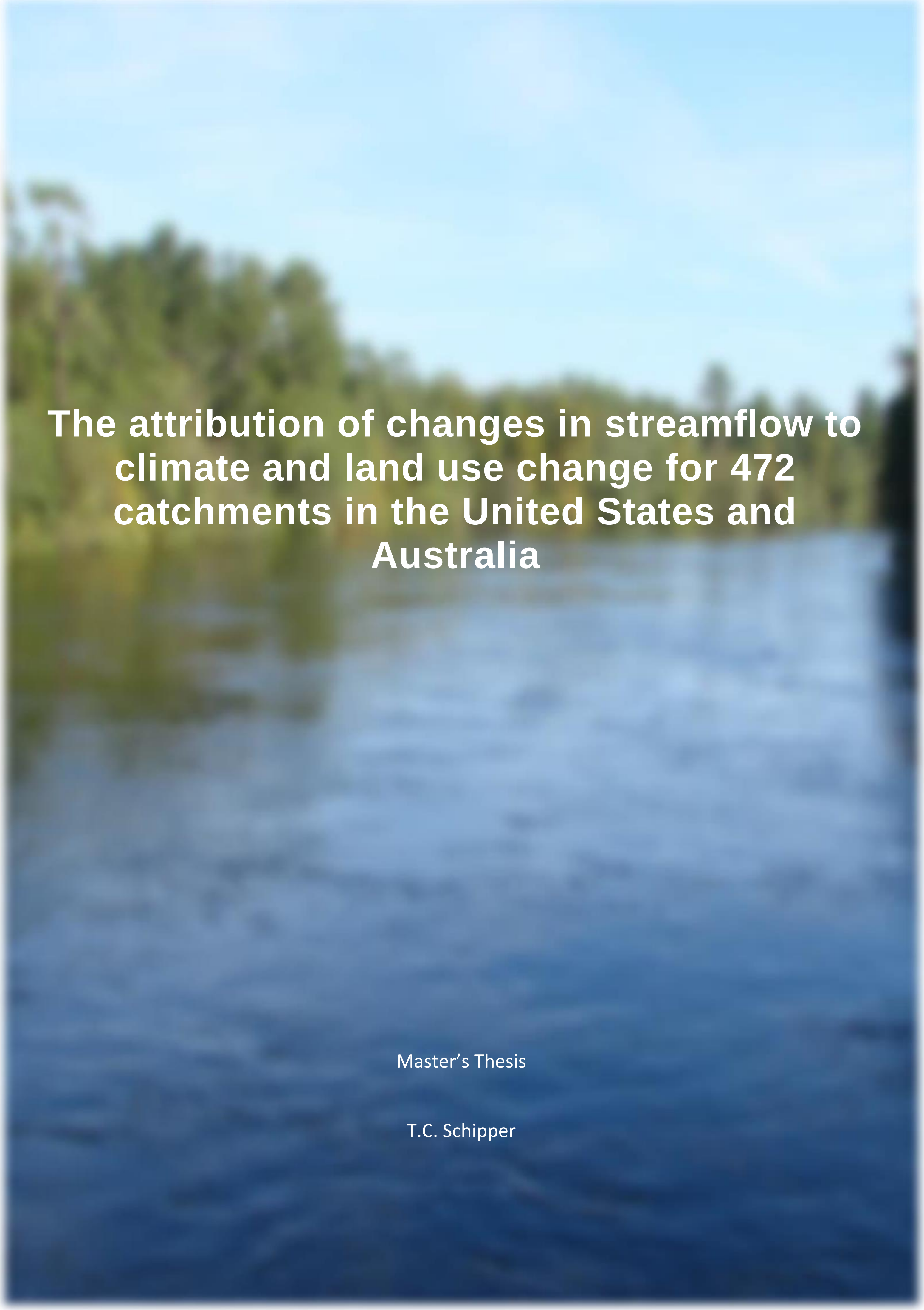

The attribution of changes in streamflow to climate and land use change for 472 catchments in the United States and Australia

Master's Thesis

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Master's Thesis

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Summary

Climate change and land use change are ongoing features which affect the hydrological regime by changing the rainfall partitioning into actual evapotranspiration and runoff. A data-based method has been previously developed to attribute changes in streamflow to climate and land use change. Since this method has not been often applied, a large sample attribution study by applying this method to catchments in different parts of the world will provide more insight in the water partitioning and will evaluate the attribution method. The results can be used by water managers of the studied catchments to obtain the main reason for changes in streamflow. The used method is applicable to a large sample set of catchments because it is a relatively fast method and it can provide quantitative results. The objective of this study is to apply a non-modelling attribution method to attribute changes in streamflow to climate change and land use change to a large sample set of catchments in different parts of the world and to evaluate the used method. 472 catchments in the United States and Australia are selected to apply the attribution method.

The attribution method calculates the water and energy budget of a catchment which could be translated to climate and land use induced changes in streamflow between two periods: a pre- and post-change period. The attribution method has been extended which make it applicable to a large sample set of catchments and which makes the results analysable by making distinctions between catchments. Some geographical features (e.g. aridity index, average catchment slope, and historical land use) were considered to explain the results. To evaluate the attribution method the results are compared with trends in potential evapotranspiration and precipitation and with documented land use changes.

The results indicate that in general an increase of the annual discharge is caused by deforestation and a wetter climate, and a decrease of the annual discharge is caused by afforestation and a drier climate. A difference between American catchments and Australian catchments is present. The changes in streamflow of American catchments are caused by a wetter climate, while these changes in streamflow of Australian catchments are caused by a wetter climate or a drier climate. Geographical features which explain the results of the attribution method are the aridity index and the historical land use. The average catchment slope seems to be less well explaining the results; however this could be the result of only including catchments with a relatively flat slope. It was expected to influence the results, because it influences the water storage capacity of a system, as the soil moisture and presence of aquifers do influence the water storage capacity too. However information about the last two features is not present for a large number of catchments so this is not included in this study. The trends in potential evapotranspiration and precipitation support the results of the attribution method. The documented land use changes support the values of land use induced changes, however for one of the fifteen catchments of which this is done the results are contra dictionary.

Based on the assumption that climate change will only affect potential evapotranspiration and precipitation, but not the actual evapotranspiration it is reasonable to assume that the land use induced change is overestimated and the climate induced change is underestimated, both to a small extent.

Generally, the method performs quite well based on documented land use change and trends in precipitation and evapotranspiration. It also can be concluded that the results are best explained by the location of the catchment, the aridity index and historical land use.

Preface

This master’s thesis is the results of the graduation project I did to complete the study programme Civil Engineering and Management at the department of Water Engineering and Management of the University of Twente. My interest in hydrology at catchment scale in combination with climate change and its influences was essential for getting the graduation project to a good end. I enjoyed studying these topics. At the start of the MSc project I was reserved for using software packages like MATLAB because my knowledge of it was limited. However I am glad I have used them and got familiar with them; in the end they turned out to be very helpful tools. Besides the ´technical´ support, this research could not have come about without the help of a number of people.

First of all I would like to thank Martijn Booij and Hero Marhaento of the department of Water Engineering and Management of the University of Twente for their supervision. They were able to point out in detail what should have been improved and they were always available in a short period of time when I had questions. Besides this, I am very glad they wanted to correct me for any grammatical error, because I am a non-native English speaker and writing an English report is still challenging for me. I also would like to thank Dr. Murray C. Peel of the University of Melbourne for complementing the Australian dataset.

Finally I would like to thank anyone who was involved in all other ways: by showing interest, listening to my progress and helping me out when I was struggling. Family, friends, graduation colleagues, and last but not least my girlfriend, without them I could not have accomplished this.

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1 Introduction

Climate change and land use change are ongoing features which affect the hydrological regime by changing the rainfall partitioning into actual evapotranspiration and runoff. These changes are for example relevant for management of water resources, agriculture and forestry. Although the task seems clear, it will be challenging to do because climate change and land use change operate at different temporal and spatial scales and strengthen each other. Besides, they both might occur in parallel and there is uncertainty to correctly attribute observed changes in streamflow to climate change or land use change (Renner et al., 2014). The attribution of streamflow is important to clarify the effects of climate change and land use change in the past and to estimate the effects of future climate change and land use change. This will be relevant for water management for individual catchments, because the effect of human influences is separated from natural changes. A large sample study will provide more insight in the attribution of streamflow to climate change and land use change, which makes the results of the used attribution method to be interpreted in the correct way. This leads to the opportunity (e.g. for water managers) to apply the method at individual catchments knowing how to interpret the results.

1.1 State of the art

There are different attribution methods which first can be divided into a modelling and a non-modelling approach. The advantage of a modelling approach is that the outcome might be more reliable; however the applicability is difficult because the underlying processes must be clear, it is data-demanding, and the model must be calibrated, which is time consuming (Zhang et al., 2012). A non-modelling approach is data driven which allows them to be performed at large scale, because the application is relatively fast. Besides, it is already known that a non-modelling approach gives reasonable results (Wang, 2014). These are the reasons of this study for focusing on a non-modelling approach only. The non-modelling approach can be divided into groups based on the used attribution method. The different methods are a coupled water-energy budget approach, a modified double mass curve approach and an approach to employ trend analysis and change detection methods (Marhaento et al., in press).

The study of Tomer & Schilling (2009) is an example of a coupled water-energy budget approach applied in the United States. This approach is based on the Budyko hypothesis to quantify the impact of climate change and land use change on mean annual streamflow. This hypothesis compares two ratios. The first one is a ratio between the mean annual actual evapotranspiration and the mean annual precipitation. The second one is a ratio between the mean annual actual evapotranspiration and the mean annual potential evapotranspiration. The actual evapotranspiration is controlled by the relative proportion and timing of available water and energy (denoted as precipitation and potential evapotranspiration), and by the type and condition of vegetation. The amount of unused water and energy is estimated by the first and second ratio respectively. A shift in these values over different periods, related to the climate conditions, will indicate whether climate change and/or land use change was the driving factor. The four catchments included in the study of Tomer & Schilling (2009) gave reasonable results. Since their study includes a small number of catchments, they were able to study them in detail and could for example find a rapid increase in soybean cultivation which was an explanation for the results of the method. Other studies which have made use of the coupled water-energy budget approach in the recent past are: Zheng et al. (2009), Wang & Hejazi (2011), Renner et al. (2014) and Marhaentho et al. (in press).

The modified double mass curve approach is for example used in the study of Wei & Zhang (2010). This method was used to remove the effect of climatic variability on streamflow in order to estimate the impact of forest disturbance on streamflow (Wei & Zhang, 2010), but also the impact of other land use changes can be estimated. The first step in this method is to calculate the difference between annual precipitation and annual evapotranspiration, i.e. effective precipitation. In a modified double mass curve the accumulated annual streamflow is plotted versus the accumulated annual effective precipitation. For periods without forest disturbance, the curve should produce a straight line. This base line describes the linear relation for the given climate conditions. Abrupt changes in the plotted curve suggest a change in annual streamflow caused by forest disturbance. The forest disturbances which had taken place in their study catchment were in line with the results of the attribution method. Another study which had made use of this approach is the research of Zhang et al. (2012).

The last method is a classical approach to employ trend analyses and change detection methods. For instance Rientjes et al. (2011) made use of this approach. Trend analysis is important to evaluate whether climatic factors and human interference significantly affected the hydrological regime of the catchment (Rientjes et al., 2011). Several methods exist to test the presence of a trend in stream flow records. An example is the Mann-Kendall test which is used in the research of Rientjes et al. (2011). The presence of a change in the mean of the stream flow is evaluated by applying the moving average *t*-test, which identifies the year at which the change in stream flow had occurred. When the change point is identified, two (or more) points in time will be determined for applying the change detection method. This method is used to identify whether land cover had changed. The results of this method are quantitative and the catchment they included in their study gave results which were able to be related to an extension of agricultural land at the expense of forest cover. Other studies which have been making use of this approach are Zhang et al. (2008) and Zhang et al. (2014).

There are multiple differences between the three attribution methods. The coupled water-energy budget approach will be used in this study, because of the possibility to present the results in a quantitative way, which is the most important advantage. This way of presenting the results has only been used by Renner et al. (2014) and Marhaento et al. (in press). Since Tomer & Schilling (2009) were the first who interpret the Budyko hypothesis in this way, there will be referred to this method as: 'the method of Tomer and Schilling'.

1.2 Research gap

To investigate changes in streamflow long time series of discharge data are needed. This is the reason that this kind of studies are being carried out since the last decades. Most of the studies only investigated one catchment or one region, consisting of different catchments. However a large sample study could on the one hand better evaluate the performance of the attribution method and on the other hand could give more insight which climate change and land use change tend to contribute more to changes in streamflow and which catchment characteristics makes them sensitive to climate change and land use change. Wang & Hejazi (2011) applied a non-modelling attribution approach to more than 400 catchments. The used method is a coupled energy budget approach, but the difference with the method of Tomer and Schilling is that Wang & Hejazi (2011) use the Budyko curve itself instead of a simpler interpretation of this curve (related to the aridity index) to attribute the change in streamflow to climate change and land use change. Different methods exist to calculate this curve, but all of them include one or more parameters which must be calibrated. This is not the case for the aridity index.

Although there exists a study on the application of an attribution method at large scale (Wang & Hejazi, 2011) it still would be interesting to extend the idea of Tomer and Schilling, as Renner et al. (2014) and Marhaento et al. (in press) did and apply this method at large scale. This extension is used to determine the climatic state of the study catchment by considering the aridity index, which makes it applicable at catchments in different climate conditions and it provides quantitative results. Application at large scale will validate the extension of the attribution method. An advantage of this method compared to the method used by Wang & Hejazi (2011) is that the application is less time consuming, due to the absence of parameters to be calibrated. Besides this, another difference is the regions which will be used to carry out the attribution method. Wang & Hejazi (2011) applied the method in the USA, where the method in this study will also be applied to catchments in Australia.

1.3 Research objective and questions

The objective of this study is to apply a non-modelling attribution method to attribute changes in streamflow to climate change and land use change to a large sample set of catchments in different parts of the world and to evaluate the used method.

To be able to achieve the objective of this research, the following research questions are formulated:

1. *What is the attribution of streamflow changes to climate change and land use change for each of the catchments?*
2. *Which geographical features can explain the results from the attribution method?*
3. *What is the performance of the attribution method?*

Geographical features, as referred to in the second research question, means geographical catchment characteristics which are assumed to influence the results of the attribution method (e.g. catchment size and average catchment slope). This means that these features might explain the results as well. The performance of the attribution method (third research question) is an evaluation of the method based on trends in potential evapotranspiration, precipitation and discharge, documented land use changes and the influence of two factors associated with the data namely the length of the measuring period and the possibility of using climatological potential evapotranspiration values.

1.4 Thesis outline

In chapter 2 the methods are described, starting with the selection of catchments and a description of the selected ones. After that the attribution method and the way of evaluating the results is described. Chapter 3 presents all the results to be able to answer the research questions. The results of the three research questions as described in section 1.3 are presented in three different sections. In chapter 4 the results are compared with other studies about the application of (large sample) attribution methods. After that the results will be interpreted, regarding the potential and limitations of the method. This will lead to a generalisation of the results. In chapter 5 the conclusions and recommendations are described.

2 Methods

As a first step in this research, the study catchments are selected as described in section 2.1. This is done based on data availability, criteria regarding the hydrological conditions of the catchments (climate conditions, human influences in the area and region of the catchments) and criteria regarding the quality of the datasets. After this the selected catchments are described per dataset. In section 2.2 the calculation method to obtain the potential evapotranspiration values, needed for the attribution method, is described. Subsequently, trend analysis is described to be able to discover trends in discharge, which is the reason for conducting an attribution method. The last part of this section is about the attribution method of Tomer and Schilling. The last section of this chapter, section 2.3, is a description of how this method is validated, based on trend analyses and documented land use changes, and evaluated, based on the lengths of the measuring periods and a analysis regarding the potential evapotranspiration.

2.1 Selection of catchments

The outcome of the research is depending on the reliability of the used data, which makes the selection of the catchments, and thus the selection of the datasets, an important part of the research. First the criteria are developed. Datasets from different parts of the world (Europe, North-America, and Australia), which are available online will be evaluated based on these criteria. The criteria are split in two parts, one part with criteria about the conditions of the catchments and the other part about the quality of the dataset. Both are listed below, starting with the criteria about the conditions:

- different climatic conditions will be taken into account as much as possible;
- different catchments in the same region will be taken into account as much as possible;
- catchments where urbanisation had taken place will not be excluded a priori;
- catchments where dams are present or being built within the study period will be treated with care;
- daily data of precipitation, discharge, and data to calculate potential evapotranspiration must be present;
- the presence of catchment characteristics (location (of the boundaries), size, climate, etc.) is an advantage.

The quality criteria are:

- the annual actual evapotranspiration must not be smaller than 0, and must always be smaller than its potential value;
- a minimum of two sequences of five hydrologic years of daily data must be present;
- earlier use in peer reviewed studies is preferred.

The above named criteria will be clarified in sections 2.1.1 and 2.1.2.

2.1.1 Criteria about the circumstances

The first criterion is about the climatic conditions. When several climatic conditions are taken into account, the evaluation of the attribution method will be conducted for a wider range of conditions which makes the results more reliable and general. If more catchments in the same region are included in the study (second criterion), this might give more insight in the method because the catchments will be similar to each other regarding the climate conditions and perhaps also land use.

The third and fourth criteria are both about human influence in the catchment. Urbanisation might have a significant influence on the streamflow. However, it is still a way of changing the land use and thus there is no need to exclude these catchments. The disadvantage of dams is the discharge which is controlled by it. Therefore information about the impact of dams on the annual discharge is preferred; the dams should not have a significant influence on the mean annual discharge

The last two criteria are about the presence of data. For precipitation and discharge daily data are required, because it increases the reliability of the datasets their quality and for potential evapotranspiration at least daily data to calculate it must be present.

2.1.2 Quality criteria of datasets

To check whether the quality of the data is good enough first the hydrologic years will be determined, in such a way that the change in storage between different years is the least. This is done by taking the month with the lowest average discharge. The end of this month is also the end of the hydrologic year and its beginning is the first day of the subsequent month. Subsequently, the annual potential evapotranspiration (depends on presence of data, see also section 2.1.3), precipitation and discharge will be calculated by summing the daily data per hydrologic year. The actual evapotranspiration will be calculated as described in section 2.2.3.

