-48.

Table 1. Study area information

Table 2. Temporal evolution of URBEXT (%) for each of the eight test catchments

Table 3. Rainfall depth statistical test results

Table 4. τ values for trends in annual Q/P ratios over time and with URBEXT

Table 5. Statistical test results for base flow

Table 6. Statistical test results for flood peaks

Figure 1. Locations of the study areas, including catchment boundaries and urban land-use classifications

Figure 2: Annual total rainfall depths (mm) from 1960 to 2020

Figure 3. Examples of annual runoff volume per area, divided by representative rainfall depth for (a) A2H054 and (b) B2H004

Figure 4. The relationship between cumulative annual Q/P and URBEXT for each of the eight test catchments

Figure 5. Co-evolution of annual Q/P and URBEXT over time for each of the eight test catchments

Figure 6. Trends in observed base flow rates expressed as percentage of the 1-year RI flood peak

Figure 7. Trends in observed peak flow rates, expressed as a percentage of the 1-year RI flood peak, and URBEXT over time

Table 1. Study area information

DWS gauging station	River	Size (km^2)	Slope (m/m)	Longest river (km)	Start of record (month/year)	End of record (month/year)	Record length (years)
A2H027	Pienaars River	357	0.011	39	05/1962	05/2021	59
A2H029	Edendale Spruit	129	0.012	24	05/1962	06/2019	57
A2H030[a]	Roodeplaat Spruit	116	0.013	23	05/1962	06/2018	56
A2H054	Hartbees Spruit	35	0.011	14	09/1982	05/2021	39
A2H055	Moretele River	106	0.011	20	10/1982	06/2018	36
A2H063	Wonderboom Spruit	30	0.009	6	05/1984	07/2018	34
B2H004[a]	Osspruit	123	0.012	15	10/1984	05/2021	37
B2H007[a]	Koffiespruit	317	0.006	25	05/1985	05/2021	36

[a] Rural catchments

Table 2. Temporal evolution of URBEXT (%) for each of the eight test catchments

DWS station number	1960			1979			1990			1995		
	URB$_{Formal}$ (%)	URB$_{Informal}$ (%)	RURAL (%)	URB$_{Formal}$ (%)	URB$_{Informal}$ (%)	RURAL (%)	URB$_{Formal}$ (%)	URB$_{Informal}$ (%)	RURAL (%)	URB$_{Formal}$ (%)	URB$_{Informal}$ (%)	RURAL (%)
A2H027	0.0	1.6	98.4	1.5	1.5	97.0	3.4	0.1	96.5	3.5	0.1	96.4
A2H029	0.0	0.0	100.0	0.0	0.0	100.0	1.5	0.7	97.8	0.0	2.8	97.2
A2H030[a]	1.7	0.0	98.3	1.7	0.0	98.3	1.7	0.0	98.3	1.7	0.0	98.3
A2H054	27.1	0.0	72.9	39.6	0.0	60.4	41.0	0.0	59.0	41.6	0.0	58.4
A2H055	20.3	0.0	79.7	28.0	0.0	72.0	39.8	0.0	60.2	45.1	0.0	54.9
A2H063	66.5	0.0	33.5	68.7	0.0	31.3	69.6	0.0	30.4	70.0	0.0	30.0
B2H004[a]	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0
B2H007[a]	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.1	0.0	99.9

DWS station number	2001			2013			2018		
	URB$_{Formal}$ (%)	URB$_{Informal}$ (%)	RURAL (%)	URB$_{Formal}$ (%)	URB$_{Informal}$ (%)	RURAL (%)	URB$_{Formal}$ (%)	URB$_{Informal}$ (%)	RURAL (%)
A2H027	5	0.1	94.9	10	0.7	88.5	12.9	3.3	83.8
A2H029	0	7.7	92.3	3.9	9.3	86.7	11.3	8.6	80.1
A2H030[a]	1.7	0.0	98.3	3.5	0	96.5	3.5	0	96.5
A2H054	44.3	0	55.7	62.3	0	37.7	62.5	0	37.5
A2H055	54.2	0	45.8	66.9	0	33.1	70.6	0	29.4
A2H063	71	0	29	71.1	0	28.9	71.2	0	78.8
B2H004[a]	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0
B2H007[a]	0.1	0	99.9	0.2	0.3	99.5	0.2	0.3	99.5

