Increase in surface runoff in the central mountains of Mexico: lessons from the past and predictive scenario for the next century

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RC C2904

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General comments:

The paper addresses a very relevant topic on the increase of surface runoff in central Mexico. It tries to link a significant increase in surface runoff to land use changes in the seventies. The conclusions are based on statistical trend analyzes between 1956 and 2001. However, concerning the analysis two points should be emphasized and/or improved:

1. The authors show that the results are not biased by the possible trend between manual measurements of the past and current automatic measurements, by comparing both techniques for water level observations for 2008. They conclude that they can be compared, since Q-manual equals Q-automatic. However, they completely neglect the possible trend over time in the Q-h relation of the flume. Especially, because the authors mention that the calibration of the flume ended in 1955. Some critical notes would be necessary, because this is the basis of their analysis.

It is true that the Q-h relationship can change noticeably if the flume section undergoes erosion or sedimentation. However, none of these phenomena was observed at the hydrological station during our stay in Mexico, from December 2005 to December 2009. Furthermore the archives at our disposal do not report any problems of that nature. To take this remark into account a comment was added in the text.

2. The authors show that surface runoff increases in the investigated period and suggest that this is caused by land use changes in the seventies. However, I think that this hypothesis can be better tested if the time series is split into two parts: the period before 1970 and the period after. Then apply on both periods the statistical tests and see if there is a significant difference between the two periods or not.

This was done. See changes in section 4.3 and Table 2.

Overall, the paper is of good quality, well written, and shows a straightforward way of assessing rainfall-runoff trends, although, (I think) one should be cautious by extrapolating 50 years of data into ‘climate change disasters’.

Our first objective was to identify trends in precipitation and its potential effect on surface runoff. The terminology “climatic change” was applied too many times in the manuscript. This has been modified: P

6876 Lines 24-25 with the sentence: "*Hence, it can be considered that water input in the watershed did not change significantly during the study period*." Instead of: "*Hence, it can be considered that climatic change, in terms of water input in the watershed were insignificant during the study period*". In section 3.1 and in the conclusion: "climate variation" instead of "climate change"

After consideration of the above mentioned comments and the specific comments below, I think this paper is suitable for publication.

Specific comments:

P = page; L = line; S = section; Eq = equation; F = figure; T = table

1. P6866 L19: It is stated that Mexico faces a decrease of about 70. done.

2. P6867 L24: Skip "in thirty years". This is redundant since the specific period is already mentioned. See response to RC C3007 specific comment P 6867 Lines 24.

3. P6867 L25-27: I do not see how the meteorological conditions 'imply' that 77. We are speaking about the strong seasonal pattern. The text has been slightly modified: "The seasonality implies that 77"

4. P6868 L15-18: This sentence is confusing, because first the land cover of 2000

is described and then the land cover of 1975 combined with 'decreases' and 'increases'. Please rewrite or add a table. To clarify the description, we decided to focus on land use changes (last paragraph). Land cover is briefly summarized by indicating that the Cointzio basin has agro-sylvo-pastoral characteristics.

5. P6869 L9-11: Maybe add correlation coefficient between the two rainfall series.

It is quite difficult to see the 'similarity' in Figure 2. It is true that the similarity can not be seen in Fig. 2. The similarity is much more evident when examining the annual rain series presented in Fig. 6. If we consider the largest continuous time series (1956-1973), the determination coefficient is $r^2 \approx 0.8$.

6. P6869 L22: Please comment on the possible difficulties caused by the ended calibration of the flume (see also 'general comments', point 1). What about changes in the rating curve due to sedimentation, vegetation growth, etc. Done, see reply to general comments.

7. P6870 L6: LT means 'Local Time'? Yes. It is a textual convention (see HESS recommendations).

8. P6870 L11-17: This does not say a thing about the errors in the discharge, this only say something about the errors in the water level (see point 1 in 'general comments'). Ok, see reply to general comments.

9. P6872 L7: What is 'Dirac precipitation'. A Dirac peak is a mathematical function that has the zero value everywhere expcept at x=0, where its value equals 1. Conceptually, a Dirac precipitation refers to a tall narrow peak.

10. P6872: This paragraph is really unclear to me. What is Qinst? What is ctte?

What does Figure 5 tell me? Qinst refers to the instantaneous water discharge (in $m3.s^{-1}$). It is stated bellow eq. 3b. ctte refers to a constant value. The terminology can be changed if necessary. Figure 5 explains the link between instantaneous and mean daily water discharge. If the water discharge remains constant during a whole day (neither rain nor flood) then the mean daily water discharge equals any instantaneous measurements. Identifying these events in the historical database is the way to perform a correct hydrograph separation.

11. P6872 L26: Rainfall has the dimension volume per time. Please add e.g. Pd<5mm/day. Done

12. P6873 Eq5: Where is this equation coming from, although I am willing to believe it. It is Kendall (1975) who described a normal-approximation test to calculate the probability associated with the MK statistic. The reference has been added.

13. P6874 L15: Replace Sect. 4.2 into Sect. 4.3. Done

14. S5: Please elaborate on the possible effect of climate change on the partitioning of base flow and surface flow. Several studies have recently documented the effects of climate change on streamflow. For instance, Juckem et al. (2008) reported that an increase in annual precipitation was found to coincide with an increase in annual baseflow. Mileham et al. (2009) correlated an increase in rainfall intensity with an increase in runoff in a tropical environment. In our case, it would be hazardous to predicate the impacts of a change in rainfall pattern; however we believe that if the basin underwent an increase in precipitation intensity, a subsequent increase in runoff extremes would be likely to occur. A potential decrease in precipitation and increase in aridity are also discussed in Section 5.

15. S6: The conclusions are not very well connected to the results of the paper. They more describe some general statements from the introduction. This can be improved.

It has been reworked to be more concise and to fit more with the results of the paper.

16. P6878 L12: Where is the 70% coming from? In your results I only see 30-50% increase. The increase from about 30% to about 50% corresponds to an increase of 70% of the value (30*1.7=51). The result is also reported in table 2.

17. T1: is gauging station 'Cointzio' part of the watershed or not? This is conflicting with the information from the text (p6868 S3.1) and Figure 1. This station does lie within the watershed of Cointzio. It borders the reservoir of Cointzio. In Fig. 1. the white circle is deliberately slightly outside the watershed in order not to hide the reservoir.

18. T2: Please add units to 'S'. Done.

19. F1: Please add abbreviations of rain stations in caption. Please clarify the difference between grey and white circles. I though it was inside or outside the catchment, but why is Acuitzio del Canje then outside of the catchment? Done.

20. F2: Please change unit of P into mm/month. Done (data in mm/days).

21. F6: Please be clear on units of P (mm/year; mm/18 days; mm/day). To our point of view, it is better to keep the y-axis units as they are: for each year (x-axis) we represent 1) the total annual precipitation (mm/y) 2) the sum of the 5% maximum values (mm/18days) and 3) the maximum value (mm/day). This was further detailed in the beginning of section 4.1

22. F7: Why is only the effect of τ on the partitioning only shown for ABF? Maybe for completeness add this 'uncertainty', although it can be calculated from 100%

minus the already drawn area. Done.