The calculated actual evapotranspiration should not be smaller than 0, because this will mean that the discharge during that hydrologic year was higher than the precipitation, which is only possible when the storage was lowered. Of course this might be realistic, but since hydrologic years are considered, the changes in storage over multiple years are reduced to a minimum. Besides, a negative value for actual evapotranspiration is just not possible, thus catchments will be excluded when at least one actual evapotranspiration value (per hydrologic year) is negative. This also holds for catchments where the actual evapotranspiration is larger than its potential value in one of the hydrologic years, because the definition of potential evapotranspiration is that it is the maximum amount of water which is able to evapotranspire, under optimal conditions.

Another quality criterion is the presence of two sequences (or more) of at least five years. This is related to the method to be conducted. Other studies applying attribution methods and splitting the time series do not use periods shorter than five years (e.g. Zhang et al., 2008, Renner et al., 2014 and Marhaento et al., in press), because climate variability is always present and must be averaged over the periods of at least five years. Sequences of ten years are desired to be more confident about averaging the climate variability. See also section 2.2.3 for a description of the way the time series will be split.

Earlier use of the datasets by peer reviewed studies increases the chance of reliable datasets. It will not directly mean that the datasets consists of high quality data, but it does mean that it has already been checked. In addition, the purpose of the studies will help to indicate the quality restrictions of the used datasets.

2.1.3 Description of selected catchments

By taking into account all criteria, described in sections 2.1.1 and 2.1.2, different datasets have been tested. Two datasets were passing the criteria and are selected because most of the included catchments were passing the criteria and contain more catchments than the other tested datasets. The selected datasets are the USA MOPEX dataset (Schaake et al., 2006) and the Australian dataset (Peel et al., 2000). Both datasets are available free of charge. Several other datasets are also freely available, but are not selected. This is the case for catchments in the UK, available from the PUB Top-Down Model Working Group, which the measuring length used in this dataset is relatively short. This means that applying an attribution method to this dataset is less useful. Another interesting dataset is the one of the French research community (Oudin et al., 2008). Unfortunately this dataset is not available, only for the French research community itself.

Table 1: Number of catchments in datasets, number of catchments not meeting certain criteria, and total number of catchments in- and excluded.

	USA	Australia	Total
Total number of catchments	431	331	762
Excluded because: ET<0 or ET>PET (annual)	164	95	259
Excluded because: sequences too short	2	29	31
Excluded because: not used in peer reviewed studies	0	0	0
Total excluded	166	124	290
Number of catchments included	**265**	**207**	**472**

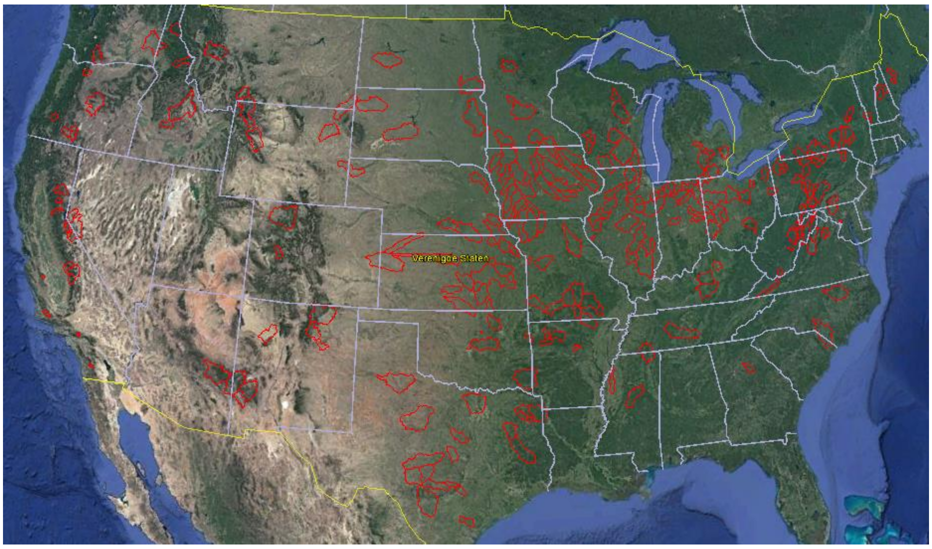

Figure 1: Map of the USA with the boundaries of catchments included in this study. (Sources: Schaake et al., 2006 and Google Earth)

Figure 2: Map of Australia with the boundaries of catchments included in this study. (Sources: Peel et al., 2000 and Google Earth)

Still not all of the included catchments of the selected datasets are meeting the criteria. The dataset of the USA consists of a total of 431 catchments and 265 of these are meeting the criteria. The Australian dataset consists of 331 catchments and 207 are meeting the criteria, which gives a total of 472 catchments to be included. In Table 1 is shown how many catchments are dropped out, including the reason. The catchments included in the study are also shown in Figure 1 and Figure 2 (USA and Australia respectively). A table with characteristics of all included catchments is shown in Appendix F.

American dataset

The primary goal of MOPEX, which had developed the dataset, has been to assemble a large number of high quality historical hydrometeorological data and catchment characteristics for a wide range of catchments with a surface area of minimal 150 km^2 and maximum 10,000 km^2. In addition, all catchments believed to be unaffected by upstream regulation. The streamflow of all of these catchments is measured with a minimum interval of one day. In the next subsections it is described how the measurements are carried out and which work has been done by MOPEX to complete the dataset.

Precipitation

Required precipitation observations must be daily values of mean areal precipitation. Missing data was completed by MOPEX, because about 30% of the daily precipitation measurements were missing. It was found that rain gauges at a given distance had the strongest correlation when the observation times (e.g. 7 AM) were the same. This knowledge was used to estimate the missing values. Most of the precipitation time series are measured once a day at a specified time, most of them in the early morning (over 70%). This had to be corrected to be in line with the streamflow measurements, by using neighbouring stations with measuring intervals of one hour.

Temperature

Daily potential evapotranspiration values are not present in this dataset, but by making use of the temperature this can be estimated. The minimum and maximum daily temperature values are present. These values usually occur in the early morning and in the afternoon respectively. However, sometimes the maximum and minimum temperatures are indicated to occur at an AM point of time, because both are measured once a day. It is assumed that they had occurred the day before, since maxima in the early morning are not likely. Using these data the mean areal maximum and minimum data are computed.

At some measuring stations the temperature is measured once a day. To estimate the minimum and maximum temperature at that station for a given day, neighbouring stations are used to be able to interpolate.

It must be noted that for more than 200 of the 265 included American catchments the daily maximum temperature is one or more times lower than the minimum daily temperature. It seems that these values have been mixed up, because the days before and after have comparable temperatures but reversed (the minimum temperature is approximately the maximum of the previous day and the maximum temperature is approximately the minimum of the previous day).

Discharge

Discharge data have been obtained by MOPEX by selecting stream gauges from a sub-set of the USGS stream gauge network. The selected stream gauges by MOPEX are not affected by upstream regulation as mentioned before and the data records are long enough to be suitable for climate studies.

Characteristics

Catchment characteristics present in the MOPEX dataset are: elevation of the measuring station, catchment boundaries, streams, soils (texture, hydraulic properties, etc.), vegetation (type, rooting depth, phenology, etc.), geology, snow cover and climatological potential evapotranspiration values among others.

Applicability

To be able to make this dataset useful for the purpose of this study, daily potential evapotranspiration data are needed which can be calculated by using the daily minimum and maximum temperature and the equation of Hargreaves (see section 2.2.1). These estimated daily values are corrected with the climatological potential evapotranspiration data as present in the MOPEX dataset. The climatological potential evapotranspiration data are based on the period 1956-1970 (Farnsworth & Thompson 1982), so the correction factor is based on the estimated daily potential evapotranspiration of this period and climatological potential evapotranspiration data. It is calculated as described in section 2.2.1.

Australian dataset

The objective of the project, for which the Australian dataset has been developed, was partially to extend unimpaired streamflow data for stations throughout Australia. Unimpaired is in this project defined as streamflow that is not subject to regulation or diversion. Catchments included in this project had to have a minimum size of 50 km^2 and a maximum of 2000 km^2. In this dataset the minimum time interval for streamflow measurements is monthly, but daily values are available. In the next subsections is described how the measurements are carried out and which work has been done by Peel et al. (2000) to complete the dataset.

Precipitation

Gridded monthly rainfall is obtained by interpolation of over 6000 daily rainfall stations in Australia. This is converted to daily rainfall by using the daily rainfall distribution from the station closest to that point. The spatial average daily rainfall (per catchment) is estimated by averaging over the grids within the catchment.

Potential evapotranspiration

The available potential evapotranspiration values in this dataset are climatological values. The 12 monthly average values available for each catchment are believed to be relatively stationary over different years. The inter-annual variability of the potential evapotranspiration, expressed in the coefficient of variation, is smaller than 0.05 as Peel et al. (2000) mention.

Discharge

A minimum of 120 months of recorded data were needed for selection of discharge stations. Missing months were allowed, as long as there was a streamflow record of 120 months in total. This is in line with the absolute minimum length to be selected in this study (two periods of five years).

Characteristics

Catchment characteristics present in the Australian dataset are: catchment surface area, mean annual rainfall and streamflow, and boundaries of the catchments.

Applicability

It is hard to verify the assumption of a low inter annual variability in potential evapotranspiration which would be preferred, because this assumption will have a big influence on the results. Since no other data (e.g. daily minimum and maximum temperature) are available, it is not possible to estimate daily potential evapotranspiration values for this dataset. However it is possible to compare it with the coefficient of variation of calculated potential evapotranspiration values of the MOPEX dataset. The coefficients of variation for the Australian potential evapotranspiration values are not above 0.05, while the highest coefficient of variation for the American potential evapotranspiration values is 0.055. Only 7 American catchments have a value higher than 0.05, which means that the coefficient of variation is approximately the same for the Australian and American catchments. To evaluate whether it is feasible to use the climatological potential evapotranspiration values, the attribution method will be applied two times at the American catchments: with and without climatological potential evapotranspiration values (see also section 2.3.4).

2.2 Attribution of changes in streamflow

After selecting the datasets and catchments, the attribution method will be applied. This starts with estimating daily potential evapotranspiration values for the American catchments (2.2.1), because this information is not present in the dataset. After that the presence of a significant trend in discharge will be detected in section 2.2.2 to determine whether annual discharge amounts have changed. In section 2.2.3 the time series will be split in two parts, one at the beginning of the measuring period and one at the end of it. These two periods will be used in section 2.2.4 to apply the attribution method, because it makes use of a pre-change and post-change period. In section 2.2.5 is described how the results of this large sample set analysis will be evaluated regarding the significance of the results and different geographic features.

2.2.1 Potential evapotranspiration

For datasets where the maximum and minimum daily temperature are present, but no potential evapotranspiration values, the procedure as described in Appendix A will be followed, where the declination and the latitude (Schaake et al., 2006) are needed to estimate the extraterrestrial radiation and subsequently the potential evapotranspiration. This is the case for the American dataset.

The equation of Hargreaves (Hargreaves & Samani, 1985) can be used to estimate daily potential evapotranspiration. This equation is used because it only requires the minimum and maximum temperature. However, the method is not applicable for calculating daily data. It must be summed to have periods of at least a length of a week. In this case this is not a problem, because it will be used for calculating annual total amounts. Equation 2 is used to correct the estimated *PET* values. The equations are as follows:

$$PET_{d,est} = 0.408 * 0.0023RA\left(\frac{T_{max} + T_{min}}{2} + 17.8\right)\sqrt{T_{max} - T_{min}} \tag{1}$$

$$PET_{d,corr} = PET_{d,est} * \frac{PET_{m\ avg,cl}}{PET_{m\ avg,est}} \tag{2}$$

where $PET_{d,est}$ is the daily estimated potential evapotranspiration in mm d^{-1}, *RA* the extraterrestrial radiation in MJ m^{-2} d^{-1}, T_{max} the maximum daily temperature in degrees Celsius and T_{min} the minimum daily temperature in degrees Celsius. The factor 0.408 is added to convert the unit from MJ m^{-2} d^{-1} to mm d^{-1}.

After the daily potential evapotranspiration values are estimated, this will be corrected with climatological monthly average potential evapotranspiration ($PET_{m\ avg,cl}$) data (Schaake et al., 2006). A correction factor for each month will be calculated by dividing monthly average potential evapotranspiration (climatological values) by the monthly average, obtained from the estimated potential evapotranspiration ($PET_{m\ avg,est}$). This factor is used to multiply it with $PET_{d,est}$. This gives the corrected daily potential evapotranspiration $PET_{d,corr}$.

2.2.2 Trends in annual discharge

A trend in the discharge will indicate that a change has occurred (driven by land use change and/or climate change). A method to discover whether a trend is present and has been used by hydrologists quite often (e.g. Marhaento et al., in press), is the Mann Kendall test. Sen's slope estimator, also often used by hydrologists (e.g. Marhaento et al., in press), gives an indication of the slope of the trend. These two methods are related to each other.

If the Mann Kendall test indicates a trend to be present in the discharge, the attribution method can be used to find the reason of this change: climate or land use changes. However, when a trend is not present, it is still possible climate and land use changes have had an (each other cancelling) impact on the discharge. Sen's slope estimator will later be used to evaluate the method of Tomer and Schilling, by estimating the slope of the trend in discharge. This provides the possibility to relate climate and land use induced changes to the annual change in discharge.

Mann Kendall test

Mann (1945) and Kendall (1975) developed a statistical method whether or not to reject a null hypothesis (H_0). In this case the null hypothesis is: no monotonic trend is present and the alternative hypothesis (H_a) is: a downward or upward monotonic trend is present. One of the assumptions for this test is that the measurements obtained over time are independent. This is true because hydrologic years are considered: the influence of a year to the subsequent year is assumed to be minimal. A detailed description of the Mann Kendall test is present in Appendix B.

Sen's slope estimator

Sen (1968) developed a statistical method, related to the Mann Kendall test, to determine the slope and direction of a trend in a dataset. A detailed description of Sen's slope estimator is present in Appendix C.

2.2.3 Splitting of time series

To be able to apply the attribution method the discharge time series must be split in at least two parts. Since this research includes many different catchments, it is important to be consistent. This also holds for splitting the time series of the annual discharge. The main challenge is to discover changes: abrupt as well as smooth changes and split the time series based on this. This is hard because of the fluctuations in annual discharge. Statistical trends might provide a solution to this problem, but the way the annual discharge changes is not the same for each catchment. This means that there is not one statistical test applicable to all. Nevertheless, also without knowledge about the annual discharge fluctuations it is possible to split the time series (Renner et al., 2014). A fixed length of sequences of annual discharge amounts will offer a solution. Two sequences of annual discharge are needed: one at the beginning and one at the end. Only these two periods will be taken into account, independent of the total length of the time series.

Missing data in the (daily) time series will not be complemented, because this is hard to do for large sample studies. This means that the complete hydrologic year must be excluded from the dataset when one or more data points are missing. This makes it more difficult to determine the sequences to be included, because these must consist of five to ten complete hydrologic years. The desired sequence length of ten years will not always be present in the datasets (two times). This is why it is accepted when the sequences have a length of minimal five hydrologic years, as long as both sequences have the same length.

The method to determine the length and start point of the sequences per catchment is as follows. First it will be determined whether two periods of ten sequential years are present. When this is the case, the first period will start with the earliest possible year and the other one will end with the latest possible year. When two sequences of ten hydrologic years are not present, the length will be reduced with one year and tested again. For each period length will be evaluated whether two sequences are present, until a length of five years. When even this short period is not included in the dataset, the catchment will not be used for further investigation which is shown in Table 1.

2.2.4 Attribution method

The general water balance equation, based on the principle of conservation of mass, is as follows:

$$P = Q + ET + \frac{\Delta S}{\Delta t} \tag{3}$$

where *P* is the precipitation in mm d^{-1}, *Q* the discharge in mm d^{-1}, *ET* the actual evapotranspiration in mm d^{-1}, ΔS the change in storage in mm, and Δt the time step in d, all in a bounded area. This equation can be reduced to a simpler form by assuming no change of storage. Rewriting gives the following equation:

$$ET = P - Q \tag{4}$$

where the dimensions for all the variables are mm. Equation 4 will be useful to estimate the actual evapotranspiration, because most datasets will not provide values for this variable; however it is needed for the attribution method.

The assumption of no change in groundwater storage and surface water storage is not completely correct. However, the change can be minimised by making use of hydrologic years instead of a calendar year. The hydrologic year is defined to be starting and ending in a period of low discharge. This is based on the monthly average discharges, over multiple years (see section 2.1.2). During a period of low discharge the groundwater storage is reduced to a minimum which leads to a minimum of fluctuations in storage.

Tomer & Schilling (2009) developed a method to separate the effects of land use and climate change on streamflow by making use of changes in the proportion of excess water relative to changes in the proportion of excess energy. Excess water can be calculated by subtracting the actual evapotranspiration (*ET*) from the precipitation (*P*) within a catchment. This amount divided by the available water (*P*) gives the dimensionless value P_{ex}. Excess energy can be calculated by subtracting the actual evapotranspiration from the potential evapotranspiration (*PET*). This amount divided by the available energy (*PET*) gives the dimensionless value E_{ex}. The values of both P_{ex} and E_{ex} will be between 0 and 1. A value close to 0 indicates nearly no excess water or energy in the system and a value close to 1 indicates a lot of excess water or energy in the system. Rewriting of the proportions gives the following equations:

$$P_{ex} = 1 - ET/P \tag{5}$$

$$E_{ex} = 1 - ET/PET \tag{6}$$

where P_{ex} is the dimensionless proportion of excess water, *ET* the actual evapotranspiration, *P* the precipitation, E_{ex} the proportion of excess energy, and *PET* the potential evapotranspiration. The dimensions of *ET*, *P* and *PET* must be the same to be able to calculate the dimensionless values P_{ex} and E_{ex}.

The indicators for proportions of excess water and energy are sensitive to climate change and/or land use change, which is an important assumption for this method. Changes in vegetation will directly affect *ET*, but not *P* and *PET*, which result in increasing or decreasing P_{ex} and E_{ex}, both in the same direction. Therefore, changes in land use, related to vegetation, will affect P_{ex} and E_{ex} in the same direction (increasing or decreasing). However, the influence of climate change on these parameters is different. Changes in climate are considered to affect *P* and *PET*, but not *ET* at a regional scale. This leads to increased P_{ex} and decreased E_{ex} in case of an increased *P*/*PET* ratio with time, or to decreased P_{ex} and increased E_{ex} in case of an decreased *P*/*PET* ratio with time.

The shift in time of the parameters P_{ex} and E_{ex} can be visualised by plotting them (see Figure 3). The direction of change indicates the driving force of the change in discharge. The direction of change is relative to the aridity index as Renner et al. (2014) added to the attribution method of Tomer & Schilling (2009). This addition is needed because this makes it possible to apply the method to all climatic conditions. Without this addition it is only applicable in regions where precipitation demands equal evaporative demands. The aridity index is the ratio between the long term average *PET* and *P*. A shift parallel to the aridity index indicates land use change as the driving force of the changing discharge, because this indicates only *ET* had changed. A shift perpendicular to the aridity index indicates climate change as the driving force of the changing discharge, because this means only the ratio of *PET* and *P* had changed.