[#] Rural catchments

Table 3. Rainfall depth statistical test results

Station	τ for monthly rainfall depth	τ for annual rainfall depth
0513255 W	0.003	0.174*
0513611 W	-0.073**	0.028
0513528 W	-0.014	0.117
0513550 W	-0.057*	-0.002
0513369 A 5	-0.051*	0.043
0513466 A W	-0.030	0.095
0513314 C 9	-0.048	0.023
0513404 A W	-0.008	0.114
0513404 6	-0.036	-0.012
0513346 0	-0.031	0.035
0513556 W	-0.010	0.129
0513742 6	-0.056*	-0.078
0513836 4	0.011	0.046
0513439 A 1	-0.060*	-0.013
0513435 A 4	-0.030	0.095
0477071 3	0.037	0.209*
0477494 W	-0.025	0.090

*Statistically significant trend at the 5% significance level

**Statistically significant trend at the 1% significance level

Table 4. τ values for trends in annual Q/P ratios over time and with URBEXT

DWS gauging station	Annual Q/P τ	
	Temporal	URBEXT
A2H027	0.592**	0.586**
A2H029	0.307**	0.342**
A2H030[a]	-0.001	0.098
A2H054	0.556**	0.603**
A2H055	0.670**	0.717**
A2H063	0.276*	0.383**
B2H004[a]	0.084	-
B2H007[a]	0.042	0.059

[a] Rural catchment

*Statistically significant trend at the 5% significance level

**Statistically significant trend at the 1% significance level

Table 5. Statistical test results for base flow

DWS gauging station	Temporal τ	URBEXT τ
A2H027	0.601**	0.575**
A2H029	0.274**	0.273**
A2H030[a]	0.035	0.141
A2H054	0.380**	0.454**
A2H055	0.562**	0.715**
A2H063	0.257*	0.319*
B2H004[a]	0.137	-
B2H007[a]	0.076	0.098

[a] Rural catchment

*Statistically significant trend at the 5% significance level

**Statistically significant trend at the 1% significance level

Table 6. Statistical test results for flood peaks

DWS gauging station	AMS analysis τ		PoT analysis τ	
	Temporal	URBEXT	Temporal	URBEXT
A2H027	-0.145 0.043[b]	-0.145 0.043[b]	-0.377** -0.179[b]	-0.377** -0.179[b]
A2H029	0.232** 0.366[b]**	0.240** 0.366[b]**	-0.128* -0.028[b]	-0.128 -0.029[b]
A2H030[a]	-0.175 0.159[b]	-0.066 0.136[b]	-0.089 0.099[b]	-0.076 -0.087[b]
A2H054	0.155	0.155	0.178	0.175
A2H055	0.006	0.006	0.154	0.091
A2H063	0.330**	0.348**	0.191	0.188
B2H004[a]	-0.002	-	0.117	-
B2H007[a]	0.092	0.110	0.000	0.003