RC C3007

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General comments.

The topic addressed by the paper, the increase of annual surface runoff for the Cointzio basin and its relationship with land uses and soil changes, is of great importance in order to understand the alterations that the hydrologic cycle is already experiencing and how to face these changes. The paper is well organized and the methods used in the analysis are well described and valid to the purpose. For this reasons in my opinion

the paper is suitable for publication. However there are some points and choices of the authors that need a clarification in order to improve the quality of the discussion.

Initially, the paper described 5 different meteorological stations. The results are shown and discussed only for the two station. Sometimes it is not clear if the investigation has been performed for all the station and why the authors have taken into account also other stations without commenting any results about them. Also the choice of the two reference stations is not completely clear. Actually, a first statistical analysis (annual rain, 95th percentiles, 75th percentile and maximum value) was conducted for the four stations (Morelia was excluded because the 1985-2001 period was not in our possession, as indicated in Table 1). The report of this preliminary analysis reveals a similar pattern for all stations. It is available if necessary (Vinson,2008).

Trends detection method was only applied on Cointzio and Santiago Undameo after a rigorous post processing of every instrumental and digital mistake. This time consuming post processing was not achieved on the other stations (over 30.000 more data).

In the present version, the text fits better with the content. We clearly state that the statistical analysis is performed at Cointzio and Santiago Undameo and it is explained that the numerical simulation was extended to three other stations to provide a regional view of potential climate change.

In my opinion the discussion needs a deeper explanation with regard to the land uses and soil changes. The authors state that the alterations in the hydrologic cycle (in terms of ratio between surface runoff and baseflow) are not caused by precipitation patterns but human impacts. While the first part of the assertion is well documented, the second part needs an improvement. Done. We added a discussion paragraph at the end of section 4.2.

Specific comment.

P 6867 Line1. To this purpose instead of to that purpose. Done.

P 6867 Line 17. downstream (without s). Done.

P 6867 Lines 24. Mean annual rainfall is described for the period 1975-2005. this is not the same period of the investigation (1956-2001). Can the authors consider the idea of keeping the same temporal reference? The work of Carlón Allende and Mendoza (2007) covers the period 1975-2005. To consider the same temporal reference, we replace the sentence by: “Mean annual rainfall is 770 mm in Morelia, ranging from 400 to 1,100 mm/y (Carlón Allende and Mendoza, 2007 and Fig. 6 in this paper).”

P 6869 Line 3. The station of Jesus del Monte has been considered in the analysis in order to examine potential orographic effect. Nevertheless, this topic does not seem to be discussed in the following. This section has been suppressed.

P 6869 Line 10. What do you mean with “the only consistent time series within the watershed”? At the exception of the meteorological station of Morelia, the stations are located in very small villages (mostly under 1000 inhabitants). The long-term time series revealed evident errors, including absence of measurements and negative values. Thus, it resulted very difficult to make a rigorous inter comparison (see the response to general comments). The meteorological station of Cointzio and Santiago Undameo were selected because their datasets are much more complete and they both lie within the watershed. A full checking was done on these two stations.

P 6870 Lines 19-20. ?

P 6872 Eq. 3: what is ctte? It is a constant value. Terminology can be modified if necessary.

P 6875 Line1. Could you add an explanation for the “5% days undergoing maximum rainfall events”. It seems very confusing to me. Maybe the description of its calculation could be helpful. Done.

P 6875 Lines 7-11. precipitation without s. Done.

P 6875 Lines 18-19. Why do not use the same order of magnitude used in Fig.7? Done

P 6875 Line 29. What do want to show when you write “the latest values remain in a tipical range of values: : :”?

“typical range of values encountered in North American watersheds (Neff et al., 2005).” We tried to enlarge the scope of the paper by checking whether our basin could be (or not) compared to other ones in comparable environments.

P 6876 Lines 2-8. The statement “surface runoff versus baseflow is not affected by precipitation patterns” needs some more explanations than the comparison with total water discharge. Could you elaborate this concept?

The corresponding section has been rewritten.

P 6876 Lines 18-22. Why the trend analysis has not been applied to all the precipitation indicator considered in the paper? As indicated in the response to the general comments, it was (quite easy) to visualise the rain pattern on all stations but the rigorous application of the trend analysis would require a complete examination of the digital errors. This was done only for Cointzio and Santiago Undameo.

Does the results of the different stations considered agree also for trend or not? Visually yes (report of Vinson, 2008) but the post-processing is not yet sufficient to calculate it for all stations.

P 6876 Lines 24-25. In my opinion speaking about possible detection of climate change signal in less than 50 years of precipitation data may be misleading. We agree and moderate our purpose in the current version. Please see RCC2904 General comments number 2.

P 6877 Line 1. Could you elaborate this statement? We believe that the increase in annual surface runoff is a global indicator of a modification in the water cycle; increase in flood intensity reflects the same response, but at a shorter timescale. Somehow, successive flood events over a year contribute to the global budget represented by the annual surface runoff. In the text, we modified “the %ASR increment (see Sect. 4.2) has **undoubtedly** contributed to the increase in extreme floods intensity depicted in Fig. 8c” by “the %ASR increment (see Sect. 4.2) has **very probably** contributed to the increase in extreme floods intensity depicted in Fig. 8c”. See also the response to the specific comment P6876 L2-8.

P 6877 Line 3. Another important aspect of the Qd max time series is its variability. You are right. This has been indicated in the text however our current level of analysis is not sufficient to explain why such behaviour is observed.

P 6877 Line 15. Centered. Done.

P 6878 Lines 7-8. The connection between the aridity index and the vegetation may require an improved discussion with regard also to agriculture practices, since the authors mention the avocados cultivation in the conclusion.

It is clear there is a growing demand of water for irrigating new established avocado orchards. This phenomenon is quite recent. Since January 2005, the USA have allowed the importation of Mexican avocados in their territory, which explains the recent boom in avocado production.

We believe that introducing a discussion on the connection between the aridity index and this agricultural practice would be complicate since management of avocado orchards in Michoacán is very diverse and recent (after the 1956-2001 period considered herein): there are some under very intensive management and others under very low-input management. We decided to drop this part from the conclusion and only comment the increasing urbanization.

Fig 2, 6, 7. Why do not represent the investigation time interval (1956-2001) in all the figures? As rain series exhibit missing data between 1999 and 2002, we decided to extend the representation of rain series until years 2003 and 2004.

References

Juckem, P. F., Hunt, R.J., Anderson, M. P and Robertson, D.M.: Effects of climate and land management change on streamflow in the driftless area of Wisconsin, J. Hydrol. 355, 123-130, 2008.

Mileham, L., Taylor, R. G., Todd, M., Tindimugaya, C. and Thompson, J.: The impact of climate change on groundwater recharge and runoff in a humid, equatorial catchment: sensitivity of projections to rainfall intensity, Hydrol. Sci. J. 54(4), 727–738, 2009.