Distinction can also be made in the direction of change, when it is in line with the aridity index. A shift to higher P_{ex} and E_{ex} values indicates an increased *ET*, which is the case when an increased amount of vegetation is present. A shift to lower P_{ex} and E_{ex} values indicates a decreased *ET*, which is the case when a decreased amount of vegetation is present.

To be able to obtain quantitative results, Marhaento et al. (in press) developed a way of calculating percentages of change related to climate and land use change, based on geometric equations. The magnitudes are based on three measures: the resultant length (*R*), the angle (θ) of change and the attribution. In this way the shift of point M_1 (P_{ex1}, E_{ex1}) to point M_2 (P_{ex2}, E_{ex2}) is calculated. To make this method applicable to a large number of catchments the way of calculating the absolute magnitudes is changed. In this adapted way there is a difference between the directions of shifts: a shift directed to the afforestation (deforestation) side of Figure 3, will be indicated with negative (positive) values for the contribution of land use change. A shift directed to the *P*/*PET* increase (*P*/*PET* decrease) side of Figure 3, will be indicated with negative (positive) values for the contribution of climate change.

First the resultant length is calculated with the following equation, based on the Pythagoras theorem:

$$R = \sqrt{(E_{ex2} - E_{ex1})^2 + (P_{ex2} - P_{ex1})^2} \tag{7}$$

by taking into account the points M_1 and M_2. Next the angle of change is calculated with the following equations, based on goniometric equations:

$$\vartheta = \frac{\frac{\overline{PET}}{\overline{P}} - \frac{P_{ex2} - P_{ex1}}{E_{ex2} - E_{ex1}}}{1 + \frac{\overline{PET}}{\overline{P}} * \frac{P_{ex2} - P_{ex1}}{E_{ex2} - E_{ex1}}} \tag{8}$$

$$\begin{aligned} \theta &= \arctan(\vartheta) + \pi && \text{for } P_{ex2} < P_{ex1} + \frac{\overline{P}}{\overline{PET}} E_{ex1} - \frac{\overline{P}}{\overline{PET}} E_{ex2} \\ \theta &= \arctan(\vartheta) && \text{for } P_{ex2} > P_{ex1} + \frac{\overline{P}}{\overline{PET}} E_{ex1} - \frac{\overline{P}}{\overline{PET}} E_{ex2} \end{aligned} \tag{9}$$

where $\overline{PET}/\overline{P}$ is the long term aridity index, ϑ a ratio indicating the angle θ in radials. π is added for some cases to be able to show results in a way such that θ has a range of 2π or 360°. These measures will be used to determine the contribution of climate change and land use change:

$$LUC = R * \cos\theta \tag{10}$$

$$CC = R * \sin\theta \tag{11}$$

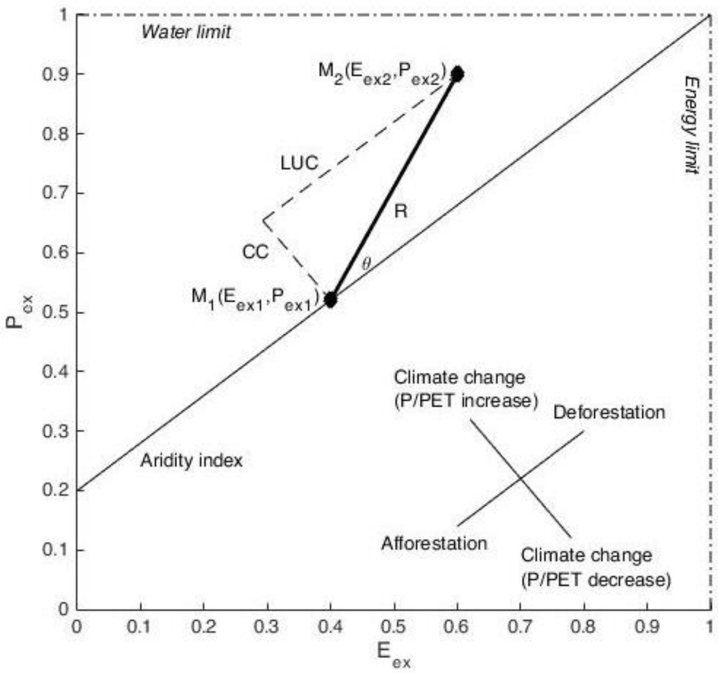

Figure 3: Framework (Tomer & Schilling, 2009) adapted by Marhaento et al. (in press) to illustrate how the fractions of excess water and energy respond to climate and land use changes. The (virtual) points M_1 and M_2 are the fractions of excess water and energy of the pre-change period (P_{ex1}, E_{ex1}) and the post-change period (P_{ex2}, E_{ex2}), respectively.

where *LUC* is the length of changes between the two periods along the aridity index line, which is the contribution of land use change to the change in streamflow and *CC* the length of the changes of the line perpendicular to the aridity index line which is the contribution of climate change to the change in streamflow.

2.2.5 Evaluation of a large sample set

To be able to analyse the results properly a distinction will be made between catchments with and without a significant change in *LUC* and/or *CC* values between the two periods. The catchments are also divided based on different geographical features. The features are selected because there are reasons to believe they will influence the results. Both are described in the next subsections.

Significance of change in *LUC* and/or *CC* values between the two periods

The results of the attribution method will especially be of interest when there is a significant change between the pre-change period (point M_1 in Figure 3) and the post-change period (point M_2). This is why a statistical method will be used to determine whether the values M_1 and M_2 significantly differ from each other. The values of M_1 and M_2 are averages of 5 to 10 points (the length of the two considered periods) and are described by two variables (P_{ex}, E_{ex}). A frequently used way of testing whether one group tends to produce different observations than another group is the Rank-Sum Test. However this test is not applicable to 2-dimensional observations. An extension of the Kolmogorov-Smirnov test is useful in such cases (Lopes et al., 2007). This extension is the Fasano and Franceschini test (Fasano & Franceschini, 1987). This test is applicable to any kind of unknown distributions and the used level of significance is 95% as in earlier statistical tests also has been used.

Geographical features

The catchments will be classified based on geographical features to be able to present the results per classification and compare the catchments with each other. The geographical features are chosen because the needed information is present and can explain the results.

First the catchments will be classified by catchment size. It is known that for large catchments it is harder to find land use changes to be the main cause of changes in the streamflow (Blöschl et al., 2007). The classes are made in such a way that they consists of approximately the same number of catchments. In addition, overlapping catchments are considered separately. This is of interest because the climate conditions and the land use in these catchments will most likely be the same. So the main difference is the catchment size.

A second classification is made based on the historical land use. It is expected that land use change is related to the historical land uses. For example it is not expected that deforestation takes place in the dessert. This will be done by making use of historical land use maps.

The third classification is based on the average catchment slope. This will be important because it influences the residence time of water in the catchment, which is an important factor to influence the vulnerability of the streamflow of catchments to changes in climate and land use.

Fourth the catchments will be classified based on the climate. A description of how this is done is made in Appendix F. There is also described what these classes mean, based on the Köppen climate classification. In this way different countries can be compared. This will also provide insight whether climate is an indicator for the vulnerability of catchments for climate change and land use change. Another way to classify the climates which is also interesting is the aridity index, because this index will be used for calculating the values of *LUC* and *CC*.

2.3 Evaluation of the attribution method

The purpose of this study is partly to evaluate the used attribution method. This will be done using different sources and compare these with the results obtained from the attribution method. The evaluation will consist of four parts. The first one is by making use of the trends in potential evapotranspiration and precipitation. The second one is the investigation of documented land use changes for catchments with the highest, lowest and closest to zero values for *LUC*. The third one is the influence of the length of the measuring period. The last one is the difference between making use of constant and variable potential evapotranspiration.

2.3.1 Trends in potential evapotranspiration and precipitation

The first source to be used for evaluation is the data itself, used to obtain the trends in potential evapotranspiration and precipitation. This might seem odd, but trend analysis will use the data in a different way than the method of Tomer and Schilling does. This method only uses proportions of these variables: one variable relative to another one. Trends in the potential evapotranspiration and precipitation will indicate whether reasonable results are obtained for the *LUC* and *CC* values.

2.3.2 Documented land use change for a number of catchments

By searching for documented land use change (literature) there will be evaluated whether a land use change which had happened (or not) according to the applied attribution method is also documented. This will be done for the catchments with the five highest and five lowest values for *LUC* for which the change in *LUC* and/or *CC* values between the two periods is significant. To compare it with catchments where land use change did not took place according to the attribution method, this procedure will also be applied for the five catchments with *LUC* values closest to zero.

An obvious way of evaluating the results of *LUC* values is to compare it with the fraction of vegetation in the study area. Although this approach of evaluating the method seems promising, this is not done. The reason for this is that such information is not available over the whole study period and that it is too time consuming to obtain the needed values (e.g. by making use of ArcGIS) for a large sample set of catchments. Other values, e.g. the greenness index in the MOPEX datasets, can be obtained; however these are not usable since the values do not indicate time dependent changes.

2.3.3 Length of measuring period

The catchments will be classified based on the length of the measuring period used in the attribution method. This classification will indicate whether or not a longer measuring period results in larger changes of *LUC* and *CC* values. It is expected that longer periods provide a catchments streamflow to change to a larger extent, attributed to climate change as well as land use change, because there is more time available to change.

2.3.4 Potential evapotranspiration analysis

Making use of climatological potential evapotranspiration values is expected to influence the results because the annual variability is removed. To detect the difference between using constant and variable values for potential evapotranspiration, the influence of *LUC* and *CC* will be calculated twice for the American catchments: with and without variable potential evapotranspiration. The difference between the two points will indicate whether it has been reasonable for the Australia catchments to exclude the variation in potential evapotranspiration, especially because the coefficient of variation appears to be comparable.

3 Results

This chapter consists of three sections. Section 3.1 shows the variables needed for the application of the attribution method and the results of this method. Section 3.2 shows the analyses to detect whether one or more of the different geographical features will explain the variation in the results. Section 3.3 shows the evaluation of the attribution method.

3.1 Attribution method and its application

In this section the core results of the attribution method will be provided. First the trends and slopes in the annual discharge will be presented to be able to cluster the results. After that the split of the time series, including the total measuring length and the length of the pre- and post-change period will be described. Finally the contribution of climate and land use change will be presented.

3.1.1 Trend in annual discharge

The presence of a trend in the annual discharge is one of the motivations for conducting an attribution analysis. This does not mean that only catchments with a significant trend in discharge are included, because the effects of climate and land use change might compensate each other.

81 American and 86 Australian catchments include a significant trend in the annual discharge. The majority of the American catchments discharge trends are positive (74 out of 81) while most trends in Australian catchments are negative (85 out of 86). The presence of a trend will be used to make a distinction between catchments. The remarkable difference between the number of negative and positive trends in the different countries will be discussed later (Chapter 4).

3.1.2 Splitting time series

The method described in section 2.2.3 is applied to the dataset to determine the length and start years of the pre- and post-change period in a consistent way. The length of these two periods extends from 5 to 10 years. The bulk of the American catchments consist of two sequences of ten years of data which is the desired length of the periods. 108 catchments, in particular from Australia, have two periods shorter than ten years (see Table 2).

The total length of the time series varies from 10 years (which is the absolute minimum to fulfil the criteria of two periods of five years) to 77 years. For the American catchments hold that the majority have a length of 50 to 59 years, for the Australian catchments this is 10 to 29 years (see Table 3).

Table 2: Length of pre- and post-change period with the number of American, Australian and total catchments, per length of both periods.

Length of pre- and post-change period (years)	Number of American catchments	Number of Australian catchments	Total number of catchments
5	1	22	23
6	1	12	13
7	1	25	26
8	0	24	24
9	2	20	22
10	260	104	364
Total	**265**	**207**	**472**

Table 3: Total length of the measuring period with the number of American and Australian catchments per class.

Total length (years)	Number of American catchments	Number of Australian catchments
10-19	5	84
20-29	11	68
30-39	26	34
40-49	45	14
50-59	178	4
60-69	0	1
70-79	0	2
Total	**265**	**207**

3.1.3 Contribution of climate and land use change

In this subsection the core results of the attribution method will be presented. The included graphs show the behaviour of the catchments divided in several groups based on statistical tests. The maps indicate the spatial distribution of the catchments.

The results of the attribution method are presented in Figure 4 and Figure 5. The values of *CC* and *LUC* are plotted which indicates the change in streamflow due to climate and land use changes respectively. Each point indicates the attribution of one catchment. In Figure 4 all the catchments are shown in one graph. In Figure 5 the results are shown in separated plots. Each plot includes one group of catchments. The groups are: country (USA and Australia), trend in discharge (positive, negative or not significant) and whether the change in *LUC* and/or *CC* values between the two periods is significant or not based on the Fasano and Franceschini test (see section 2.2.5). This statistical test shows that 61 out of the 81 American catchments and 21 out of the 86 Australian catchments have significantly changed *LUC* and/or *CC* values between the two periods. This gives a total of 12 plots.

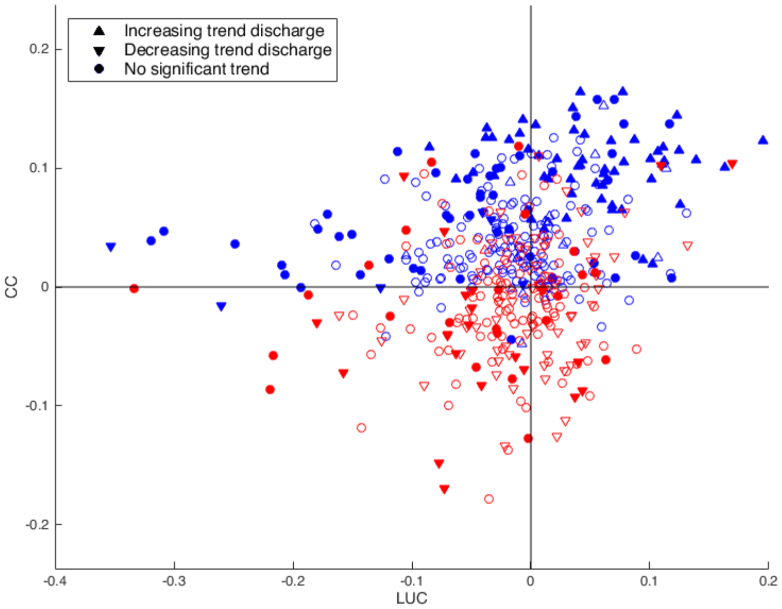

Figure 4: The contribution of climate (y-axis) and land use (x-axis) change for the American (blue) and Australian (red) catchments. The filled symbols indicate a significant change in *LUC* and/or *CC* values between the two periods. Open symbols indicate that this change is not significant.

The difference between the countries, the USA and Australia, is the most obvious one. The American catchments have hardly negative values for *CC*, while many Australian catchments have *CC* values between -0.2 and 0. This indicates that the ratio *P*/*PET* for nearly all the catchments in the USA is increasing, while in Australia it is increasing and decreasing.

The second observation is the trend in discharge. A positive trend in discharge (Figure 5a, d, g, and j) is shown to include catchments with higher values for *CC* than the catchments with a negative trend in discharge (Figure 5b, e, h, and k). The first statement is based on American catchments since only one Australian catchment shows a positive trend in discharge. This is very different for the USA, where nearly all catchments show a positive trend in discharge when a significant trend is present. The group of catchments without a significant trend in discharge (Figure 5c, f, i, and l) are shown to include catchments in a wider range: close to the origin as well as further away and in all directions.

There is also a difference between catchments with and without a significant change in *LUC* and/or *CC* values between the two periods. The catchments with a significant change (Figure 5a, b, c, g, h, and i) are located further from the origin than the catchments without a significant change (Figure 5d, e, f, j, k, and l). This will be further explained at the next page.

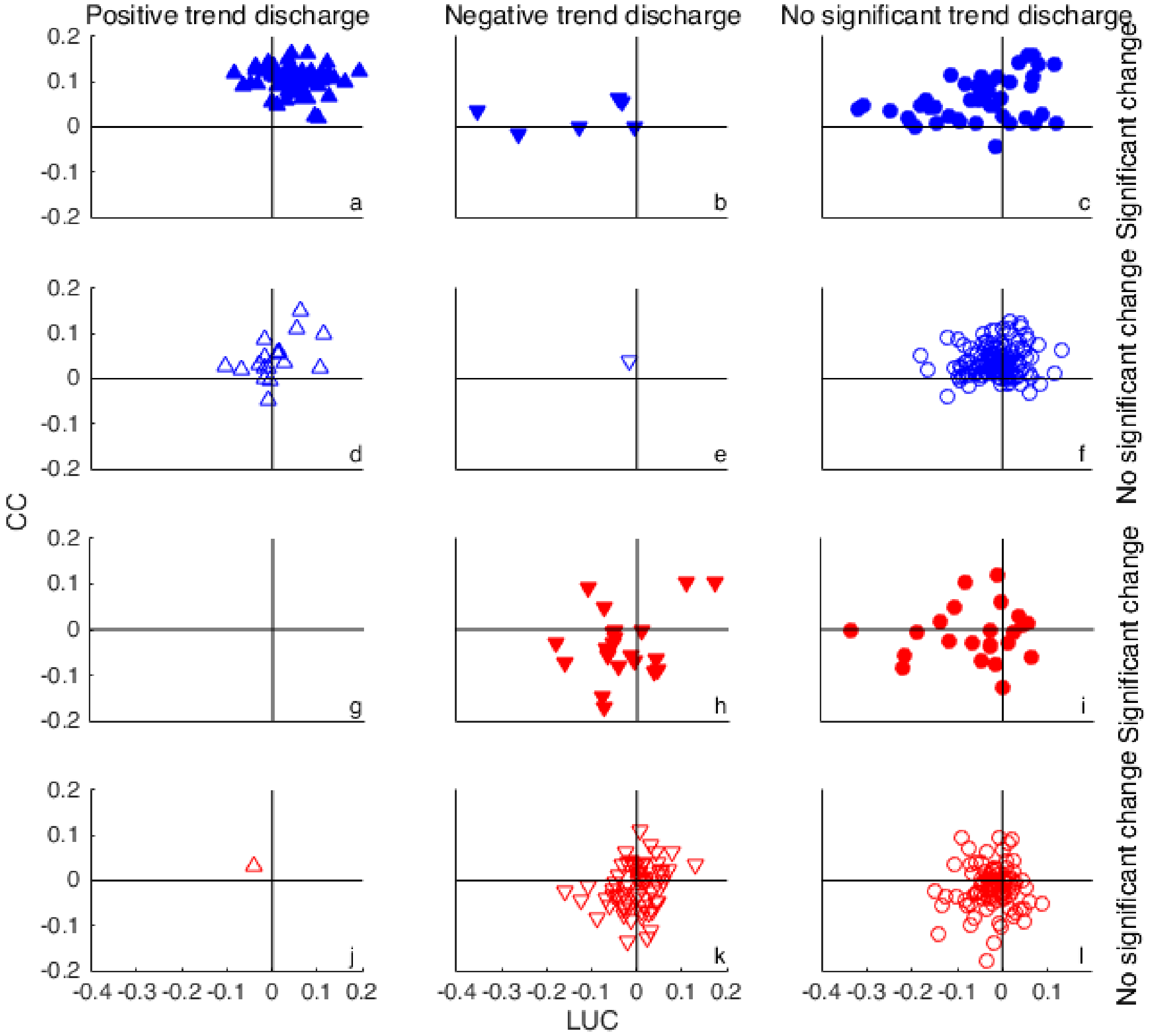

Figure 5: The contribution of climate (y-axis) and land use (x-axis) change for the American (blue) and Australian (red) catchments. The first and third (second and fourth) rows include catchments with (without) a significant change in *LUC* and/or *CC* values between the two periods.