[a] Rural catchment

[b] Results for analysis only considering data after October 1982

*Statistically significant trend at the 5% significance level

**Statistically significant trend at the 1% significance level

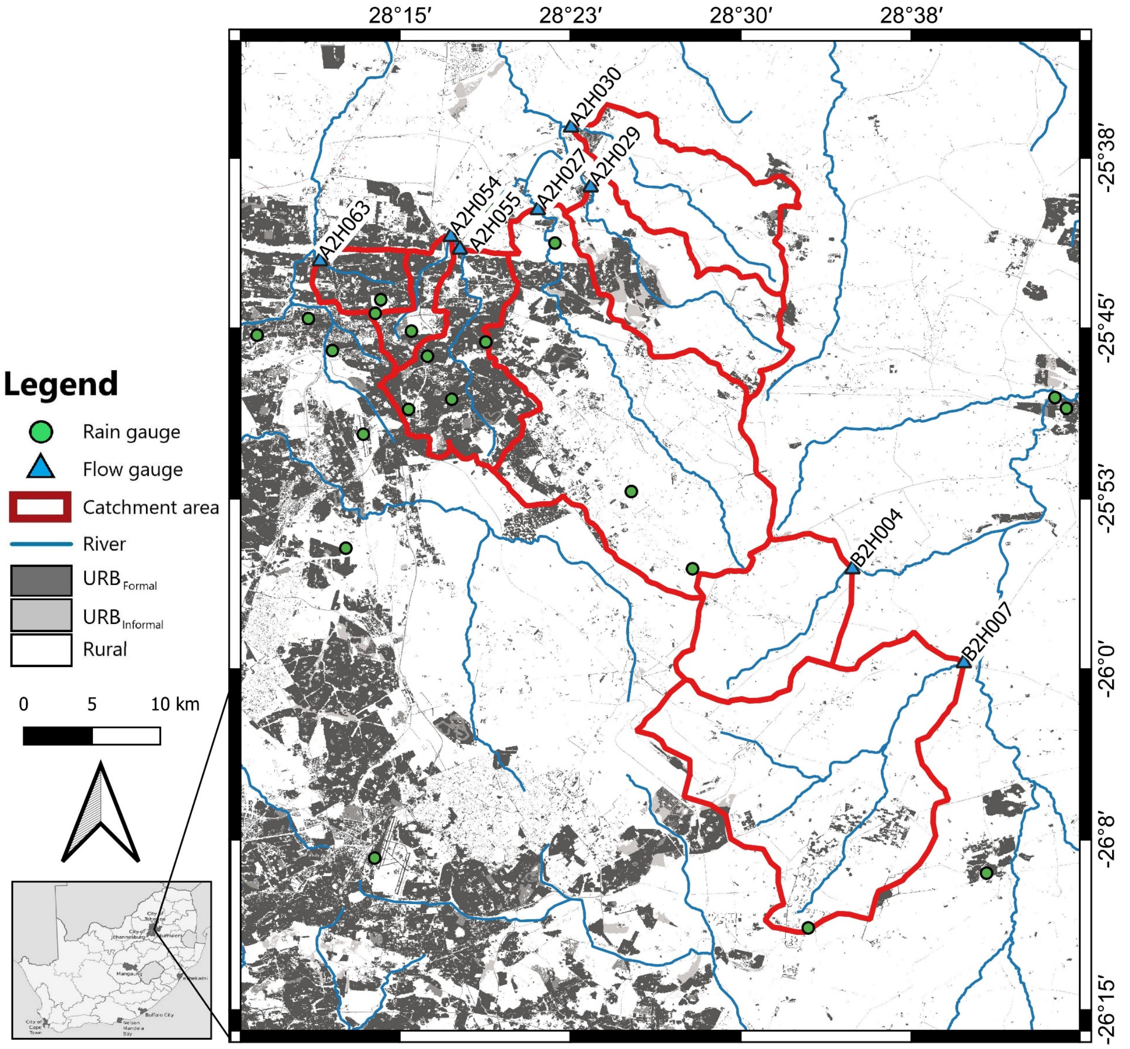

Figure 1. Locations of the study areas, including catchment boundaries and urban land-use classifications