Increase in surface runoff in the central mountains of Mexico: lessons from the past and predictive scenario for the next century

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Abstract

The hydrological response of a medium scale mountainous watershed (Mexico) is analysed over half a century. The hydrograph separation highlights an increasing surface runoff contribution since the early 1970's. This increase is attributed to land use changes while the meteorological forcing (rains) remains statistically stable over the same period. As a consequence, the intensity of annual extreme floods has tripled up over the period of survey, increasing flood risks in the region. The paper ends with a climatic projection over the 21st century. The decrease of precipitation and the increase of temperature should accentuate the trend engaged since the 1970's by reducing groundwater resources and increasing surface-runoff and associated risks.

1 Introduction

Over the last decades, Mexico has suffered from degradation of its surface water bodies which is imposing undeniable economical costs (Alcocer and Escobar, 1993). Nowadays Mexican water resources are commonly considered poor in quality and sparse in quantity (Vidal et al., 1985), a situation exemplified in Michoacán state. A recent study led by various local institutions (Ortiz Ávila, 2009) stressed that water contamination, solid residuals management and drinkable water are the main environmental priorities of the Michoacán settlements. In terms of quantity, the state has been facing a decrease of about 70% in its surface water resources over the last century (Vargas Uribe, reported by Morales, 2007). This evolution has been correlated with the high emigration rate in Michoacán (63% of total population), which contributed to the main soils and water resources use changes (López-Granados et al., 2006).

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The present paper aims at investigating water cycle changes from 1956 to 2001 in the Cointzio watershed (Michoacán state), a medium scale mountainous basin representative of the Central Transvolcanic Mexican Belt.

Our approach considers the impact of climate and human-induced environmental changes on water runoff in the watershed. To this purpose a hydro-meteorological database running from 1956 to 2001 was employed following the latter methodology:

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Available rain and water discharge series were gathered (and digitalized when necessary) and criticized (missing data and quality control) to provide reliable series. A particular effort was paid to estimate the accuracy of the historical water discharge data in relation with sampling frequency (Section 3). In a second time, hydrograph separation technique was applied to water discharge records to define the baseflow/surface-runoff ratio and its evolution over decades. The generated time series were tested with various statistical methods in order to provide accurate hydro-climatic trends and objective interpretations (Section 4). Finally, a climate model was applied to five meteorological stations to go towards scenarios of evolution for the coming century (Section 5).

2 Study area

The Cointzio watershed is located in the hydrological region of Lerma-Chapala, within the Central Transvolcanic Mexican Belt, in the state of Michoacán (Fig. 1). It drains a surface of about 650 km^2, ended by the Cointzio reservoir (4km^2, 65Mm^3). The latter provides about

22% of drinking water distributed in Morelia, capital of the state situated 13 km downstream. Water demand of the city has been growing over the last decades because of increasing individual water consumption coupled with a severe urban growth: Morelia experienced an augmentation of its population of 600% during the period 1975–2000 (López-Granados et al., 2001) and counts now over 700,000 inhabitants (INEGI, 2006).

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The climate of the region is temperate sub-humid, characterized by a rainy season from May to October and a dry season the rest of the year (Rubio, 1998). Mean annual rainfall is 770 mm in Morelia, ranging from 400 to 1,100 mm/y (Carlón Allende and Mendoza, 2007 and Fig. 6 in this paper). The seasonality implies that 77% of the drainage system consists of temporary watercourses active only during rainy season (Susperregui et al., 2009). The main river of the watershed is the Rio Grande de Morelia whose source lies about 25 km upstream of the Cointzio reservoir.

Supprimé : in thirty years (period 1975-2005)

Supprimé : These meteorological conditions

Supprimé : y

The Cointzio basin is underlain by igneous rocks (both lavas and pyroclasts) originating from Quaternary volcanic activity. Soils and landforms developed in most of the watershed have been derived from these volcanic materials (Carlón Allende et al., 2009). Such soils present susceptibility to erosion (Poulenard et al., 2001). They are mainly Andisol in the headwater areas, Acrisol in the hillsides and Luvisol in the plain (INEGI, 2002).

According to López-Granados et al. (2001), the basin can be classified as agro-sylvo-pastoral. Using GIS to represent data of land cover and land use, Mendoza and López-Granados (2007) were able to identify the major changes in the Cointzio watershed over the period 1975-2000. The main changes in surface were increase of scrublands (9.6%), recovery of forests (6.2%), deforestation (5.5%), degradation of forests (4.1%) and urbanization (1.3%). The major part of these changes occurred during the 1986-1996 period.

Supprimé : In 2000, major land cover and land uses were scrublands (23.7%), forests (19.6%), rain fed agricultural lands (18.5%), irrigated cultures (15.5%) and grassland (6.3%) (López-Granados et al., 2001). According to these uses, the

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3 Data and methods

3.1 The hydrometeorological historical database and its limitation

Rain series were extracted from the Mexico Climatological Station Network Data (CLICOM). This database reports all of the meteorological stations surveyed by the Servicio Nacional de Meteorología de México. A pre-analysis was realized by Vinson (2008). Among the eighty meteorological stations in the state of Michoacán, five are located within (or close to) the Cointzio watershed, namely the stations of Acuitzio del Canje (2020 m), Santiago Undameo (2020 m), Cointzio (2000 m), Jesus del Monte (2180 m) and Morelia (1920 m) (Ac, SU, C, JdM and M in Fig. 1). The quality of time series has been examined and is summarized in Table 1. All years presenting missing values have been rejected as well as years presenting evident data capture errors. Following this pre-processing of data, we decided to focus the analysis to the stations of Contzio and Santiago Undameo. These latter are the only consistent time series within the watershed (see Vinson, 2008 for more details). The three other stations have been considered during the modelling exercise presented in section 5 to offer a regional projection of potential climate variation.

The gauging station of Santiago Undameo (SU in Fig. 1) constitutes the ultimate control upstream the reservoir of Cointzio: it drains 628 km². Its monitoring has been launched in 1939, year of construction of the reservoir of Cointzio. A Parshall flume was built, allowing a control of the hydraulic section, and a stage-discharge rating curve was established by the Comisión Nacional del Agua (CNA). The monitoring ended in 2001.

The 1939-1985 period was previously digitalized by the CNA (BANDAS database), while the 1985-2001 period was digitalized as part of our investigations. Although overall database covers the 1939-2001 period, we decided to focus on 1956-2001 series since the first flume was destroyed during a major event in 1953. The re-building and its calibration ended during 1955. The CNA archives at our disposal do not report any change of the flume section (by sedimentation, erosion or vegetation growth) ; therefore the stage-discharge rating curve was assumed to remain constant between 1956 and 2001. The water discharge database is presented in Fig. 2b. Some minor missing period events were identified in 1975, from the 17th to the 20th of October because of a flood event. Four days of missing data are reported in 1992 and one more in 1997. With a period of missing data of several weeks in September and October, the year 1998 could not be considered in our analysis.

Supprimé : five were considered of interest. Three

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Supprimé : of Jesus del Monte (2180 m) and Morelia (1920 m) that are close to the watershed delimitation were also taken into account (JdM and M in Fig. 1). The first one is of interest to examine potential orographic effects and the second one because of its reliability and local importance.