To start with Figure 5a: a trend towards positive *LUC* and *CC* values is present, which means a positive trend in discharge is the result of deforestation (positive *LUC* values) and a wetter climate (positive *CC* values). In Figure 5b and h, a trend toward negative values of *LUC* and *CC* is shown. This means that a negative trend in discharge is the result of afforestation (negative *LUC* values) and a drier climate (negative *CC* values). For the Australian catchments the changing climate is a more important factor for the negative trend in discharge than for the American catchments.

In Figure 5b and h, some catchments are located very close to origin, meaning neither *CC* nor *LUC* are influencing the streamflow while a (negative) trend in discharge is present. However in Figure 6 is shown that the slope of the trend, estimated with Sen's slope estimator (see next subsection for the average slope of the annual discharge), is minimal (smaller than 1 mm/y). The reason for the trend still being significant is that the variation is relatively small and the length relatively long. This makes it easier to detect a trend, despite its flat slope. Besides this also the level of significance to detect a trend in discharge (determined at 95%) plays a role. For some catchments a significant trend in discharge is detected, while this is not the case. In Figure 5h also some positive values for *CC* and *LUC* are shown, which is not expected. Also these decreasing trends in discharge have a smaller slope than 1 mm/year.

In Figure 5c two catchments are located relative far from the origin, while there is no significant trend in discharge detected. This is a result of the very large variation of annual discharge. Large variability in discharge makes it hard to detect a trend while the slope is relatively large. This is also the case for the Australian catchment shown in Figure 5i, located relative far from the origin. Besides the large variability in annual discharge, the length of the measuring period of this catchment is only 11 years. This low number of points makes it even harder to detect a trend in discharge.

Slopes of trends in discharge

The slopes of the annual discharge of catchments with a significant trend in discharge are determined with Sen's slope estimator. The results are shown in Table 4. Positive (negative) values indicate positive (negative) slopes. In Figure 6 the American and Australian catchments with a significant trend in discharge are shown, indicated with the slope.

Table 4: Ranges of Sen's slope estimator (S) with the number of American, Australian and total catchments, per range.

Sen's slope estimator (mm y^{-1})	Number of American catchments	Number of Australian catchments	Total number of catchments
-4<S<-3	1	0	1
-3<S<-2	0	1	1
-2<S<-1	2	4	6
-1<S<0	3	16	19
0<S<1	7	0	7
1<S<2	13	0	13
2<S<3	28	0	28
3<S<4	6	0	6
4<S<5	1	0	1
No significant trend and/or no significant change	204	186	390
Total	**265**	**207**	**472**

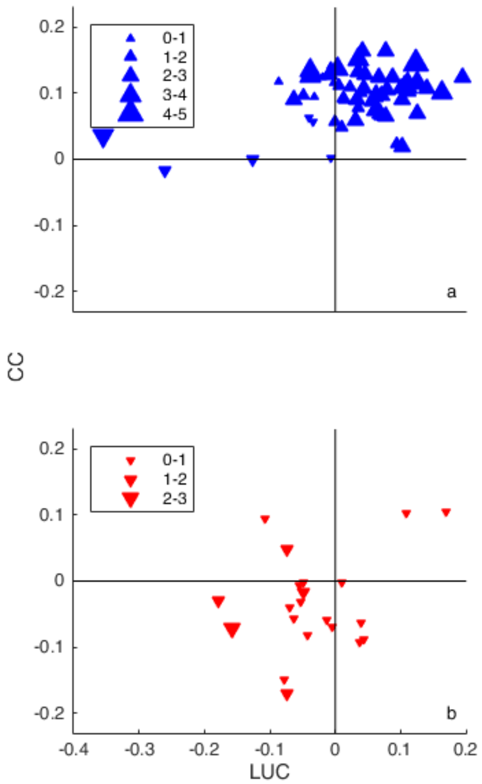

Figure 6: The contribution of climate (y-axis) and land use (x-axis) change for the American (a) and Australian (b) catchments with a significant trend in discharge and a significant change in *LUC* and/or *CC* values between the two periods. The magnitude (estimated with Sen's slope estimator) is shown in mm y^{-1}.

It is shown that American catchments with a slope in discharge higher than 3 mm y^{-1} or lower than -3 mm y^{-1} are further from the origin than catchments with smaller slopes. Besides this, negative slopes tend to have negative values for *LUC* meaning that afforestation had played an important role for decreasing the discharge.

For Australian catchments it is shown that catchments with a negative slope for the discharge smaller than -2 mm y^{-1} are further away from the origin than catchments with a flatter slope.

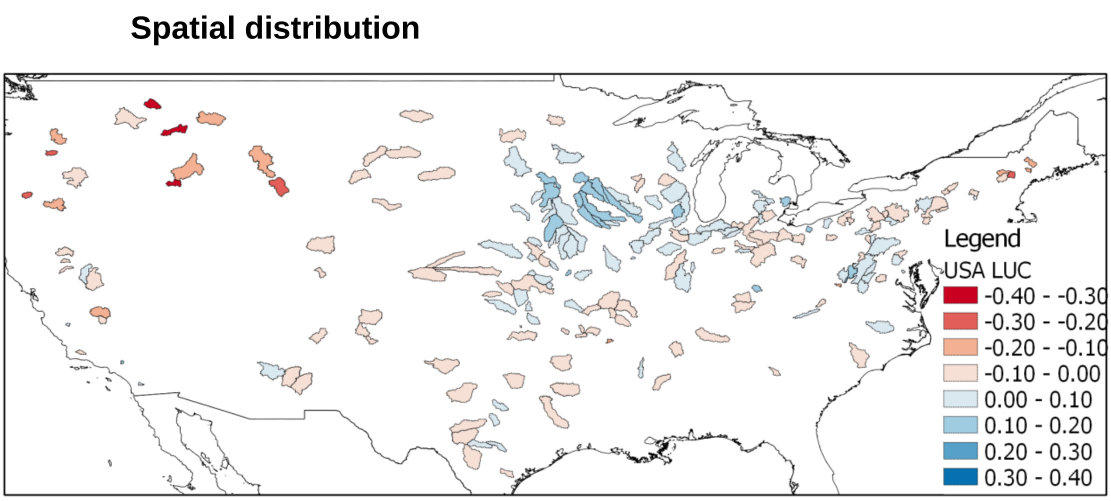

Figure 7: Spatial distribution of *LUC* values of the American catchments.

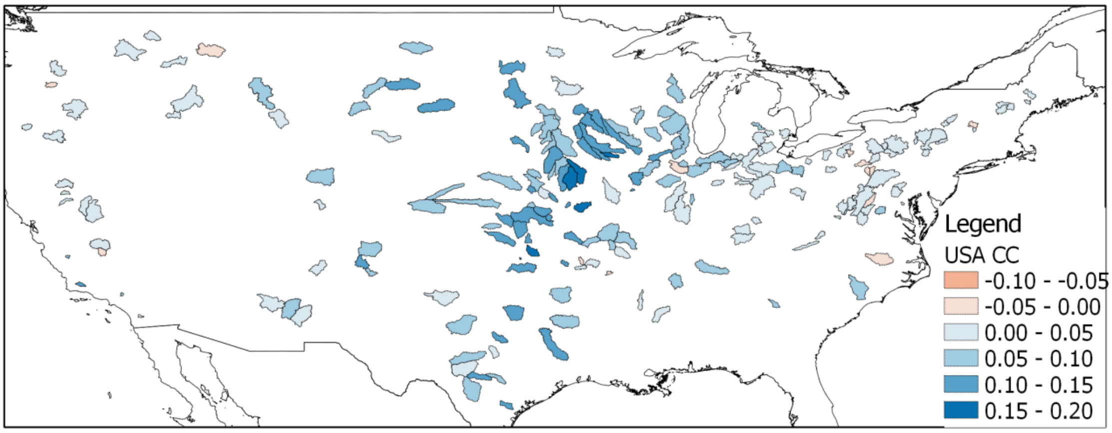

Figure 8: Spatial distribution of *CC* values of the American catchments.

The spatial distribution of the *LUC* and *CC* values of the American catchments is shown in Figure 7 and Figure 8 respectively. In both maps some patterns are detectable. The catchments with the lowest *LUC* values are located in the northwest while the highest values are especially located in the middle north part of the USA. For the *CC* values a horizontal pattern is present. From the west to the middle the *CC* values increase and further to the east the values decrease again.

In Appendix D, the maps of Australia are shown in Figure 17 and Figure 18. A pattern is not detectable for both the *LUC* and *CC* values.

3.2 Geographical features

To further investigate the results, a couple of geographical features are selected to classify the catchments in this section. The different characteristics are: catchment size, historical land use, average catchment slope and climate. Those are described one by one in the following subsections. All of them are assumed to influence the results.

3.2.1 Catchment size

The catchment sizes of all the included catchments range from a few tens of square kilometres to 10,000 square kilometres. A lot of small catchments are in Australia and the larger ones are mainly located in America. A classification is made (Table 5) such that the number of included catchments per class is approximately the same. The classes are used to create Figure 9 with both the American and Australian catchments, based on the contribution of climate and land use change and the catchment sizes.

For the larger American catchments it seems that relative more catchments are indicated to have a significant trend in discharge and a significant change in *LUC* and/or *CC* values. However this is not the case for the Australian catchments. Besides, it is hard to detect a trend in distribution of the catchments, related to the size of it for the American as well as the Australian catchments. The catchments seem to be equally distributed over the ranges of *LUC* and *CC*. The trend which was expected might be lost because of other factors. Catchments in the same area, of which only the size is different, might provide a better explanation.

Table 5: Surface areas with the number of American and Australian catchments (with a significant trend in discharge and a significant change in *LUC* and/or *CC* values between the two periods).

Area (km^2)	Number of American catchments		Number of Australian catchments	
	Significant trend in discharge and significant change in *LUC* and/or *CC* between two periods	All catchments	Significant trend in discharge and significant change in *LUC* and/or *CC* between two periods	All catchments
0-250	1	7	9	81
250-500	1	9	5	52
500-1000	4	33	6	50
1000-2000	10	65	1	24
2000-5000	29	91	0	0
5000-10000	16	60	0	0
Total number of catchments	**61**	**265**	**21**	**207**

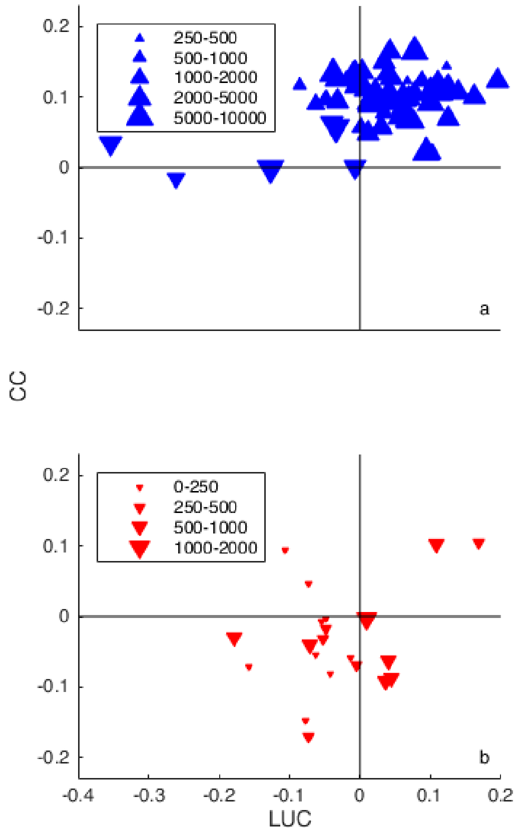

Figure 9: The contribution of climate (y-axis) and land use (x-axis) change for the American (a) and Australian (b) catchments with a significant trend in discharge and a significant change in *LUC* and/or *CC* values between the two periods. The surface area is indicated by symbol sizes.

Overlapping catchments

Table 6: Catchment groups with different levels of (sub-)catchments, including the differences in *LUC* values.

Number of catchment groups with:	Catchments groups in the USA	Catchments groups in Australia
Smaller *LUC* values for the downstream catchments	16	7
Approximately same *LUC* values (± 0.03)	7	3
Smaller *LUC* values for the upstream catchments	14	2
Total	37	12

To exclude variabilities like climate conditions, overlapping catchments are of interest because the most important difference between the catchments is the size of it. In total there are 37 groups of overlapping catchments in the USA and 12 in Australia. The groups consist of at least two catchments, but some of the groups consist of up to six catchments at a maximum of three different levels of sub-catchments.

Table 6 shows numbers of catchment group with different categories. It is expected that most of the catchment groups will belong to the first category which consists of downstream catchments with smaller *LUC* values than the upstream (smaller) catchments. The second category indicates the catchments of which the sub-catchments are consisting of similar *LUC* values. The last one indicates the catchments of which the smaller catchments have smaller values for *LUC*. The latter one is expected to include few catchments.

The American catchments are relative equally distributed over the first and third category. This is in contradiction with the expected distribution. It might be that other (local) factors are important, such as local land use changes within the downstream part of the catchments. However in Australia a more expected distribution is shown. The first category is the one with the most catchments, which support the hypothesis that the *LUC* values reduce when the catchments size increases.

3.2.2 Historical land use

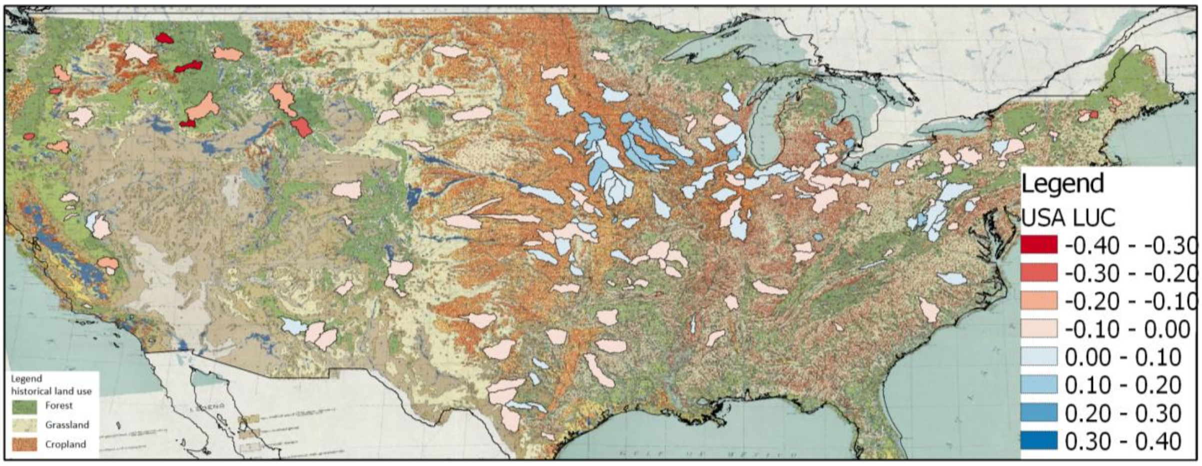

Figure 10: Spatial distribution of *LUC* values of the American catchments, with the historical land use of 1950.

The land use in 1950 in the USA (Marschner, 1950) is shown in Figure 10. The pattern of the spatial distribution of *LUC* is to some extent related to the pattern as shown in the historical land use. In the forests the *LUC* values are negative and in cropland the values are positive. This indicates that in the forests afforestation had taken place and in the croplands deforestation. In this case afforestation might also include: increased forages and conservation cover and deforestation might also include: conservation tillage and removal of perennials. In the middle part of the USA, where grassland is present the *LUC* values are close to zero, indicating that land use did not change.

For Australia it is more difficult to relate the historical land use to *LUC* values because the pattern in *LUC* is less clear and the resolution of the map (Australia and New Zealand Land Use, Agriculture and Minerals, 1962) is not as high as the map of the USA. The Australian map is shown in Appendix D, Figure 19.

It is clear that a relation between the historical land use and the *LUC* values exists for the American catchments. However the relation found indicates that the forest becomes denser and the cropland becomes less dense. The last one is hard to believe because most farming activities have increased. However this could have taken place in combination with deforestation, but evidence is not present for this explanation. Besides, the relation found is not supported by the Australian catchments.

3.2.3 Average catchment slope

The average catchment slopes are used to detect a relation between *LUC*, *CC*, or *R* and these slopes. It is reasonable to believe a relation is present between these variables because the slope influences the water storage capacity of a catchment: higher slopes will reduce it. This means that catchments with high slopes should be more sensitive to changes (Bruijnzeel, 2004).