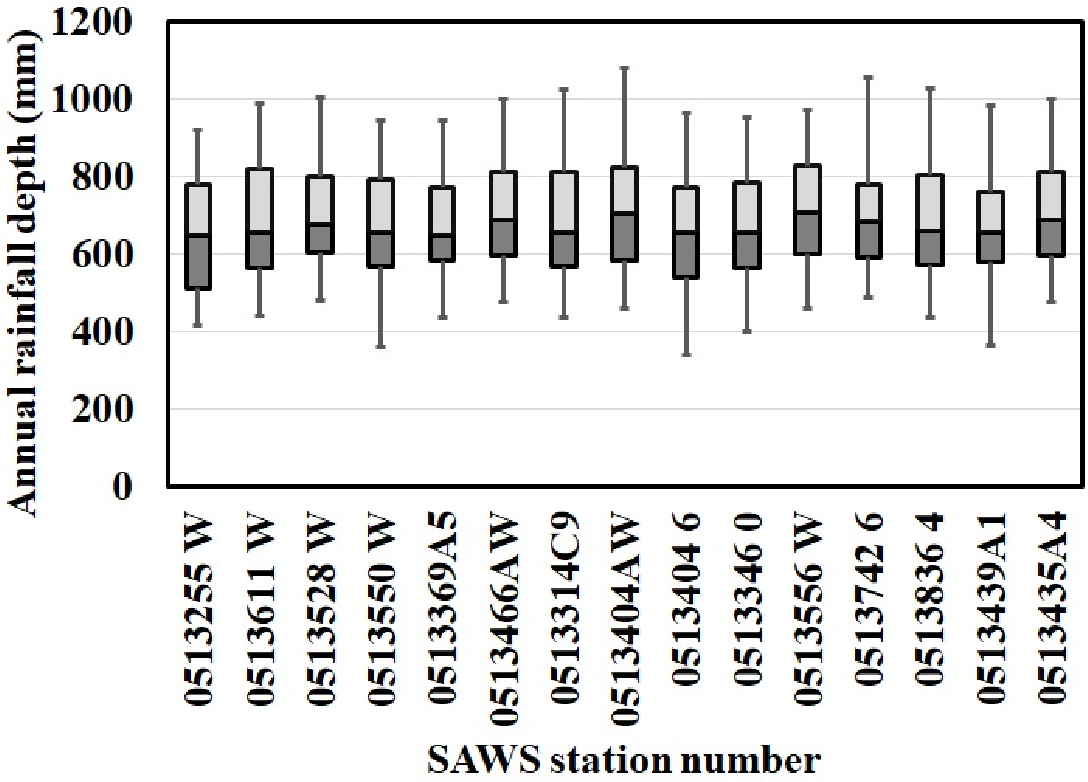

Figure 2: Annual total rainfall depths (mm) from 1960 to 2020

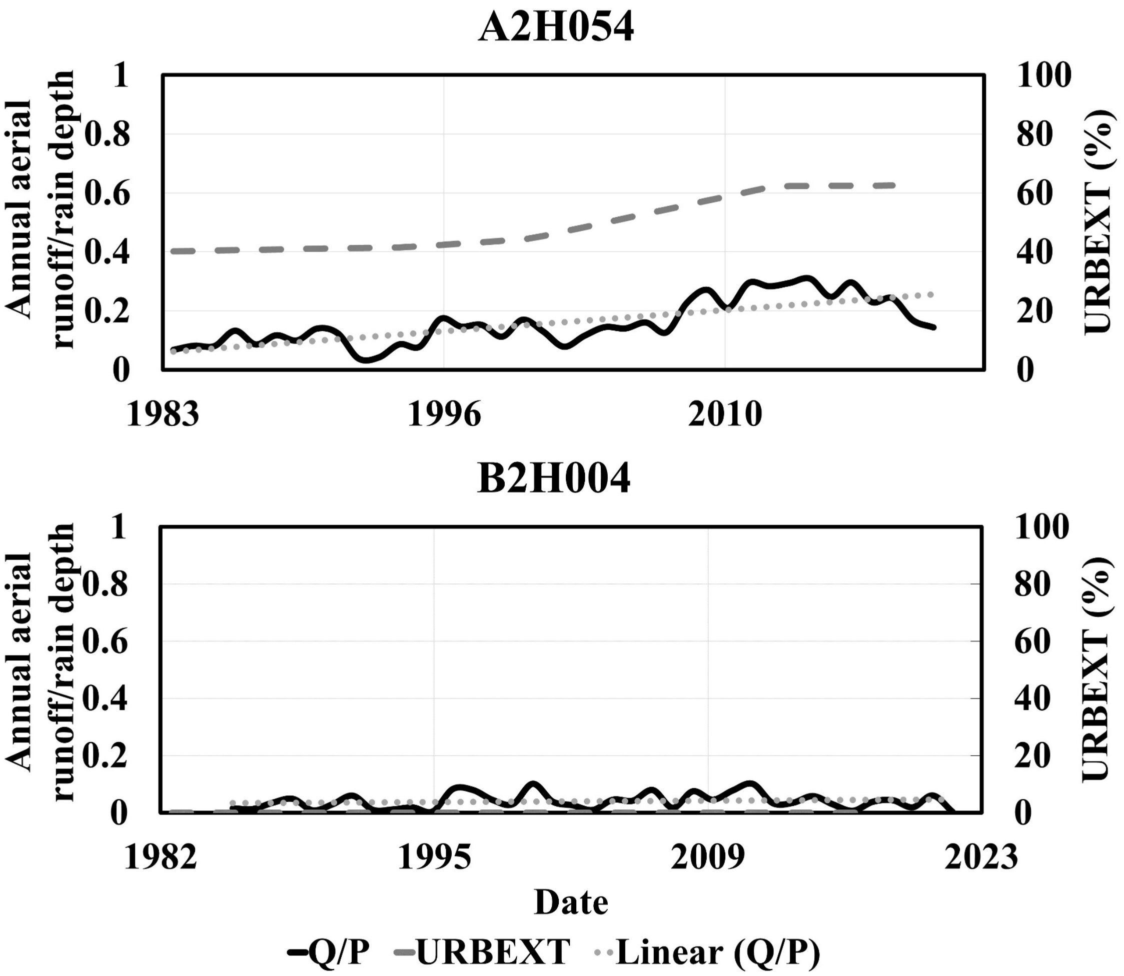

Figure 3. Examples of annual runoff volume per area, divided by