Supprimé : The quality of time series has been examined and is summarized in Table 1. All years presenting missing values have been rejected as well as years presenting evident data capture errors. The station of Acuitzio del Canje (Ac) is the only one showing significant gaps during the whole period. For a reason of clarity, results presented in section 4.1 focus on the precipitation series of Santiago Undameo and Cointzio (Fig. 2a). These latter are the only consistent time series within the watershed and the five series exhibit a very similar pattern (for details see Vinson, 2008).¶

From the beginning of 2008, the station has been updated to estimate instantaneous water and sediment discharges. Water level was surveyed at a five minute time-step with a Thalimede OTT water-level gauge. Water discharge time-series were determined through the stage-discharge rating curve. Our aim was to take advantage of this high-frequency monitoring to evaluate the accuracy of daily discharge values provided by historical time-series, and thus to carry out a long-term analysis without misinterpretation.

Daily discharge data was historically deduced by the CNA from a minimum of three manual measures (respectively at 6:00 LT, 12:00 LT and 18:00 LT). Taking into account the occurrence of flash flood events in the basin, the historical sampling frequency is questionable. To validate the methodology, a sub-sampling of the real-time-series acquired in 2008 was generated. Resulting mean daily discharges were then compared to reference mean daily discharges derived from the high-frequency time-series (Fig. 3).

Reference discharge values and sub-sampled ones exhibit a strong linear relationship (Fig. 3a). Distribution of the relative error presented in Fig. 3b exhibits a Gaussian shape, centred on zero and characterized by a low standard deviation of about 7%. Such pattern demonstrates the reliability of the historical sampling. Loss of accuracy remains very limited if focusing on short-term dynamics as well as on seasonal water budgets calculation (maximum under-estimation of 2% of reference volume). The further processing of 1956-2001 historical time-series is thereby validated.

3.2 Hydrograph separation technique

We aimed to consider the effects that may have induced an alteration of physical characteristics of the watershed, such as land use change, on the hydrological cycle. We subsequently focused on the characterization of annual baseflow/surface-runoff ratio and its evolution over the past fifty years at Santiago Undameo.

Stream flow hydrographs were separated into Annual BaseFlow (ABF) and Annual Surface-Runoff (ASR) components. The baseflow component has traditionally been associated with groundwater discharging into the stream and the surface-runoff component with precipitation that enters the stream as overland runoff (Sloto and Crouse, 1996; Chapman, 1999). The aim of this paper is not to work on the physically based concept of hydrograph separation; the technique was applied as a tool for detecting trends in water discharge behaviour. The reader can refer to Chapman (1999) and Nathan and McMahon (1990) to get an overview of techniques commonly used by engineers to quantify the baseflow contribution of a watershed.

A variant of a hydrograph separation method was programmed using Matlab© software. The algorithm used is based on the concept developed by Pettyjohn and Henning (1979) and is commonly referred as the "smoothed minima technique" in the literature (Brodie and Hostetler, 2005). This method can be described as connecting with straight lines the minima of fixed intervals τ of the hydrograph. The sequence of these connecting lines defines the baseflow hydrograph. In case of missing data, a mean value calculated from nearest neighbours was used. Calculated Base Flow delimitation (CBF) was thus obtained as follows:

$$CBF(d,\tau) = \min_{d \in \left[d - \frac{\tau}{2}, d + \frac{\tau}{2} \right]} \overline{Q_d}(d) \qquad (1)$$

With *d*: day of the year

τ : interval parameter (in days and necessarily pair)

$\overline{Q_d}$: mean daily water discharge (in $m^3.s^{-1}$)

Annual Base Flow (ABF) and Annual Surface Runoff (ASR) were then estimated by:

$$\begin{aligned} ABF &= \sum_{d=1}^{365} CBF(d) \\ ASF &= \sum_{d=1}^{365} \overline{Q_d} - ABF \end{aligned} \qquad \text{(2a) and (2b)}$$

In our analysis, we tested a broad range of τ values from four to fourteen days. From a general point of view, it is clear that CBF (and thus ABF) will decrease for increasing τ.

Such behaviour is illustrated in Fig. 4a and 4b for two contrasted hydrological years that occurred in 1993 and 1994. Year 1993 was hydrologically active with many significant flooding periods lasting several days. CBF function decreases significantly for increasing τ values from six to fourteen days. Conversely, in the case of year 1994 (Fig. 4b), periods with high water discharge were scarce and never exceeded a couple of days. As expected, CBF function does not vary significantly with τ.

To determine whether a large τ value (fourteen days or more) or a low one (six days or less) is more appropriate, it is necessary to introduce a physically based analysis. Let's imagine a theoretical Dirac precipitation uniformly distributed on the watershed. The water surface runoff increases rapidly at the outlet before its recession. The baseflow reacts slowly and its level increases slightly (Fig. 5a, first day). Considering an independent event occurring the following day, the watershed reacts similarly (Fig. 5a, second day). Since historical database only provides some mean daily discharges (circle, cross, square and triangle in Fig. 5a), the estimation of baseflow level requires a minimal period of one day without significant precipitation. In that case:

$$Q_{inst} \approx ctte$$
$$\overline{Q_d} = \frac{1}{N}\sum_{i=1}^{N} ctte \approx Q_{inst} \qquad \text{(3a) and (3b)}$$

With Q_{inst}: instantaneous water discharge (in $m^3.s^{-1}$),

N: number of samples per day.

The real situation occurring in September 1993 illustrates perfectly the concept. It is presented in Fig. 5b as part of the series presented in Fig. 4a. Significant rainfalls occurred at the meteorological stations of Cointzio and Santiago Undameo until 17th of September (black and grey bars in Fig. 5b) and were followed by a four days dry period. The hydrological response follows this meteorological forcing with a delay of one to two days. In that case, it is clear that baseflow level is reached during the period extending from 19th to 23rd of September.

By examining the precipitation database at our disposal, it appeared that the longest time-interval required to reach a day without significant rainfall event (P_d < 5mm/day) is approximately of five days. The upper discussion highlights that a τ interval of six days is best suitable in Fig. 4a, while coinciding with both rainfall pattern and hydrograph visual examination.

However, to prevent any misinterpretation, the algorithm was also run with both a shorter (four days) and a longer (ten days) τ value.

3.3 Trends detection from statistical methods

Statistical significance of gradual trends was detected by applying the rank-based Mann-Kendall test (Mann, 1945; Kendall, 1975) and magnitude of trends was estimated from Sen's method (Sen, 1968).

The Mann Kendall test is a non parametric statistic that has been widely used to assess the significance of monotonic trends in hydro-meteorological time-series (e.g. Lettenmaier et al., 1994; Marengo and Tomasella, 1998; Jiang et al., 2007; Zhang et al., 2008; among others). The test assumes that there is no serial correlation in the data. Such assumption is reasonable for the rainfall and runoff records presented in this paper.

The null hypothesis H_0 is that the sample of data is independent and identically distributed. The alternative hypothesis H_1 is that a monotonic trend exists in the time-series. Mann-Kendall method was applied by considering the statistic S as:

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} sign\left(x_i - x_j\right) \tag{4}$$

Where x_i and x_j are the sequential data values, n is the length of the time-series and $sign\ (x_i - x_j)$ is -1 for $(x_i - x_j) < 0$; 0 for $(x_i - x_j) = 0$ and 1 for $(x_i - x_j) > 0$.