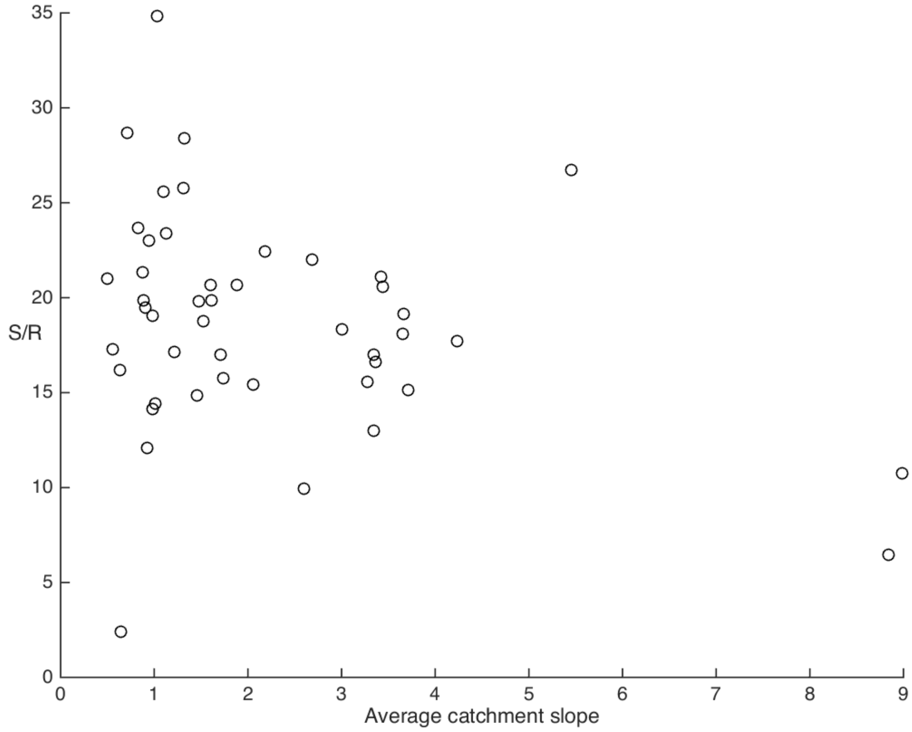

Figure 11: The average catchment slope in degrees (x-axis) related to the ratio of Sen's slope estimator (S) and the resultant length (R) in mm yr^{-1} (y-axis) for American catchments with a significant trend in discharge and a significant change in *LUC* and/or *CC* values between the two periods.

The slope analysis is only done for the American catchments because the presence of high resolution slope data (1 arc-second) for this part of the world. The data is available from the U.S. Geological Survey (USGS, 2015). From this data the average catchment slopes are derived. For some (15 out of 61) catchments the data were incomplete so the average slope could not be calculated.

To be able to compare the catchments in a reasonable way to each other, Sen's slope estimator is used to estimate the annual change in discharge. This parameter divided by *LUC*, *CC*, or *R* relates the annual change in discharge of a catchment to the three different outputs. In Figure 11 this is shown for the *R* values. *LUC* and *CC* are not included because these ratios do not provide more information.

A clear trend as expected is not shown. If a trend is present then it is a decreasing one instead of an increasing trend. This might be the result of only including relatively flat catchments. Perhaps when more catchments with a slope steeper than 4 degrees are included, a trend is shown. Also for the *LUC* and *CC* values no clear trend is present.

3.2.4 Climate

Climate might also be an important factor to influence the results of the attribution method. The climate map of Peel et al. (2007) is used to present the maps of the USA (Figure 12) and Australia (Appendix D, Figure 20). The variability of climates in the USA is larger for the catchments included in this study than the variability in Australia. However in none of the countries, the pattern shown for the *CC* values can be explained by the climate conditions. For example the *CC* values in the USA are showing a horizontal pattern. The climate in the eastern half of the USA, however, shows a vertical pattern. So the climate classification of Köppen is not the best way of relating the climate conditions to the *CC* values. The aridity index might provide more insight.

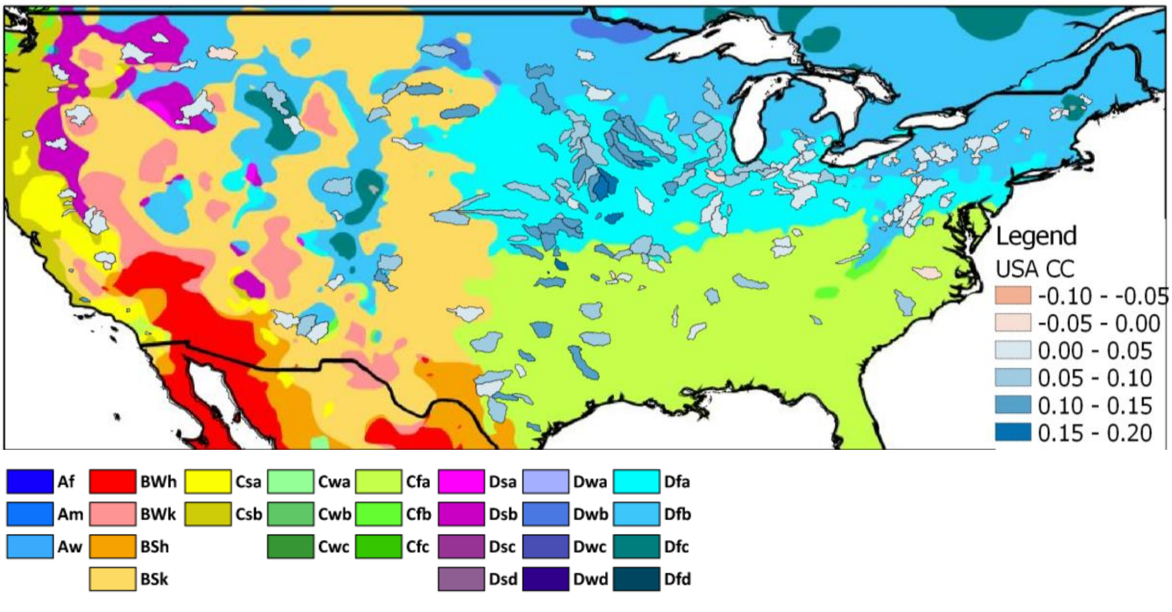

Figure 12: Spatial distribution of the *CC* values of the American catchments, with the Köppen climate classification.

Aridity index

Besides the Köppen climate classification there are other ways to analyse the influence of the climate. The aridity index is an example of a parameter, related to the climate, which should have a relation with the results because it is included in the attribution method to calculate the values *LUC* and *CC*. The relations between the aridity index and the values *LUC*, *CC* and *R* are calculated in the same way as is done in section 3.2.3 for the slope analysis, by dividing Sen's slope estimator by *LUC*, *CC* or *R*. Only the figures including *S* over *R* are included in this report because the other graphs do not provide additional insight. The relation for the American catchments is shown in Figure 13 and for the Australian ones in Figure 14. A semi logarithmic plot is used because this increases the readability of the figures.

The American and Australian catchments are showing comparable results when looking to corresponding aridity indices. However the trend is clearer for the American catchments because catchments are spread over a wider range of the aridity index. This trend is directed downward by increasing aridity index, as shown in Figure 13. The drawn trend line is exponential (semi-log graph paper) and the coefficient of determination is 0.565, meaning that 56.5% of the variability is accounted by this trend. This trend can be explained by the fact that wet catchments (low aridity indices) have more water stored, which means that there is a larger opportunity for changes. In dry catchments less water is available, so a change in this small amount of water is more difficult to occur. Besides, it also seems that the storage capacity of a catchment is not related to the aridity index, because this should have led to an increasing trend instead.

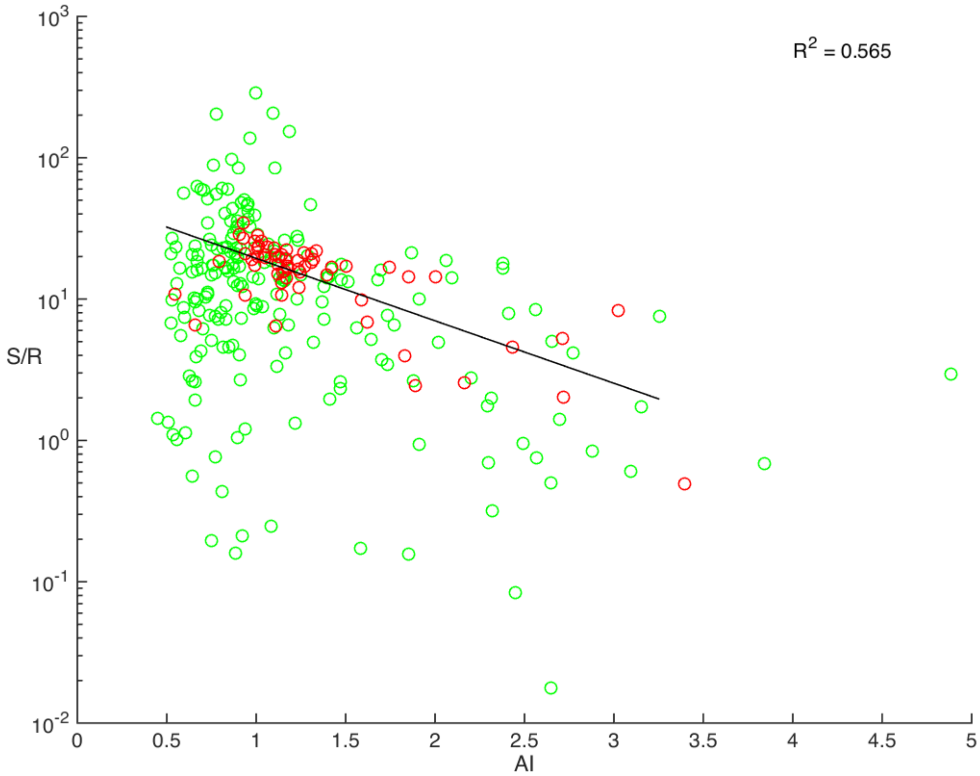

Figure 13: The aridity index (AI) (x-axis) related to the ratio of Sen's slope estimator (S) and the resultant length (R) mm yr^{-1} (y-axis) for American catchments. Red indicates catchments with a significant trend in discharge and a significant change in *LUC* and/or *CC* values between the two periods and green indicates the other catchments. The exponential (black) trend line is based on the red points and the coefficient of determination (R^2) is shown.

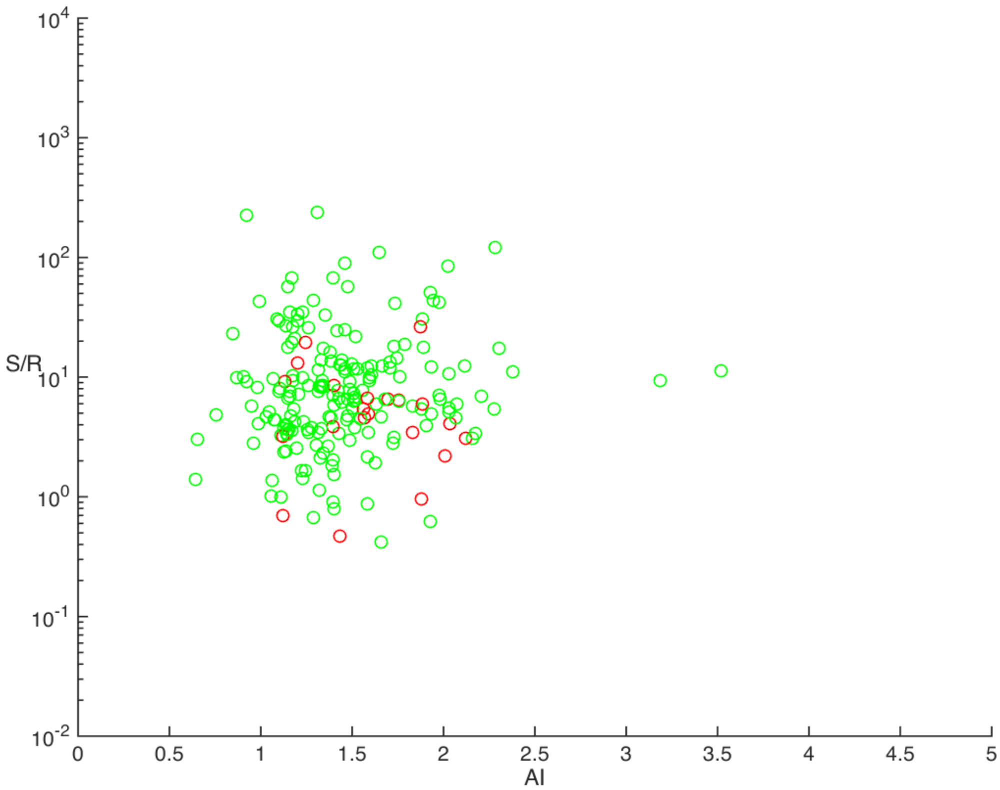

Figure 14: The aridity index (AI) (x-axis) related to the ratio of Sen's slope estimator (S) and the resultant length (R) mm yr^{-1} (y-axis) for Australian catchments. Red indicates catchments with a significant trend in discharge and significant change in *LUC* and/or *CC* values between the two periods and green are the other catchments.

3.3 Evaluation of attribution method

The evaluation results consist of four parts and these are described in one subsection each. This includes the evaluation by calculating the presence of trends in potential evapotranspiration and precipitation (and discharge). This will be linked to the values for *CC* (and *LUC*). Second the catchments with the highest, lowest or closest to zero values for *LUC* will be compared with land use changes which have taken place within the measuring period and which are documented. The third part is the evaluation of the effect of the measuring length on the results of the attribution method. The last part is about the effect of the presence and absence of variable potential evapotranspiration on the results of the attribution method.

3.3.1 Trends potential evapotranspiration and precipitation

Another way to interpret the values of *CC* and *LUC* is by comparing the trends in *PET* and *P* (and *Q*), if a significant trend in discharge is present for a certain catchment (81 American catchments and 86 Australian catchments). There are two situations possible for each catchment: positive or negative values for *CC* and positive or negative values for *LUC*, meaning that each catchment belongs to two situations, one related to its value of *CC* and the other related to its value of *LUC*. Positive values for *LUC* (deforestation) should cause a positive trend in discharge. While negative values (afforestation) should cause a negative trend in discharge. Positive values for *CC* (increase of *P*/*PET* ratio) should be caused by a significant positive trend in *P* amounts and/or a significant negative trend in *PET* amounts. While negative values for *CC* (decrease of *P*/*PET* ratio) should be caused by a significant negative trend in *P* amounts and/or a significant positive trend in *PET* amounts. The results are shown in Table 7.

Table 7: Number of American and Australian catchments with trends in *P*, *PET* and/or *Q* as expected (and the percentages of catchments behaving as expected) due to the presence of positive or negative values of *LUC* and *CC*.

Condi-tions	Expected trend	Number of American catchments with a significant trend in discharge				Number of Australian catchments with a significant trend in discharge			
		Expected trend *P* and/or *PET*	Expected trend *Q*	Out of	Expected (%)	Expected trend *P* and/or *PET*	Expected trend *Q*	Out of	Expected (%)
***LUC*>0**	Q increase	-	53	53	100	-	0	41	0
***LUC*<0**	Q decrease	-	7	28	25	-	44	45	98
***CC*>0**	P/PET increase	53	-	76	70	0	-	30	0
***CC*<0**	P/PET decrease	2	-	5	40	47	-	56	84

For the American catchments it is shown that the positive values of *LUC* and *CC* are quite well explained by the presence and direction of significant trends in *P*, *PET* and *Q* (100% and 70% of the catchments included). However, the negative values are less well explained by it (25% and 40% of the catchments included). This is the other way around for the Australian catchments: for the positive values of *LUC* and *CC* the percentages are 0% and 0% and for the negative 98% and 84%.

Two reasons explain the American catchments in the *CC* categories which are not behaving as expected. The first one is whether or not a trend in discharge is present does not necessarily mean that the slope of this trend (estimated with Sen's slope estimator) is steep or flat. The slope can still be relatively steep, only not significant due to the Mann Kendall test. Secondly, a significant trend in a ratio does not necessarily be the result of a trend in one of the parameters included in the ratio. For example a positive *CC* value is caused by an increase of *P*/*PET* ratio. In Table 7 is only indicated whether or not the individual variables consist of a significant trend.

For the Australian catchments the same reasons apply as for the American catchments. However two additional reasons are present. The first one is that nearly all catchments included in the categories with positive *LUC* or *CC* values, are not significantly changed in *LUC* and/or *CC* values between the two periods. Including only these catchments does not change the other percentages, neither the American catchments. The second reason is the absence of any trends in *PET* for Australian catchments, so these can also not be detected by looking at an increase or decrease in *P*/*PET* ratio.

The category with a low percentage for expected behaviour, but not explained by any of the above mentioned reasons is the one with negative *LUC* values for American catchments. It is not known why this percentage is low (25%) in particular because most of these catchments have significantly changed *LUC* and/or *CC* values between the two periods.

3.3.2 Documented land use changes

The three different categories of catchments which have been used to find documented land use changes will each be evaluated separately. In Appendix E, Table 9 a summary is shown of the documented land use change for each of the fifteen selected catchments.

The first category includes the catchments with the lowest (negative) *LUC* values. This means that afforestation should have taken place. For three of the five investigated catchments holds that documented land use change had taken place. However this mostly contains logging activities and forest fires. For two of these three catchments is described that forest had been regenerated over the measuring period.

The second category includes the catchments with the highest (positive) *LUC* values. This means that deforestation should have taken place. For three of the five catchments is documented information available. Two of the catchments have improved the crop production during the measuring period.

However it is not mentioned that it is at the expense of forests. In the third catchment logging activities took place from 1800, but this is found in a description about a larger region than the catchment only.

The last category includes the catchments with the lowest absolute *LUC* values. This means that land use change should not have taken place. For all of the five catchments holds that reports about the catchments do not mention anything about any kind of land use change.

It must be noted that not for every catchment information is available. Especially for the Australian catchments it is hard to find documented information about the historical land use of the catchments. For the American catchments more information is available. So it can be concluded that information about land use change is only present when *LUC* values are high or low, not when they are close to zero. However the land use change as it is documented is not always as expected given the results of the attribution method.

3.3.3 Length of measuring period

A classification based on the total length of the measuring period is made, see Table 8. In this table only catchments with a significant trend in discharge and a significant change in *LUC* and/or *CC* between the two periods are included. The classes are up to 59 years, as shown. The three Australian catchments with a longer measuring period than 59 years were excluded because the trend in discharge is not significant or the change in *LUC* and/or *CC* values between the two periods is not significant. Figure 15 shows the length of the measuring period of the included American and Australian catchments.