representative rainfall depth for (a) A2H054 and (b) B2H004

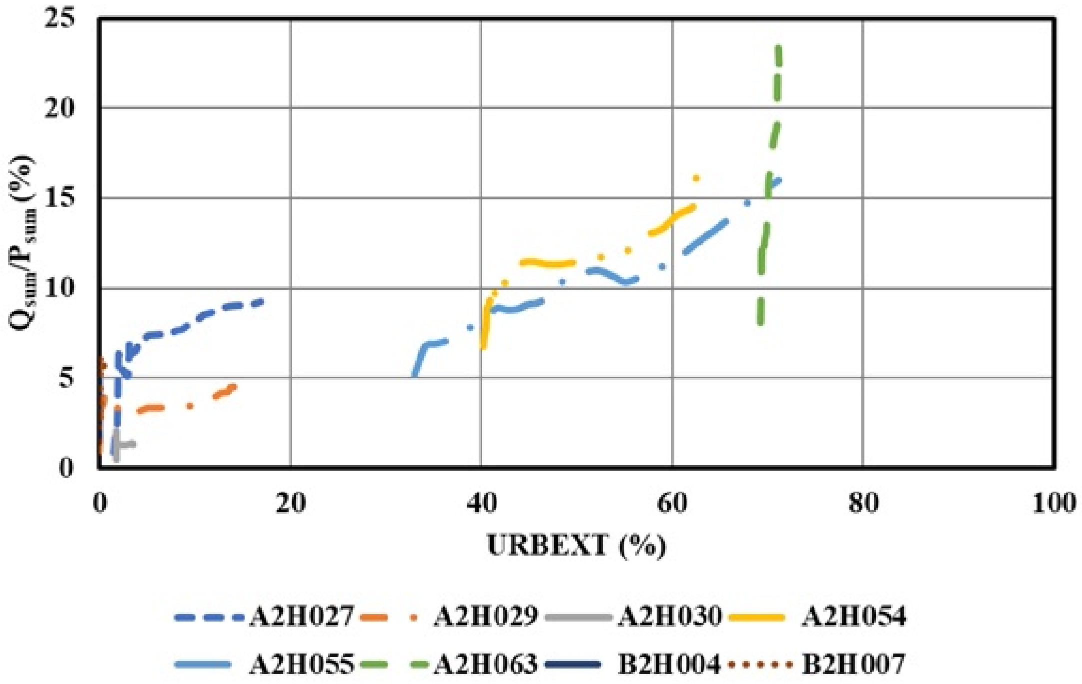

Figure 4. The relationship between cumulative annual Q/P and URBEXT for each of the eight test catchments