In the absence of ties, the variance Var [S] of the statistic S was obtained as (Kendall, 1975):

$$Var[S] = \frac{n(n-1)(2n+5)}{18} \tag{5}$$

The standardized statistical test Z was computed by:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{Var[S]}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{\sqrt{Var[S]}} & if\ S < 0 \end{cases} \tag{6}$$

Positive value of Z indicates an increasing trend while negative Z indicates a decreasing trend. When testing monotonic trends at an α significance level, H_0 was rejected for absolute value of Z greater than $Z_{(1-\alpha/2)}$, where $Z_{(1-\alpha/2)}$ is the value of the standard normal distribution with a probability of α/2. In this work, significance level of α = 0.01 (99% confidence) was applied and null hypothesis was rejected if $|Z| > Z_{0.995} = 2.575$.

Sen’s method is a non-parametric statistic used in determining the presence and magnitude of a trend slope. This test proceeds by calculating the slope as a change in measurement per change in time. Trend slopes magnitudes were obtained following the method of Hirsch et al. (1982):

$$\beta = \mathrm{Median}\left[\frac{(x_j - x_i)}{(j - i)}\right] \quad \forall\, i < j \tag{7}$$

Where x_j and x_i are data points measured at times j and i, respectively.

Mann-Kendall test and Sen’s method were applied on precipitation, surface runoff and water discharge time series. Results are presented in Sect. 4.3.

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4 Results

4.1 Pattern of the precipitation time-series from 1956 to 2001

Our analysis is based on the examination of three statistical indicators, namely the total annual precipitation (in mm/y), the maximum daily precipitation (in mm/day, from year to year) and the sum of the 5% days undergoing maximum rainfall events (in mm/18days, from year to year). The latter basically corresponds to a virtual “top eighteen days” each year (sum of the rain data exceeding 95th percentile).

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Annual precipitation series fluctuates significantly in the range 650-1200 mm/y; however there is no evidence of tendencies over the last fifty years. Cumulated top 5% precipitations correspond to about 400-500 mm of total annual precipitation, which means that 50% of annual volumes are precipitated in 5% of the time. Such ratio highlights the heavy rainfall pattern characterizing the region during wet season.

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Maximal precipitation exhibits the same pattern than annual volumes and top 5% precipitations. Although maximum daily precipitation fluctuates from year to year, it basically remains stable in the range 35-60 mm and roughly corresponds to 5% of annual precipitation.

4.2 Pattern of the Annual Surface Runoff (ASR) from 1956 to 2001

Annual Surface Runoff (ASR) and Annual Base Flow (ABF) were calculated from 1956 to 2001 by applying equations (1) and (2) with τ intervals of four, six and ten days.

As shown in Fig. 7a, ASR volume series remains globally constant over 1956-2001 period, in the range [1-4] $10^7 m^3.y^{-1}$. ABF volume is always predominant. It fluctuates in the range [3-8] $10^7 m^3.y^{-1}$. Unlike ASR, ABF volume exhibits clear inter-decades trends. It shows a continuous decrease from the beginning of the seventies to the end of the eighties that could

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be correlated to the dry cycle discussed by Carlón Allende and Mendoza (2007) and Metcalfe et al. (2007).

Another interesting pattern is depicted by %ASR and %ABF series presented in Fig. 7b. Unlike ASR volume, %ASR has been increasing substantially since the seventies. It remains almost constant (nearly 25%) until 1970 and then increases to reach about 40% by the end of the eighties to 2001. This significant water balance change does not depend on the hydrograph separation processing as it is observed for every τ value (grey shading in Fig. 7b). The latest values remain in a typical range of values encountered in North American watersheds (Neff et al., 2005).

Looking simultaneously at volumes and percentages it appears that surface runoff versus baseflow is not affected by the precipitation pattern. This is well illustrated by couples of years 1956-1957 and 1993-1994. Between years 1956 and 1957, the total water discharge tripled up, from 3.9 10^{7}m^{3} to 11.3 10^{7}m^{3} (Fig. 7a) without modifying the partition between runoff and baseflow. As shown in Fig.7b, %ASR (or %ABF) remained remarkably stable with a value of 28.5% for the dry year (1956) and of 33% for the wet year 1957. A similar pattern is observed four decades latter for years 1993 and 1994. The total water discharge dropped from 15.3 10^{7}m^{3} to 4.4 10^{7}m^{3} while %ASR (or %ABF) did not change significantly (34% to 36%). Accordingly, a pronounced stability is observed in the partition of water for consecutive years whatever the annual amount of precipitation (rainy or dry year).

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The last two paragraphs point out that the ratio ASR/ABF and its evolution over years does not depend on meteorological forcing. Hence, it is the partition of rainfall input between surface-runoff and baseflow that has changed gradually in Cointzio. Between 1956 and 2001 the watershed has progressively been retaining less surface runoff and sustaining lower baseflow. In other words, water discharge series progressively showed narrower peaks over years. This change in hydrological response is very likely to be associated with physical alterations of the watershed, such as land use change and surface impermeabilization.

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During the 80's, the state of Michoacán experienced very strong migration fluxes which contributed to the abandonment of many rain-fed agricultural lands in steep relief (López-Granados et al., 2006). Inhabitants have been leaving countryside while Morelia (capital of Michoacán) has been growing tremendously, from 100,000 inhabitants in 1950 to 700,000 in 2005. As a consequence, water bodies now suffer higher turbidity level than in the past, as a response of deforestation and growing urbanization (Rendón López et al. 2007).

4.3 Evolution of water discharge extreme events

Supprimé : Consequently, %ASR evolution is hereafter considered as an indicator of the human-induced environmental changes in the watershed.¶

The goal of the present section is to quantify hydro meteorological trends and evaluate the relative impacts of both meteorological and human-induced changes on floods. The Mann Kendal test was applied to annual rain (Cointzio weather station), %ASR series and water discharge. Results are presented in Table 2 and trends are depicted in Fig. 8.

As specified in Sect. 4.1, rain series does not exhibit any trend (Fig. 8a, Table 2). Hence, it can be considered that water input in the watershed did not change significantly during the study period. Conversely, %ASR increases significantly between 1956 and 2001. Applying Sen’s method, the resulting trend slope has amplitude of 0.33, which corresponds to an increase of 69% in the contribution of surface-runoff to overall water discharge. Looking into more details, the series can be split into two distinct periods: from 1956 to 1970 values are slightly decreasing and from 1970 to 2001 there is a clear increase (Table 2). The human-induced changes at the origin of the %ASR increment (see Sect. 4.2) have very probably contributed to the increase in extreme floods intensity depicted in Fig. 8c. This graph displays the annual flood peak $\overline{Q_d}$ max. The series exhibits a clear increase with trend slope amplitude of 0.50. It corresponds to an increase rate of $\overline{Q_d}$ max as high as 232% over half a century. The series also shows a clear increment of the variability since 1975 but there is no doubt that flood risk has increased over years.

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5 Potential evolutions over next decades

In terms of water management, it is crucial to evaluate whether the engaged trend will continue or not.