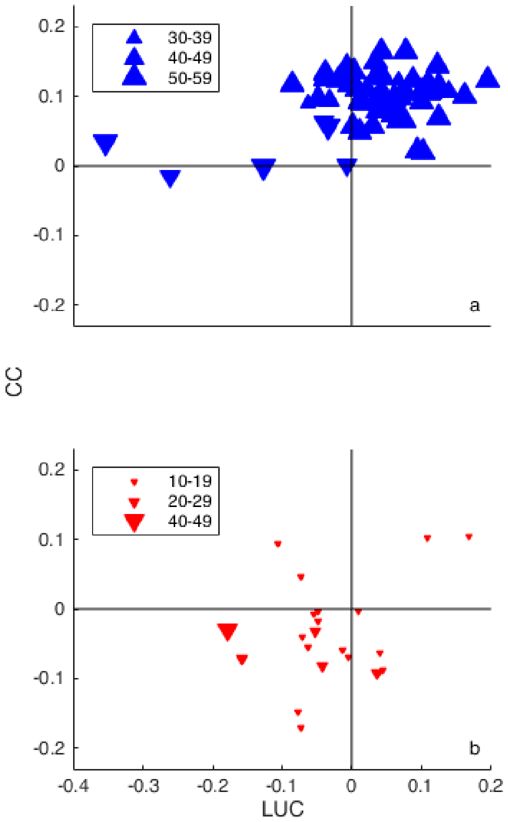

Figure 15: The contribution of climate (y-axis) and land use (x-axis) change for the American (a) and Australian (b) catchments with a significant trend in discharge and a significant change in *LUC* and/or *CC* values between the two periods. The length of the total measuring period is indicated by symbol sizes.

Table 8: Number of American and Australian catchments with a significant trend in discharge and a significant change in *LUC* and/or *CC* values between the two periods per class of total length of measuring period.

Total length (years)	Number of American catchments	Number of Australian catchments
10-19	0	16
20-29	0	4
30-39	2	0
40-49	8	1
50-59	51	0
Total number of catchments	**61**	**21**

Figure 15 does not show a clear pattern in distribution of the length of the measuring period for both countries. This is partly due to the fact that nearly all catchments have a measuring period length of 50 to 59 years and 10 to 19 years for the American and Australian catchments respectively. It is of course expected that a longer time between the two measuring periods will provide the system more time to change.

3.3.4 Potential evapotranspiration analysis

An interesting difference between the datasets of the two countries is how the *PET* values have been obtained, which might have led to different results for Australia (using climatological *PET* values) and the USA (using estimated daily *PET* values). Figure 16 shows the differences between the results of the attribution method, calculated with and without variable *PET* values. The *LUC* and *CC* values calculated using variable *PET* is subtracted from the *LUC* and *CC* values calculated using climatological *PET* values.

It is shown that most of the catchments have a negative difference for *CC* and positive differences for *LUC*. This means that using constant *PET* values, instead of variable, will lead to lower *CC* values and higher *LUC* values. One can also conclude that there is less deforestation and less decrease in *P*/*PET* ratio than estimated with variable *PET* values. The differences are relative small, only up to 0.04 for both *LUC* and *CC* values.

The Cfa climate of the Köppen climate classification is used to compare the USA with Australia in a way such that the conditions are more comparable, because in both countries quite a lot of catchments are present in this climate class. The distribution of this climate is comparable to the other climates so it seems that the climate conditions do not influence the difference of using daily and climatological *PET* values.

Despite there is a difference in using variable and constant *PET* values, the values of *LUC* and *CC* do not change a lot and nearly all in the same directions. This means that the results of studied catchments with constant *PET* values (the Australian catchments) are still useful, as long as it is taken into account and the coefficient of variation of *PET* is not higher than 0.05. When this is higher, it should be investigated to what extent the *LUC* and *CC* values change, regarding the larger variation in *PET* values.

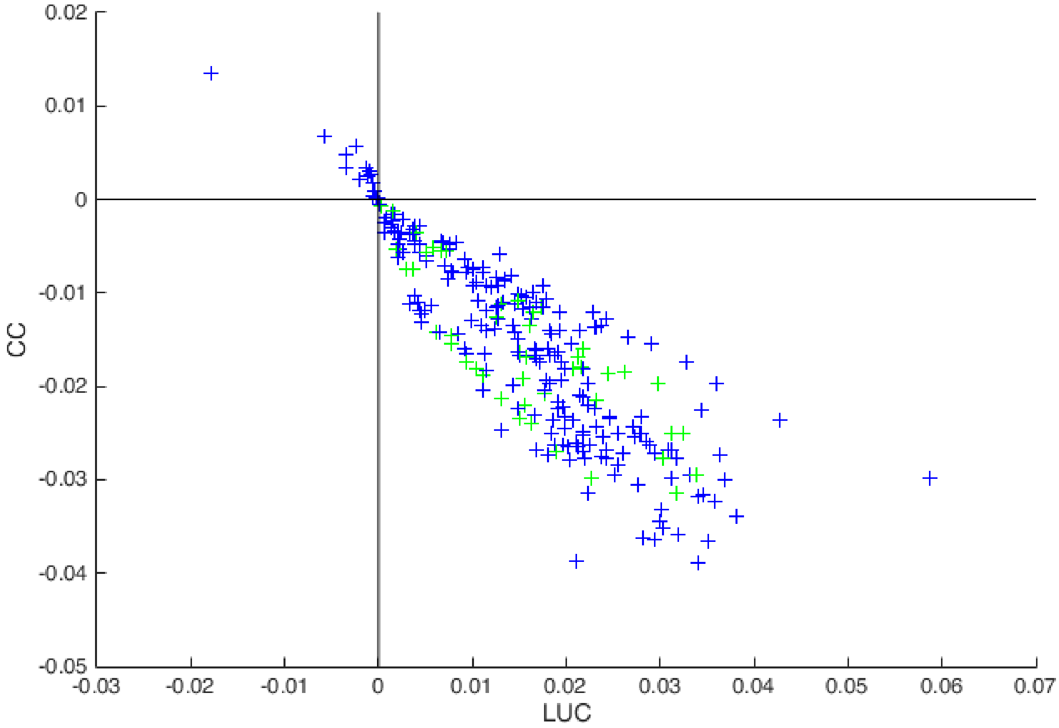

Figure 16: The differences in contribution of climate (y-axis) and land use (x-axis) change for all the American catchments between calculating with variable and constant potential evapotranspiration values. Green indicates a Cfa climate, and blue the other climates.

4 Discussion

This chapter is structured as follows. First some results of this study are compared with a large sample attribution study for American catchments in section 4.1. After that the potential of the used attribution method is described in section 4.2 and its limitations in section 4.3. In section 4.4, a generalisation is made of the performance of the used attribution method.

4.1 Comparison with study on catchments in United States

To be able to compare the results as accurately as possible, the large sample study of Wang & Hejazi (2011) is considered, because it has used the MOPEX dataset as well. This dataset consists of a total of 431 American catchments. Two topics are compared, because these have been taken into account in both studies in a comparable way: the spatial pattern of the results in the USA and the influence of the aridity index on the results. These will be described in the next subsections.

4.1.1 Spatial pattern of results in the USA

Comparing the results is done by visually comparing the spatial distribution of the contribution of climate and land use change. The higher (positive) values of *CC* are in both studies located in the middle part of the USA. While negative values are especially located in the north-western part. The highest (positive) *LUC* values are located in the middle north in both studies. However the lowest (negative) values are located in the middle part of the USA according to Wang & Hejazi (2011). This is not the case for the results of this study. The lowest values of LUC are located in the north-western part.

For comparing these studies, it is important to point out the differences in methods. First the way of selecting catchments is different. Wang & Hejazi (2011) selected the study catchments based on the amount of missing data. For their research, 413 of the 431 MOPEX catchments consist of enough data are included. This is done regardless the quality of data, which might have led to less reliable results.

Besides this Wang & Hejazi (2011) have used a different way of splitting the time series. They have selected a change point (around 1970 for every catchment) at which the streamflow is assumed to change. This is in line with the documented increase in streamflow they have found around this point. This had resulted in two periods: 1948-1970 and 1971-2003. These two periods are used for every catchment passing the data availability criterion. This is different from the splitting method used in this study, where shorter periods have been used. The advantage of using longer periods is that the climate variability has been removed to a larger extent, because of averaging over a longer period. However a longer period between the pre- and post-change period will lead to a larger difference (*R*), assuming that the change is not an abrupt one. In addition, Wang & Hejazi (2011) have based their change point on the presence of one dry year, which had occurred in the USA around 1970. However it is not sure that this had led to the largest change in annual discharge over all the considered American catchments, so it seems to be an arbitrary way of splitting the time series.

The last difference is the way of applying the attribution method. The attribution method itself is in both cases based on the Budyko hypothesis to quantify the impact of climate and land use change on mean annual streamflow. The difference, however, is the way of using it. Wang & Hejazi (2011) have used equations to estimate the Budyko curve. A change in this curve is assumed to be caused by climate change, whereas changes from the original Budyko curve to another one are assumed to be caused by human influence (e.g. land use change). The equations used to calculate the Budyko curve are single-parameter equations. This parameter is calibrated on the first period (1948-1970). It is difficult to determine which method performs better than the other because advantages and disadvantages can be found for both methods. The Budyko curve has been used more often so there is more knowledge about the method. However, using the method of Tomer and Schilling is less time consuming because there is no need for calibration.

All these differences in approach might be reasons that differences in spatial pattern have occurred. It is not clear which difference is the main reason for the differences in results, nor which of both studies gives more appropriate results. A comparison regarding the aridity index might provide more insight.

4.1.2 Influence of the aridity index on the results

For comparing the aridity index, the study of Wang & Hejazi (2011) is used again. They take all catchments into account in their study if the data are present. For this reason the influence of the aridity index will be compared with all the American catchments included in this study (265), not only catchments with significant trends in discharge and a significant change in *LUC* and/or *CC* values between the two periods.

In the study of Wang & Hejazi (2011) a very clear relation between climate and human induced streamflow changes (in mm) versus the aridity index is present. For both relations an increasing trend is shown for an increasing aridity index. Based on these observations they conclude that arid regions are more vulnerable for climate and land use changes impacts on streamflow than wet regions.

Figure 13 shows the relation between the aridity index and the *S*/*R* ratios. This ratio is used because this makes the catchments comparable to each other, due to different ratios of changes in streamflow. This is done in another way in the study of Wang & Hejazi (2011). They used absolute values of change in discharge (in mm) related to climate or land use change. This makes comparing the studies somewhat harder, because Wang & Hejazi (2011) do not calculate the proportions of the contributions of *LUC* and *CC* values related to the observed change in streamflow. Both the influences of land use and climate change might be high, but cancel each other such that the change in streamflow is minimal. Besides, using absolute values for the change in streamflow due to climate change and land use change limits the possibility to check whether the change in streamflow in arid catchments is less than in dry catchments, because comparing the catchments to each other is hard using only these values.

However presenting *R* values instead of *CC* and *LUC* should not make a big difference in this case. *R* is just a way of combining *CC* and *LUC*, which gives a trend in the same direction as *CC* and *LUC* do, because they both show a negative trend. Figure 13 shows a decreasing trend in *S*/*R* ratio, which means that the sensitivity of arid catchments for changes is less than for wet catchments. This might be the reason of the amount of available water which is less in dry regions than in wet regions, leading to fewer opportunities for the system to change. This seems to be the opposite as Wang & Hejazi (2011) concluded, but can be related to the absolute contributions of climate and land use change which they use, which does not present the sensitivity of catchments to changes.

4.2 Potential of attribution method

An interesting potential of the used attribution method is that it is applicable to a large sample of catchments, however some adaptions are needed. The method of Tomer and Schilling has been adapted several times before for different purposes (Renner et al., 2014 and Marhaento et al., in press). Three extensions are needed in order to apply it at a large sample set of catchments. The first one is the detection of a significant trend in discharge, the second one is the presentation of results (e.g. in *LUC* and *CC* values) and the third one is the distinction between catchments with and without a significant difference in excess water and energy between the two periods. These are described in the first subsection. The second sub-section is about the potential to use climatological values for potential evapotranspiration instead of daily values.

4.2.1 Extensions for large sample set application

The first extension is needed to discover whether or not a significant trend in discharge is present. A change in annual discharge is the reason for applying an attribution method to a certain catchment. Marhaento et al. (in press) applied some statistical tests to get insight in an Indonesian catchment to which they applied the attribution method. The same tests (Mann Kendall test and Sen's slope estimator) are used in this study to detect a significant trend in discharge and determine the slope of it. In this way further investigation of the results of a large sample set of catchments is possible by also taking into account the presence of a significant trend and its slope: a distinction can be made between catchments with and without a significant trend in discharge. In addition the values for Sen's slope estimator are used in this study to compare different catchments to each other. In this way the change in streamflow can be related to other parameters, such as the aridity index and the average catchment slope.

The second extension is about the outcome of the method. Marhaento et al. (in press) did work to present the results in percentages of the contributions of climate and land use change. This, however, causes information to be lost. The direction of change is not clear anymore, so this is included in the way of calculating θ, *LUC* and *CC* to be able to apply the method at a large sample set of catchments. Calculating percentages of the contributions of climate and land use change is still possible, but this limits the information included in the values again. For this reason this is not done in this study.

The third extension is the distinction between catchments with and without a significant difference in excess water and energy between the two periods. This is related to the resultant length (*R*), but not only dependent on this value. Introducing a threshold seems to be the most logical step to solve this. However this is not completely correct because it will not take the distribution into account. To be specific the excess of water and energy are averages over five to ten points (one point for each year included in the pre- and post-change period). Whether or not these two sets of points are different from each other, is determined by introducing a statistical test: the Fasano and Franceschini test as described in this study. This distinction is used to be able to evaluate catchments with and without a significant change in *LUC* and/or *CC* values between the two periods separately.

4.2.2 Climatological potential evapotranspiration

The Australian catchments were selected while there were no data available to calculate daily values of *PET*. The reason for still including these catchments was because Peel et al. (2000) mentioned that the coefficient of variation of *PET* is low enough to only consider climatological values. However the coefficient of variation of *PET* of the American catchments is comparable to the coefficient of variation of *PET* of the Australian catchments. This was the reason for applying the attribution method to the catchments in the USA by making use of climatological *PET* values too. Interesting enough, although a clear difference is shown between the two ways of calculating *LUC* and *CC*, the directions of change are the same. Using constant *PET* values, instead of variable, will lead to lower *CC* values and higher *LUC* values. This means that using climatological *PET* values is possible, as long as it is considered that the pattern of *LUC* and *CC* values is shifted, and only when the coefficient of variation is not higher than 0.05. For higher values additional studies should be necessary.

4.3 Limitations of attribution method

The limitations of the used attribution method are described in this section. First the main important assumptions of the method and their consequences for the results are described. After that the effects of including the aridity index in the calculation method are described.

4.3.1 Assumptions

There are two basic assumptions in the method of Tomer and Schilling to attribute changes in streamflow to climate and land use changes. The first one is that land use changes will affect *ET*, and the second one is that climate change will affect *P* and/or *PET*. This results in changes in a certain direction of P_{ex} and E_{ex}, which can be interpreted as climate and land use related impacts on streamflow. The basic assumptions, however, are not completely correct. The influence of climate change on *ET* is not equal to zero, especially when the catchment surface area increases. At regional scale this might be true, but the more the climate changes, the more *ET* will change in the same direction as *PET* changes (Blöschl et al., 2007).

Renner et al. (2014) applied the attribution method in Germany and found some land use related anomalies in sub-catchments where no deforestation or other land use changes have been detected. The above mentioned assumption might have led to an overestimation of *LUC* values and underestimation of *CC* values.

Another assumption made to simplify the water balance is that changes in water storage can be neglected. There is however, no evidence that these changes are indeed small. In most of the catchments this would be reasonable, because hydrological years are considered, but there still might be cases where changes in water storage are not negligible and thus influence the results.

4.3.2 Aridity index

The addition Renner et al. (2014) made to the attribution method of Tomer and Schilling seems promising. They extended the range of aridity indices to which the method is applicable, by adding this index to the attribution method. However the performance is not clear. The results of *LUC*, *CC* and *R* related to the aridity index are quite different from the results of Wang & Hejazi (2011), but comparing the results is hard because of their way to present the results (see section 4.1.2).

4.4 Generalisation

The used attribution method is applicable to every catchment, as long as time series of daily data of discharge, precipitation and potential evapotranspiration are available for a period of at least ten years. A change point or trend in the time series of annual discharge is needed to attribute the change in streamflow to climate and land use change. It is also important that there is knowledge about the change in water storage. The change in water storage is neglected in this study to be able to calculate the actual evapotranspiration. The total water storage in a catchment might for example be obtained from remote sensing products (i.e. Gravity Recovery and Climate Experiment), which leads to more accurate values of the actual evapotranspiration. This will improve the reliability of the results.

It is expected that similar catchments will provide similar results. Whether or not catchments are similar depends on: the location, the aridity and the historical land use. It is also expected that it depends on the water storage capacity of the catchment. The higher the storage capacity the less sensitive the catchment is to changes. This statement should be validated with some in depth studies to a couple of catchments.

5 Conclusions and recommendations

The objective and the research questions are answered in this chapter. The objective of this study is to apply a non-modelling attribution method to attribute changes in streamflow to climate change and land use change to a large sample set of catchments in different parts of the world and to evaluate the used method.

The research questions are firstly answered in section 5.1, and subsequently the objective is considered as well. In section 5.2 recommendations are made.

5.1 Conclusions

1. *What is the attribution of streamflow changes to climate change and land use change for each of the catchments?*

Two datasets are considered in this study: the MOPEX dataset (American catchments) and an Australian dataset. 472 catchments were selected from these two datasets.

If a positive (negative) significant trend in annual discharge is present and the change of *LUC* and/or *CC* values between the two periods is significant, then this is caused by deforestation (afforestation) and a wetter (drier) climate in most cases. When no significant trend in annual discharge is present, the results are spread over a wider range. For catchments without a significant change in *LUC* and/or *CC* values between the two periods hold that they have smaller values for both *LUC* and *CC*. Some catchments do not meet the first statement. For these catchments hold that the slope of the trend in annual discharge is flat while the trend is still significant, or that the slope is steep while there is no significant trend.

2. *Which geographical features can explain the results from the attribution method?*

In the USA a clear spatial pattern is visible when looking at the *CC* values. Catchments further inland, are more influenced by climate changes than catchments near the oceans. A reason for this might be the dampening effect of the ocean, which reduces the climate induced changes. In Australia all studied catchments are located near the coast, which made a comparison of these catchments impossible.

The aridity index is an important parameter which influences the results. The drier the conditions the less sensitive the catchment is for changes in streamflow due to climate and land use changes. In these catchments less water is available which might be the reason for being less sensitive. Historical land use is an important indicator for the direction of *LUC* change. Deforestation is the main driver of the changes in streamflow when agricultural activities took place during the starting period of the measurements. Afforestation is the main driver when forest was the main land use in the past in the USA.

Other geographical features which were taken into account in this study, but could not explain the results are the average catchment slope, the climate conditions based on the Köppen climate classification and the catchment size. It should be noted that the average catchment slope was expected to influence the results, because it influences the water storage capacity. Steeper average slopes reduce the storage capacity and these catchments are thus expected to be more sensitive to changes. However the average slopes found in this study are quite flat (most of them up to 4 degrees), so perhaps including catchments with steeper average slopes will support this assumption.