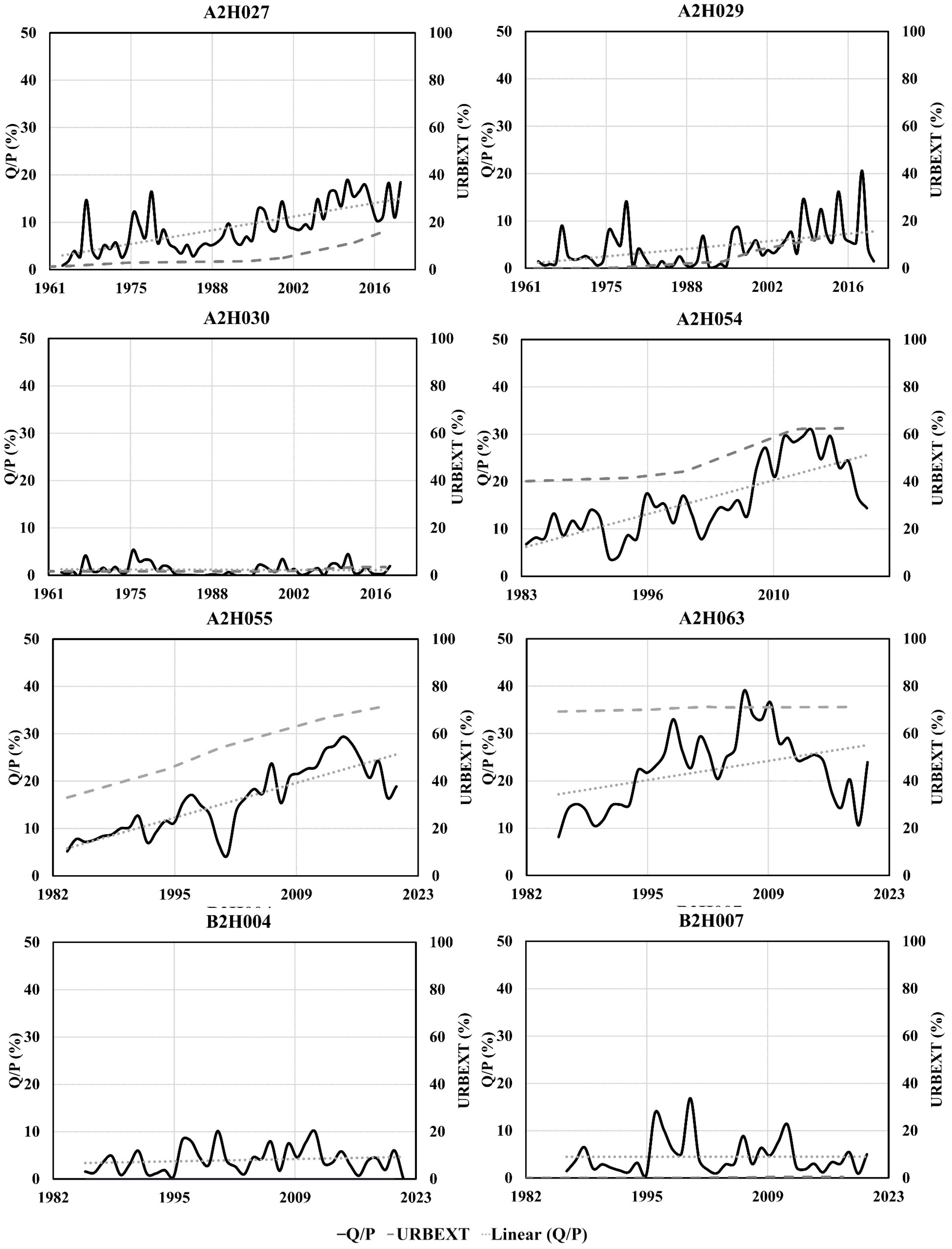

Figure 5. Co-evolution of annual Q/P and URBEXT over time for each of the eight test catchments