Future climate change prediction was thus conducted for the five weather stations at the vicinity of the watershed. Estimates of mean annual precipitation and temperature presented in Fig. 9a and 9b are deduced from a spline climatic model developed for a normalized period (years 1961 to 1990, nominated “contemporary climate”) and updated with weighted outputs from a Global Circulation Model (Canadian Centre for Climate Modelling and Analysis), emission scenario A2, for the decades centered in the years 2030, 2060 and 2090 (Crookston 2008, Saenz-Romero et al., 2009). Following Saenz-Romero et al. (2009), precipitation and

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temperature series are combined to provide an aridity index (ratio of the square root of annual degree days > 5°C to annual precipitation) that represents the potential for moisture stresses to develop in the vegetation (Fig. 9c).

Average estimations among the five weather stations for the contemporary climate and compared to the global change scenario, indicate an expected decrement in precipitation of 15.4, 19.1 and 27.7%, and an increment in mean annual temperature of 1.6, 2.5 and 4.4 °C, for the decades centred in the years 2030, 2060 and 2090, respectively.

In terms of extreme events, it would be inappropriate to associate the annual precipitation decreasing pattern with a decrement in flood intensity: flood dynamics is governed by instantaneous rainfall intensity rather than by annual budgets.

The combination of increment of temperature and decrement of precipitation evidently causes an increment of aridity, measurable through the annual aridity index (Fig. 9c, where smaller values mean a climate colder and moister and larger values indicate a climate warmer and dryer). Since the aridity index is closely related to the type of vegetation (Rehfeldt 2006, Rehfeldt et al. 2006), it is reasonable to expect that climate change will cause a decrement of the vegetation coverage, and consequently, an increment of runoff contribution, as previously reported by Ranzi et al. (2002) and García-Ruiz et al. (2008).

6 Conclusion and perspectives

Over half a century, significant changes have occurred in the water balance of Cointzio, a medium scale watershed representative of the mountainous highlands of Central Mexico. Surface-runoff has increased of about 70% and has consequently led to a severe increase in extreme flood events (magnitude has tripled up over 1956-2001). During the same period, precipitation exhibited no statistical trend in the region, attesting the absence of significant modification of the annual budget. The main annual surface runoff increase occurred from the 1970’s and is believed to be principally driven by human-induced changes.

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Supprimé : The state of Michoacán experienced very strong migration fluxes which contributed to the main soils and water resources use changes, as revealed by López-Granados et al. (2006) from remote sensing analysis. Within the watershed, inhabitants have been leaving countryside while Morelia (capital of Michoacán) has been growing tremendously, from 100,000 inhabitants in 1950 to 700,000 in 2005. During the same period, precipitation exhibited no statistical trend in the region, attesting the absence of significant climatic change.¶

Predicting in which proportion water cycle disequilibrium engaged since the 1970’s will extend in the coming decades is a key issue. First, substantial climate modifications are likely to occur: numerical simulations presented herein indicate a drastic reduction in rain budget (-28% in 2090) and an increase of the aridity. These changes are expected to alter vegetation coverage and consequently, accentuate the surface-runoff contribution. Secondly, the growth in water consumption related to urbanization will reinforce the pressure on local water resources.

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Supprimé : Secondly, substantial climate changes are likely to occur: numerical simulations presented herein indicate a drastic reduction in rain budget (-28% in 2090) and an increase of the aridity. These changes are expected to alter vegetation coverage and consequently, accentuate the surface-runoff contribution.

At a global scale, Bates et al. (2008) recently reported that flash-floods and inundation should become more frequent worldwide. A regional analysis of precipitation intensity would be required to further improve our understanding of flood risk in the highlands of Central Mexico.

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Table 1. Quality of the rain database for the five stations considered. A value of one corresponds to a complete time-series.

		1955-60	1961-70	1971-80	1981-90	1991-00	2001-10	2030-90
within watershed	AC	no data	0,5	1,0	0,9	0,3	0,8	simulation
	SU	1,0	1,0	0,9	0,9	0,9	0,8	
	C	1,0	1,0	0,9	0,5	0,8	0,8	
outside watershed	JdM	1,0	1,0	1,0	1,0	0,9	0,9	
	M	1,0	1,0	1,0	0,5	not at our disposal		

Table 2. Results of Mann-Kendall and Sen's tests for runoff, extreme discharges and precipitation time-series.

	S [-]	Calculated Z score	Critical Z value at α=0.01	Significant trend at 99% confidence	Trend slope β	Increase between 1956 and 2001
%ASR 1956-2001	541	5.11	2.575	Increasing	0.33	+69%
%ASR 1956-1970	-53	-2.67	2.575	Decreasing	-0.33	
%ASR 1970-2001	254	4.10	2.575	Increasing	0.47	
Q_d max 1956-2001	463	4.37	2.575	Increasing	0.50	+232%
Precipitation 1956-2006	-4	-0.04	2.575	-	-	-

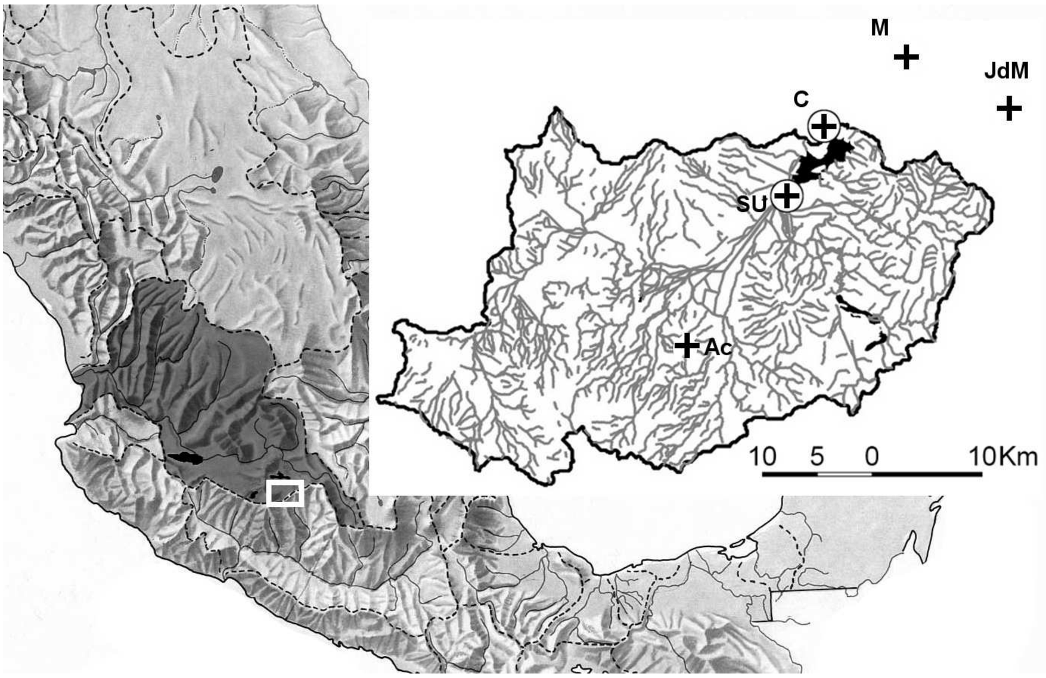

Figure 1. Localisation of the Cointzio watershed in the Transvolcanic Mexican Belt. The darkened area delimits the Lerma-Chapala Basin system. The white box delimits the study area. Crosses and circles are associated witth the meteorological stations of Santiago Undameo (SU), Cointzio (C), Acuitzio del Canje (Ac), Morelia (M) and San Jesus del Monte (JdM). Circles: analysis of the historical rain series; plus: numerical modelling of climate projections. The black area is the reservoir of Cointzio. The general map is source of the Univ. of Texas Libraries.