3. *What is the performance of the attribution method?*

The performance of the attribution method is evaluated based on the trends in discharge, precipitation and evapotranspiration and based on documented land use changes. The trends support quite well the *LUC* and *CC* values especially when only considering catchments with a significant change in *LUC* and/or *CC* values between the two periods. This means that deforestation (afforestation) as a result of the attribution method caused a positive (negative) trend in annual discharge. It also means that a wetter (drier) climate as a result of the attribution method went along with an increasing (decreasing) trend in annual precipitation and/or a decreasing (increasing) trend in annual potential evapotranspiration. The documented land use changes are in particular present for catchments of which the *LUC* values are high or low. For catchments with *LUC* values close to zero no documented land use changes were present. Those are convincing results, however for one of the fifteen catchments in total the type of documented land use change was not supporting the direction indicated by the *LUC* value.

Due to the assumptions made in the method that climate change influences the potential evapotranspiration, but not the actual evapotranspiration, it is reasonable to believe that the *LUC* values are overestimated and the *CC* values are underestimated on average. Besides, it is not clear whether it is reasonable to neglect changes in water storage (e.g. groundwater losses) for all of the catchments.

The attribution method seems to provide reasonable results when using climatological *PET* values at least when the coefficient of variation is smaller than 0.05. Still, it is important to know whether or not climatological *PET* values have been used, because it will result in lower *CC* values and higher *LUC* values.

5.2 Recommendations

The results of this study can be used by the water managers of the studied catchments to obtain the reason of a change in streamflow in the past. This can be climate change, land use change or both. With the results of this study the managers will also be able to assess more precisely to what extent the streamflow will change as a result of some future land use changes, especially when they are able to relate it to a land use change in the past which is comparable. For water managers of other catchments this method can be applied at their catchment as long as the needed data are available. In this way they will also be able to obtain insight in the reason of changes in streamflow.

To be able to validate the method of Tomer and Schilling it is important that some individual catchments will be studied in depth. In this way more effort could be done in obtaining data which might have influenced the results. Besides validating the method, this will also provide more insight in the attribution of changes in streamflow to climate and land use change. Parameters to be included in such studies are: the presence of aquifers and their depth and soil moisture. These are expected to influence the water storage capacity of catchments which influences the sensitivity of changes in streamflow for climate and land use changes. Also variables such as deep groundwater losses and surface water storage changes should be included, to determine whether or not it is reasonable to neglect these. This might for example be obtained from remote sensing products which can also be used for validating the *LUC* values by estimating the change in vegetation density in the catchments between the two periods.

Also other large sample set studies, using this attribution method, might provide more insight. Especially, it would be interesting if catchments with a steeper average slope are included. This might be the case for the catchments included in the French dataset. This is a non-open source dataset, but it includes lots of catchments and it is expected that the quality is good, because it has been used in several studies before (Le Moine et al., 2007, Oudin et al., 2008 & Van Esse et al., 2013).

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Appendix A Calculation of extraterrestrial radiation

For applying the equation of Hargreaves (Hargreaves & Samani, 1985), it is needed to calculate the extraterrestrial radiation (*RA*) in MJ m^{-2} d^{-1}, which is a parameter indicating the intensity of the solar irradiation directly outside the earth's atmosphere (Allen et al., 1998):

$$RA = \frac{G_{sc}}{\pi} d_r * \omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s \tag{12}$$

where the inverse relative distance earth-sun (d_r) and the sunset hour angle (ω_s) are calculated by:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} n\right) \tag{13}$$

$$\omega_s = \cos^{-1}(-\tan\delta \tan\phi) \tag{14}$$

and G_{sc} the solar constant, which is 118.1 MJ m^{-2} d^{-1}. The declination (δ in radians), the angle between the sun and the earth's equator is calculated by the following equation (Spencer, 1971):

$$\begin{aligned}\delta = 0.006918 - 0.399912 \cos B + 0.070257 \sin B - 0.006758 \cos 2B \\ + 0.000907 \sin 2B - 0.002697 \cos 3B + 0.001480 \sin 3B\end{aligned} \tag{15}$$

where:

$$B = (n-1)\frac{360}{365} \tag{16}$$

at the n^{th} day of year. The number 365 indicates the number of days in a year, so days in a leap year will be calculated by making use of 366 instead of 365. This also holds for equation 14. For latitudes (L) in decimal degrees, the next equation will be used for translating to radials:

$$\phi = L * \frac{\pi}{180} \tag{17}$$

where ϕ is latitude in radials, which makes it applicable for substituting in equation 13 and 15.

Appendix B Mann Kendall test

Gilbert (1987) described the Mann Kendall test with examples included, which is used for applying the test. The advantages he named of this test are: missing values are allowed and the data need not conform to any particular distribution. The minimum number of data points present to be able to apply the test on it is 4 however it is hard to detect a trend for small datasets. That is why it is recommended to use at least 6 data point, which is true for all of the datasets the Mann Kendall test is applied at.

There are two ways of making use of this method: one when the number of data points is smaller than or equal to 40 and the other one is applicable to all numbers of data. The latter is used in this research, because there is no need for obtaining values from a table and it is always applicable.

The first step is computing S with the following equation:

$$S = \sum_{k-1}^{n-1} \sum_{j-k+1}^{n} \mathrm{sgn}(x_j - x_k) \tag{18}$$

where *x* indicates the data points, ordered over time. The subscribed denotes which observation it is, with 1 to be the first and n to be the last one. $\mathrm{sgn}(x_j - x_k)$ is the difference between the j^{th} measurement and the k^{th} measurement, with $j > k$. This parameter will be 1 if the difference is positive, 0 if equal to 0 and -1 if smaller than 0. This is indicated in the equation by $\mathrm{sgn}(x_j - x_k)$.

After this the variation of S can be calculated by the following equation:

$$\mathrm{VAR}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p-1}^{g} t_p(t_p - 1)(2t_p + 5)\right] \tag{19}$$

where g is the number of tied groups, t_p the number of observation in the p^{th} tied group. The equation will be reduced to a simpler form, because the absence of tied groups which leads to: $g = 0$ and $t_p = 0$ and to the next equation:

$$\mathrm{VAR}(S) = \frac{1}{18} n(n-1)(2n+5) \tag{20}$$

where the parameters are still the same. Next the Mann Kendall test statistic (Z) can be calculated with the following equations:

$$Z_{MK} = \frac{S-1}{\sqrt{\mathrm{VAR}(S)}} \; if \; S > 0 \tag{21}$$

$$Z_{MK} = 0 \text{ if } S = 0 \tag{22}$$

$$Z_{MK} = \frac{S + 1}{\sqrt{VAR(S)}} \text{ if } S < 0 \tag{23}$$

where a positive Z_{MK} indicates the data tend to increase with time and a negative Z_{MK} indicates the data tends to decrease with time. Because on forehand it cannot be known whether the trend is upward or downward, the null hypothesis will be rejected (and the alternative hypothesis accepted) when $|Z_{MK}| \geq Z_{1-\alpha/2}$, where α is the tolerable probability that the Mann Kendall test will falsely reject the null hypothesis. α is chosen to be 0.05 because this is most common for hydrological studies. This means that $Z_{1-\alpha/2}$ is the 97.5th percentile of the standard normal distribution. From tables (Gilbert, 1987) can be found that $Z_{97.5}$ is 1.96.

Appendix C Sen's slope estimator

For calculating Sen's slope estimator a dataset with *N* pairs of data is needed:

$$Q_i = \frac{x_j - x_k}{y_j - y_k} \qquad (24)$$

for i is from 1 to *N*, which gives *Q* the slope of a pair. *x* and *y* are the data values at the j^{th} and k^{th} place, where $j > k$.

The median of the slopes I, is also known as Sen's slope. The sign indicates the direction of the trend and the value indicates the steepness of the trend. Together with the Mann Kendall test (Appendix B) it can be determined whether the trend is significant or not.

Appendix D Spatial distribution of *LUC* and *CC* values of the Australian catchments

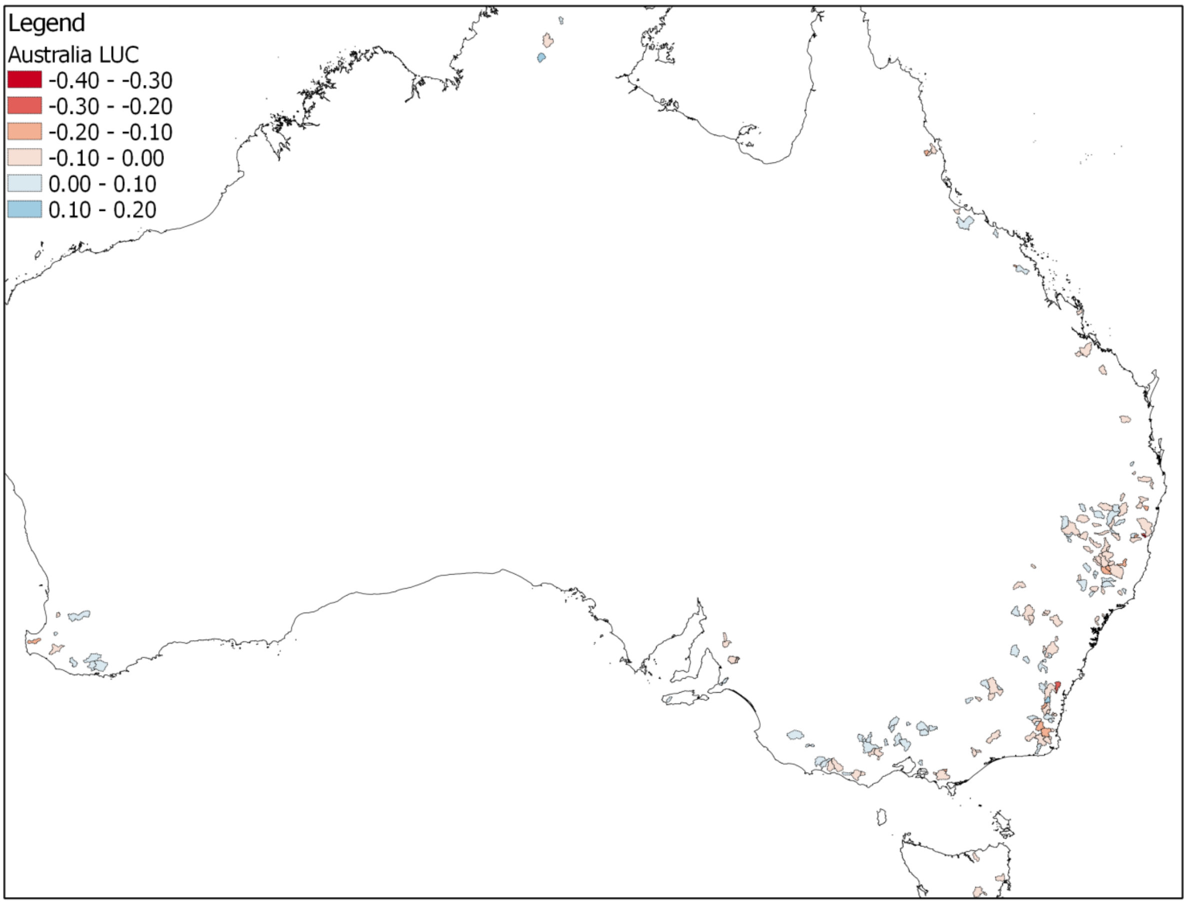

Figure 17: Spatial distribution of *LUC* values of the Australian catchments.

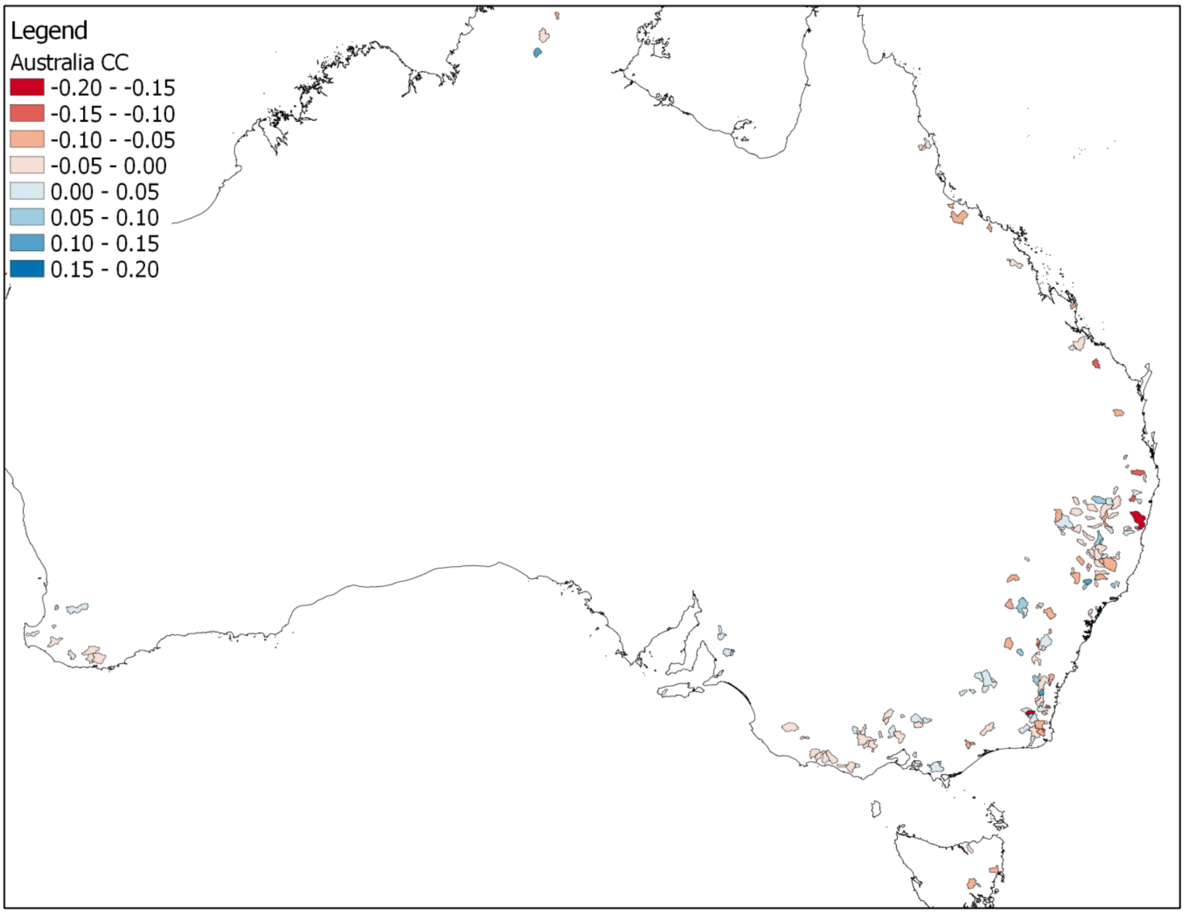

Figure 18: Spatial distribution of *CC* values of the Australian catchments.

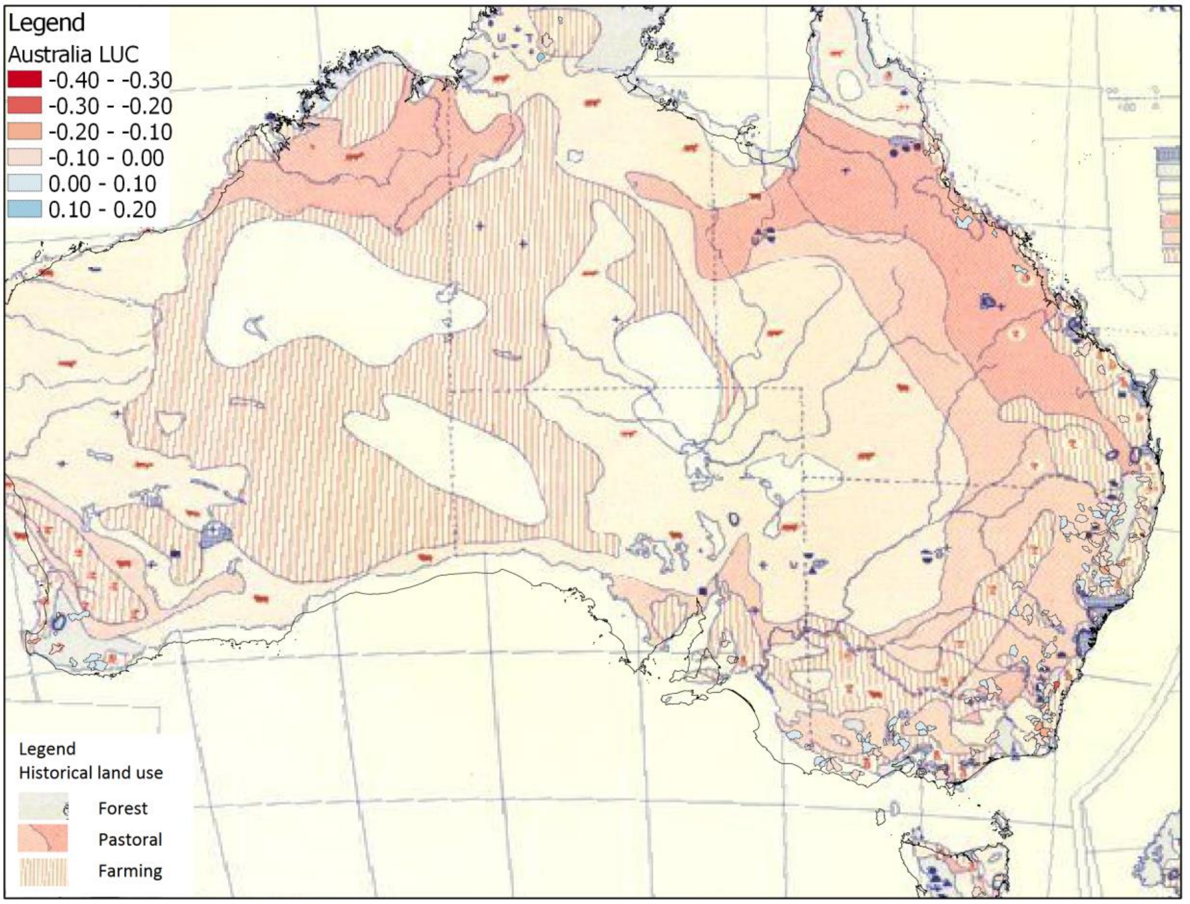

Figure 19: Spatial distribution of *LUC* values of the Australian catchments, with the historical land use of 1962.