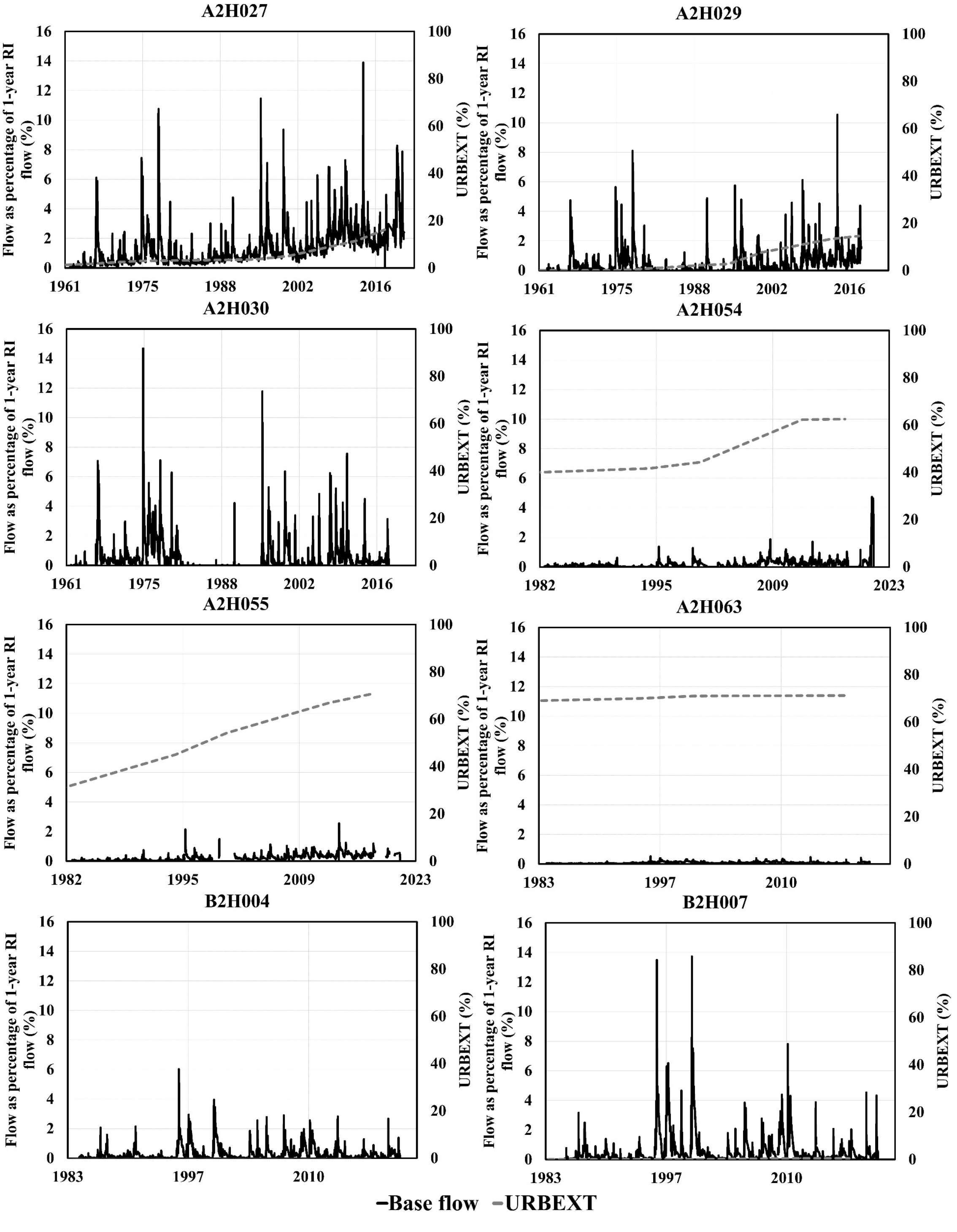

Figure 6. Trends in observed base flow rates expressed as percentage of the 1-year RI flood peak