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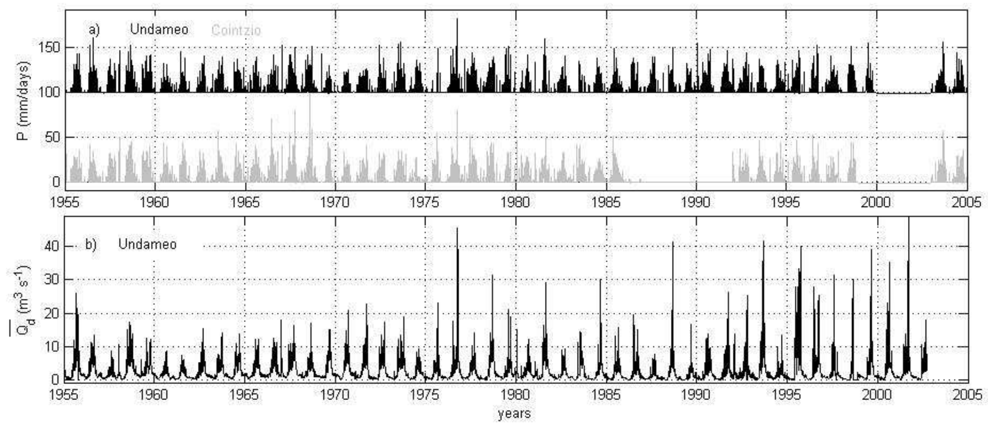


Figure 2. Hydrometeorological time-series. a) Rain series at Santiago Undameo (black line) and Cointzio (grey line). b) Mean daily discharge at Santiago Undameo.

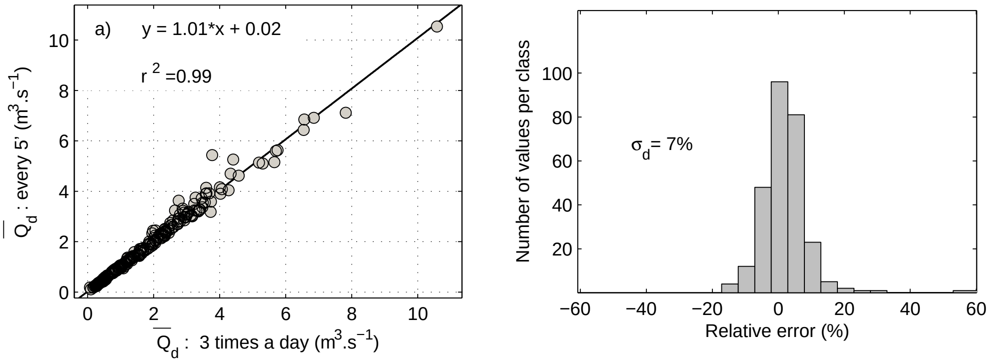


Figure 3. a) Inter-comparison of sub-sampled time-series (three times a day) and real-time water discharge measurements for the 2008 year. b) Distribution of the relative error for the time series presented in Fig.3a.

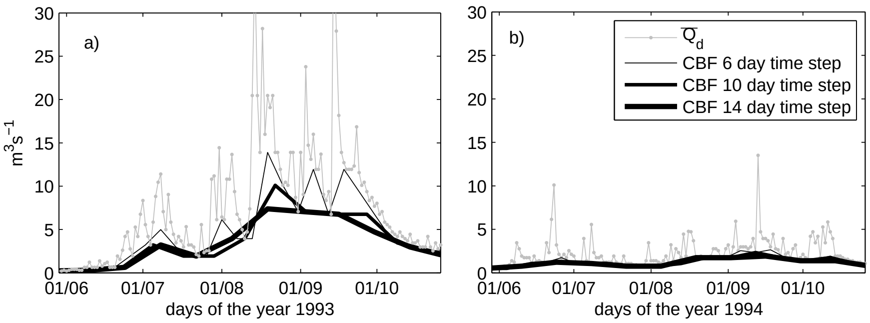


Figure 4. Application of the hydrological separation method (Eq. 1 and 2) for a) wet year 1993 and b) dry year 1994.

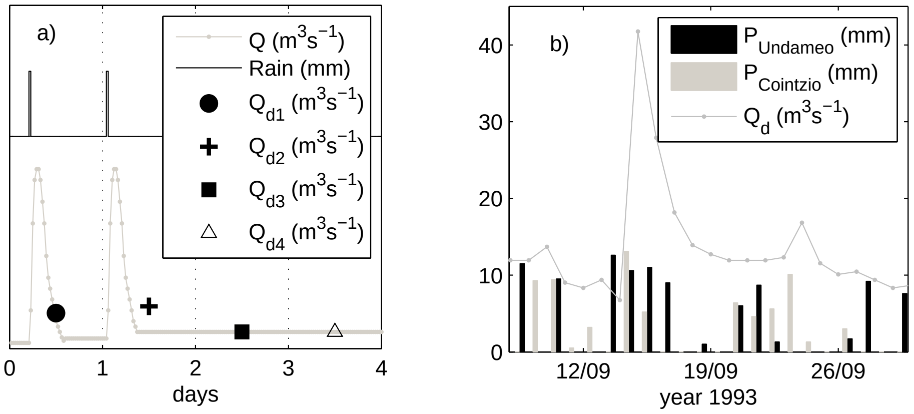


Figure 5. Hydrograph separation when considering mean daily discharge Q_d. a) Conceptual description of Eq.3. While working with Q_d instead of Q_{inst}, a reliable estimation of baseflow (versus surface-runoff) is only possible for days without rain. In our example, Q_{d3} and Q_{d4} are the only days satisfying Eq.3b. b) Illustration through a real case. In 1993, four days of significant rains occurred in the watershed from September 14th to 17th (black and grey bars). It induced a strong flood event with high mean daily water discharges from September 15th to 19th. After this period, mean daily water discharges (grey dotted line) remained almost constant from September 19th to 23rd, and thus equal to baseflow value.

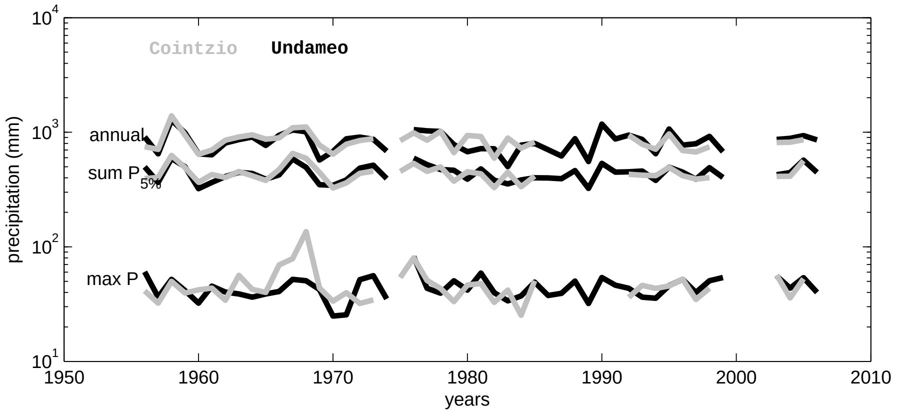


Figure 6. Main statistical indicators of precipitation time-series at Santiago Undameo and Cointzio.

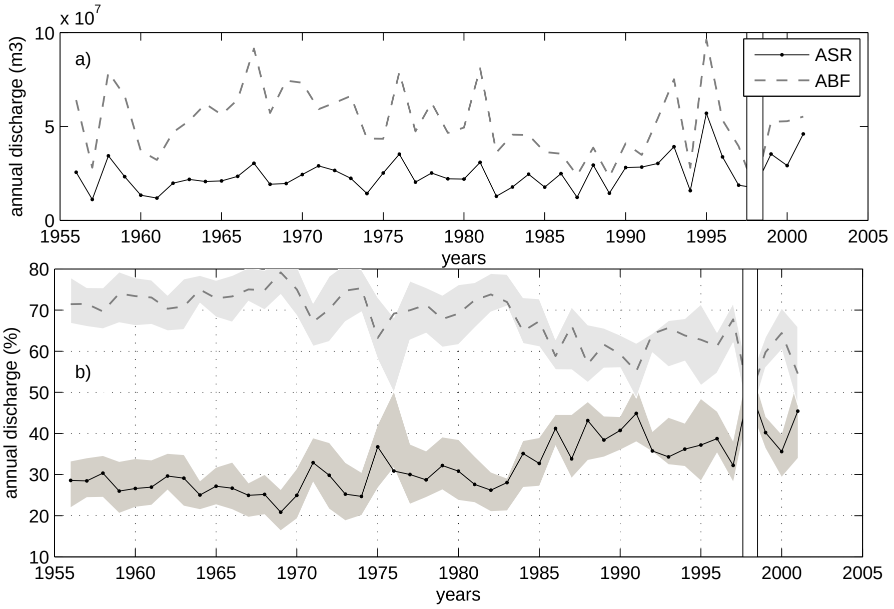
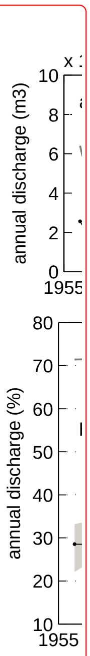


Figure 7. Evolution of Annual Surface Runoff (ASR) and Annual Base Flow (ABF) through 1956 to 2001: a) in volume, b) in percentage. The grey shading in Fig. 7b shows the range of predictions given by a four and a ten days τ value.



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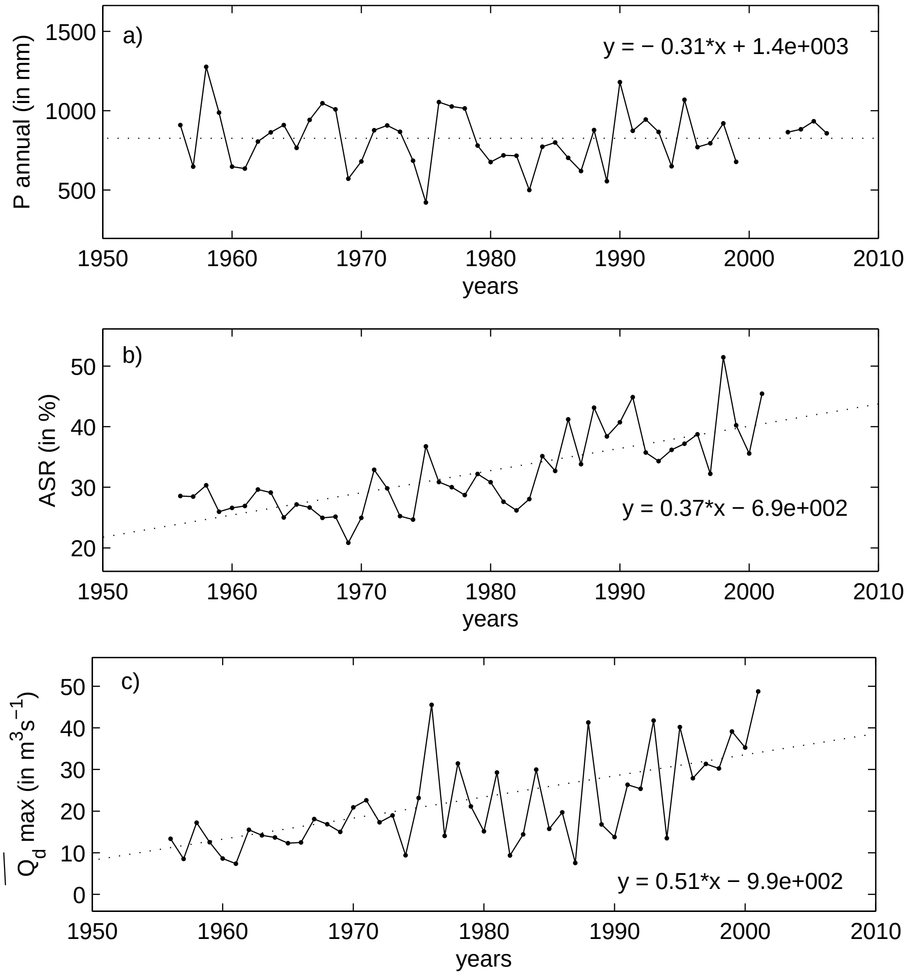

Figure 8. Trends in precipitation, surface-runoff and extreme water discharges over the 1956-2001 period.

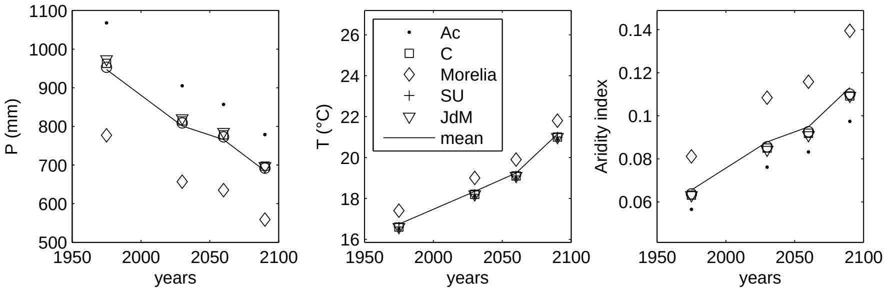

Figure 9. a) Estimated annual precipitation for contemporary climate (period 1961-1990, centred in 1975), and for a climate change scenario for decades centred in 2030, 2060 and 2090. b) Estimated mean annual temperature for contemporary climate (period 1961-1990, centred in 1975), and for a climate change scenario for decades centred in 2030, 2060 and 2090. c) Annual aridity index for contemporary climate (period 1961-1990, centred in 1975), and for a climate change scenario for decades centred in 2030, 2060 and 2090.