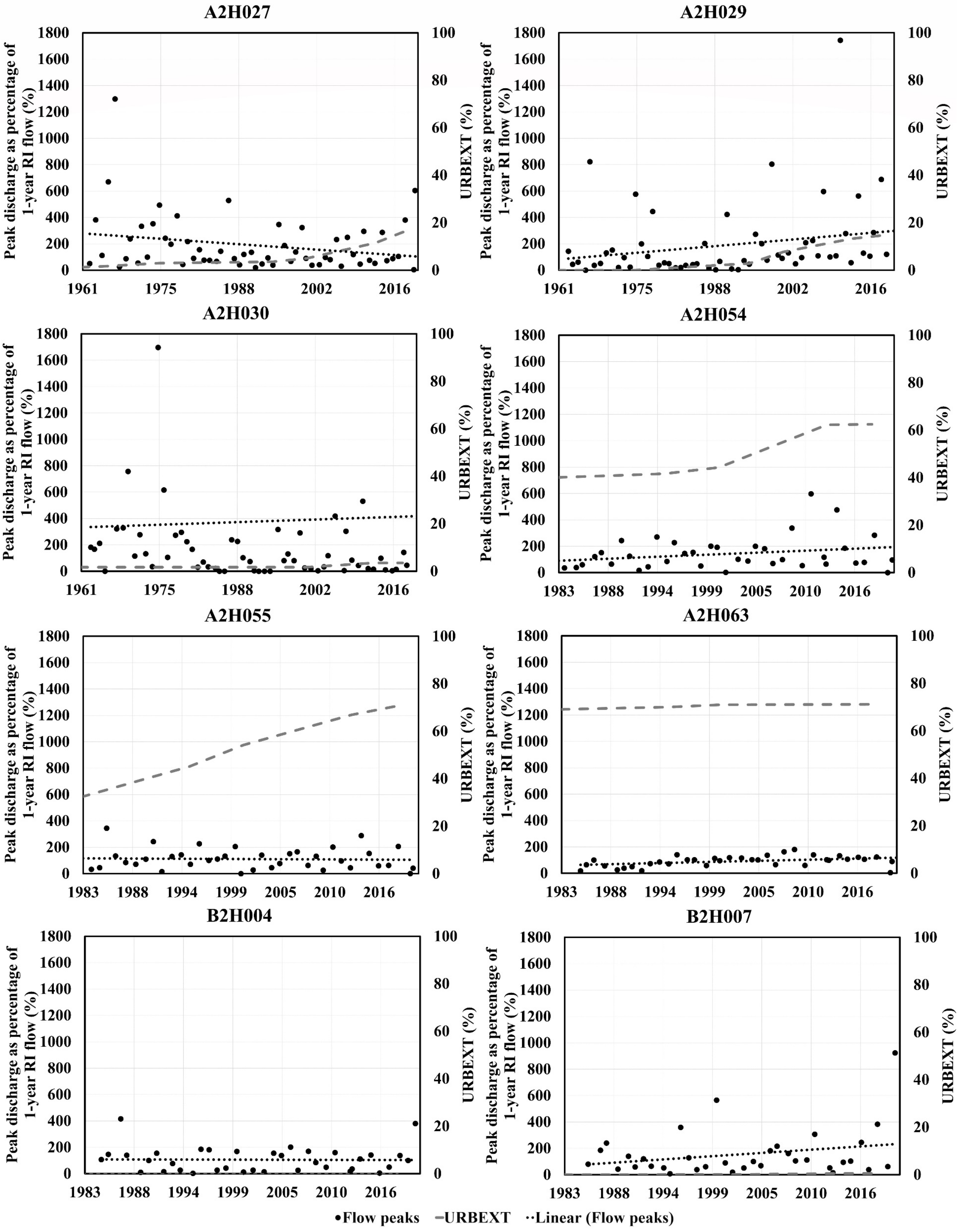

Figure 7. Trends in observed peak flow rates, expressed as a percentage of the 1-year RI flood peak, and URBEXT over time
]