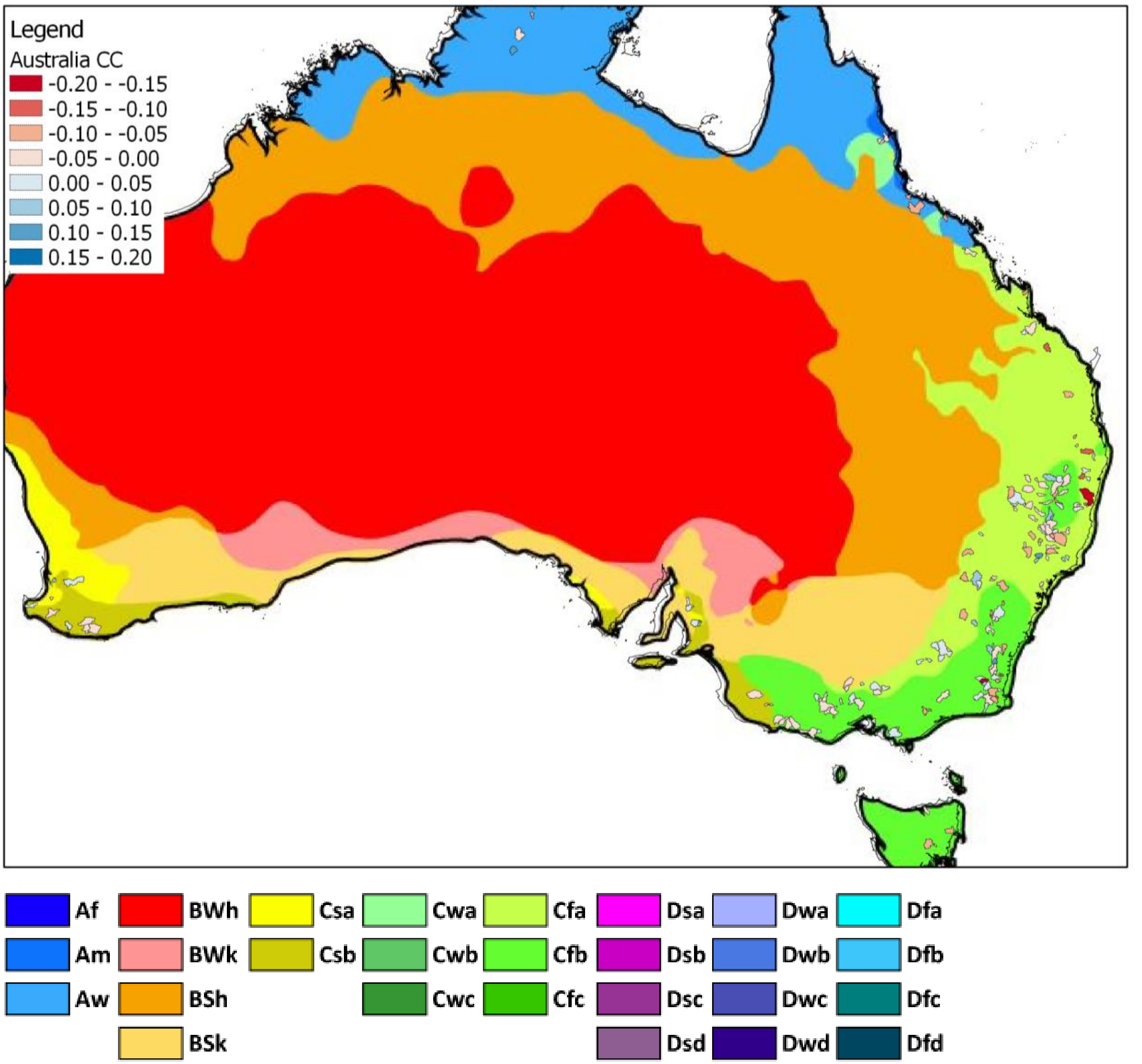

Figure 20: Spatial distribution for *CC* values of the Australian catchments, with the Köppen climate classification.

Appendix E Documented land use change

Table 9: Documented land use change for fifteen selected catchments.

Country	ID	Measuring period	*LUC*	Summary of documented historical land use change	Source
USA	13337000	1949-2002	-0.3535	Large scale commercial logging started in 1953, other plants have been replaced	Bugosh (1999)
USA	12413000	1949-2002	-0.3088	Timber harvest began in late 1800's ended in 1943. Between 1870 and 1931 fire events occurred.	Rothrock (2007)
USA	13186000	1949-2002	-0.3196	No documented information found	
USA	14101500	1949-1990	-0.2607	Logging from 1850 to 1980, with a replacement fire in 1973. From 1980 area regenerating, no logging anymore since that year.	Lamson & Clark (2004)
Australia	205014	1989-1999	-0.33348	No documented information found	
USA	5320500	1951-2002	0.1948	Mostly agriculture cultivation (82%). Hydrology has changed in catchment by channelization and drainage.	Boettcher (2015)
Australia	215008	1979-1992	0.1691	In area surrounding catchment, logging activities had taken place from 1800.	Rogers & Woodroffe (2015)
Australia	418020	1967-1976	0.131597	No documented information found	
USA	5462000	1955-2002	0.139278	No documented information found	
USA	5481000	1949-2002	0.162827	Agricultural and crop production have been improved (drain wetlands, cut down forests).	Simpson et al. (2016)
USA	7172000	1949-2002	0.000206	No documented information found	
USA	1574000	1949-2002	-0.00014	No documented information found	
USA	5517000	1949-2002	0.000419	No documented information found	
Australia	206025	1979-1999	-0.00097	No documented information found	
Australia	407253	1968-1996	0.000602	No documented information found	

Appendix F Characteristics of catchments

In Table 11 and Table 12 the characteristics of catchments in the USA and in Australia are presented, respectively. The Catchment ID of the catchments is the same ID as in other (hydrology) studies is used, the state is indicated by its standard abbreviation and the surface area is shown in squared kilometres. The climate is indicated by the Köppen climate classification as described below. The total length is the length of the time series used to apply the attribution method and the time frame length is the length of both the pre- and post-change period.

To determine the climate conditions per catchment, the Köppen climate classification (see Table 10) is used. It is chosen to use the updated version of Peel et al. (2007), because it is the most recent and reliable one, even though the time series used in the attribution method are starting from 1930 in some cases.

Table 10: Description of climate classification and number of catchments per classification.

Köppen climate classification	Description	Number of catchments		
		USA	AUS	Total
Aw	Tropical - Savannah	0	7	7
BWk	Arid - Desert - Cold	1	0	1
BSk	Arid - Steppe - Cold	12	2	14
Csa	Temperature - Dry Summer - Hot Summer	11	0	11
Csb	Temperature - Dry Summer - Warm Summer	1	19	20
Cwa	Temperature - Dry Winter - Hot Summer	0	3	3
Cfa	Temperature - Without dry season - Hot Summer	47	78	125
Cfb	Temperature - Without dry season - Warm Summer	7	98	105
Dsb	Cold - Dry Summer - Warm Summer	13	0	13
Dfa	Cold - Without dry season - Hot Summer	108	0	108
Dfb	Cold - Without dry season - Warm Summer	62	0	62
Dfc	Cold - Without dry season - Cold Summer	3	0	3
Total number of catchments		**265**	**207**	**472**

Table 11: Characteristics of catchments in the USA.

Catch-ment ID	State	Station name	Area (km²)	Climate (Köppen classifi-cation)	Total length (years)	Time frame length (years)
1048000	'ME'	SANDY RIVER NEAR MERCER	1336	Dfb	46	10
1055500	'ME'	NEZINSCOT RIVER AT TURNER CENTER	438	Dfb	48	10
1064500	'NH'	SACO RIVER NEAR CONWAY	997	Dfc	54	10
1076500	'NH'	PEMIGEWASSET RIVER AT PLYMOUTH	1611	Dfb	54	10
1138000	'NH'	AMMONOOSUC RIVER NEAR BATH	1023	Dfb	32	10
1321000	'NY'	SACANDAGA RIVER NEAR HOPE	1272	Dfb	54	10
1329500	'NY'	BATTEN KILL AT BATTENVILLE	1020	Dfb	20	10
1334500	'NY'	HOOSIC RIVER NEAR EAGLE BRIDGE	1321	Dfb	54	10
1348000	'NY'	EAST CANADA CREEK AT EAST CREEK	749	Dfb	46	10
1423000	'NY'	WEST BRANCH DELAWARE RIVER AT WALTON	860	Dfb	51	10
1500500	'NY'	SUSQUEHANNA RIVER AT UNADILLA	2543	Dfb	46	10
1503000	'NY'	SUSQUEHANNA RIVER AT CONKLIN	5781	Dfb	54	10
1512500	'NY'	CHENANGO RIVER NEAR CHENANGO FORKS	3841	Dfb	54	10
1514000	'NY'	OWEGO CREEK NEAR OWEGO	479	Dfb	30	10
1520000	'PA'	COWANESQUE RIVER NR LAWRENCEVILLE	772	Dfb	50	10
1520500	'NY'	TIOGA RIVER AT LINDLEY	1997	Dfb	36	10
1531000	'NY'	CHEMUNG RIVER AT CHEMUNG	6491	Dfb	54	10
1534000	'PA'	TUNKHANNOCK CREEK NEAR TUNKHANNOCK	992	Dfb	54	10
1541000	'PA'	WEST BRANCH SUSQUEHANNA RIVER AT BOWER	816	Dfa	54	10
1541500	'PA'	CLEARFIELD CREEK AT DIMELING	961	Dfa	54	10
1543500	'PA'	SINNEMAHONING CREEK AT SINNEMAHONING	1774	Dfb	54	10
1548500	'PA'	PINE CREEK AT CEDAR RUN	1564	Dfb	54	10
1556000	'PA'	FRANKSTOWN BR JUNIATA RIVER AT WILLIAMSBURG	754	Dfa	54	10
1558000	'PA'	LITTLE JUNIATA RIVER AT SPRUCE CREEK	570	Dfa	54	10
1559000	'PA'	JUNIATA RIVER AT HUNTINGDON	2113	Dfa	54	10
1560000	'PA'	DUNNING CREEK AT BELDEN	445	Dfa	54	10
1562000	'PA'	RAYSTOWN BRANCH JUNIATA RIVER AT SAXTON	1958	Dfa	54	10
1567000	'PA'	JUNIATA RIVER AT NEWPORT	8687	Dfa	54	10
1574000	'PA'	WEST CONEWAGO CREEK NEAR MANCHESTER	1321	Dfa	54	10
1595000	'MD'	NB POTOMAC R AT STEYER	189	Dfa	46	10
1608500	'WV'	SOUTH BRANCH POTOMAC RIVER NEAR SPRINGFIELD	3810	Dfa	52	10
1610000	'MD'	POTOMAC R AT PAW PAW	8052	Dfb	54	10
1611500	'WV'	CACAPON RIVER NEAR GREAT CACAPON	1753	Dfb	47	10

1628500	'VA'	S F SHENANDOAH RIVER NEAR LYNNWOOD	2808	Dfb	54	10
1634000	'VA'	N F SHENANDOAH RIVER NEAR STRASBURG	1989	Dfb	54	10
1643000	'MD'	MONOCACY R AT JUG BRIDGE NR FREDERICK	2116	Dfa	54	10
1649500	'MD'	NE B ANACOSTIA R AT RIVERDALE	189	Cfa	53	10
1663500	'VA'	HAZEL RIVER AT RIXEYVILLE	743	Cfa	44	10
1664000	'VA'	RAPPAHANNOCK RIVER AT REMINGTON	1606	Cfa	54	10
2083500	'NC'	TAR RIVER AT TARBORO	5654	Cfa	45	10
2135000	'SC'	LITTLE PEE DEE R. AT GALIVANTS FERRY	7226	Cfa	52	10
2219500	'GA'	APALACHEE RIVER NEAR BUCKHEAD	1129	Cfa	30	10
3010500	'PA'	ALLEGHENY RIVER AT ELDRED	1424	Dfb	54	10
3011020	'NY'	ALLEGHENY RIVER AT SALAMANCA	4165	Dfb	54	10
3020500	'PA'	OIL CREEK AT ROUSEVILLE	777	Dfb	54	10
3024000	'PA'	FRENCH CREEK AT UTICA	2663	Dfb	54	10
3032500	'PA'	REDBANK CREEK AT ST. CHARLES	1368	Dfb	54	10
3054500	'WV'	TYGART VALLEY RIVER AT PHILIPPI	2372	Dfb	52	10
3065000	'WV'	DRY FORK AT HENDRICKS	894	Dfb	45	10
3069000	'WV'	SHAVERS FORK AT PARSONS	554	Dfb	45	10
3069500	'WV'	CHEAT RIVER NEAR PARSONS	1860	Dfb	52	10
3070000	'WV'	CHEAT RIVER AT ROWLESBURG	2427	Dfb	48	10
3075500	'MD'	YOUGHIOGHENY R NR OAKLAND	347	Dfb	54	10
3079000	'PA'	CASSELMAN RIVER AT MARKLETON	989	Dfb	54	10
3109500	'OH'	L BEAVER C NR EAST LIVERPOOL	1285	Dfb	54	10
3136000	'OH'	MOHICAN R AT GREER	2455	Dfa	33	10
3159500	'OH'	HOCKING R AT ATHENS	2442	Dfa	53	10
3179000	'WV'	BLUESTONE RIVER NEAR PIPESTEM	1020	Dfb	50	10
3186500	'WV'	WILLIAMS RIVER AT DYER	332	Dfb	52	10
3265000	'OH'	STILLWATER R AT PLEASANT HILL	1303	Dfa	54	10
3266000	'OH'	STILLWATER R AT ENGLEWOOD	1683	Dfa	54	10
3269500	'OH'	MAD R NR SPRINGFIELD	1269	Dfa	54	10
3274000	'OH'	G MIAMI R AT HAMILTON	9402	Dfa	54	10
3289500	'KY'	ELKHORN CREEK NEAR FRANKFORT	1225	Cfa	48	10
3301500	'KY'	ROLLING FORK NR BOSTON	3364	Cfa	52	10
3308500	'KY'	GREEN RIVER AT MUNFORDVILLE	4333	Cfa	51	10
3326500	'IN'	MISSISSINEWA RIVER AT MARION	1766	Dfa	54	10
3328500	'IN'	EEL RIVER NEAR LOGANSPORT	2044	Dfa	54	10
3331500	'IN'	TIPPECANOE RIVER NEAR ORA	2217	Dfa	54	10
3339500	'IN'	SUGAR CREEK AT CRAWFORDSVILLE	1318	Dfa	54	10
3346000	'IL'	NORTH FORK EMBARRAS RIVER NEAR OBLONG	824	Dfa	52	10
3348000	'IN'	WHITE RIVER AT ANDERSON	1052	Dfa	44	10
3381500	'IL'	LITTLE WABASH RIVER AT CARMI	8034	Dfa	53	10
3490000	'VA'	N F HOLSTON RIVER NEAR GATE CITY	1740	Dfb	33	10
3603000	'TN'	DUCK RIVER ABOVE HURRICANE MILLS	6623	Cfa	34	10
4073500	'WI'	FOX RIVER AT BERLIN	3471	Dfb	54	10

4079000	'WI'	WOLF RIVER AT NEW LONDON	5853	Dfb	54	10
4100500	'IN'	ELKHART RIVER AT GOSHEN	1538	Dfa	54	10
4113000	'MI'	GRAND RIVER AT LANSING	3186	Dfb	53	10
4115000	'MI'	MAPLE RIVER AT MAPLE RAPIDS	1124	Dfb	53	10
4144000	'MI'	SHIAWASSEE RIVER AT BYRON	945	Dfb	35	10
4165500	'MI'	CLINTON RIVER AT MOUNT CLEMENS	1901	Dfa	53	10
4176500	'MI'	RIVER RAISIN NEAR MONROE	2699	Dfa	53	10
4178000	'OH'	ST. JOSEPH RIVER NEAR NEWVILLE	1580	Dfa	54	10
4183500	'OH'	MAUMEE R AT ANTWERP	5514	Dfa	33	10
4185000	'OH'	TIFFIN R AT STRYKER	1062	Dfa	54	10
4191500	'OH'	AUGLAIZE R NR DEFIANCE	6004	Dfa	54	10
4198000	'OH'	SANDUSKY R NR FREMONT	3240	Dfa	53	10
4201500	'OH'	ROCKY R NR BEREA	692	Dfb	54	10
4212000	'OH'	GRAND R NR MADISON	1505	Dfb	26	10
4221000	'NY'	GENESEE RIVER AT WELLSVILLE	746	Dfb	29	10
4221500	'NY'	GENESEE RIVER AT SCIO	798	Dfb	24	10
5053000	'ND'	WILD RICE RIVER NR ABERCROMBIE	5387	Dfb	54	10
5244000	'MN'	CROW WING RIVER AT NIMROD	2616	Dfb	43	10
5280000	'MN'	CROW RIVER AT ROCKFORD	6527	Dfb	54	10
5320500	'MN'	LE SUEUR RIVER NEAR RAPIDAN	2875	Dfa	52	10
5383000	'WI'	LA CROSSE RIVER NEAR WEST SALEM	1031	Dfb	22	10
5408000	'WI'	KICKAPOO RIVER AT LA FARGE	689	Dfb	54	10
5410490	'WI'	KICKAPOO RIVER AT STEUBEN	1779	Dfb	54	10
5412500	'IA'	Turkey River at Garber	4002	Dfa	54	10
5418500	'IA'	Maquoketa River near Maquoketa	4022	Dfa	54	10
5422000	'IA'	Wapsipinicon River near De Witt	6035	Dfa	54	10
5430500	'WI'	ROCK RIVER AT AFTON	8651	Dfa	54	10
5435500	'IL'	PECATONICA RIVER AT FREEPORT	3434	Dfa	52	10
5440000	'IL'	KISHWAUKEE RIVER NEAR PERRYVILLE	2846	Dfa	52	10
5447500	'IL'	GREEN RIVER NEAR GENESEO	2598	Dfa	53	10
5451500	'IA'	Iowa River at Marshalltown	3968	Dfa	54	10
5452000	'IA'	Salt Creek near Elberon	521	Dfa	54	10
5454500	'IA'	Iowa River at Iowa City	8472	Dfa	54	10
5455500	'IA'	English River at Kalona	1484	Dfa	53	10
5457700	'IA'	Cedar River at Charles City	2730	Dfb	30	10
5458500	'IA'	Cedar River at Janesville	4302	Dfb	54	10
5462000	'IA'	Shell Rock River at Shell Rock	4522	Dfb	48	10
5471500	'IA'	South Skunk River near Oskaloosa	4235	Dfa	54	10
5472500	'IA'	North Skunk River near Sigourney	1891	Dfa	53	10
5476500	'IA'	Des Moines River at Estherville	3553	Dfa	43	10
5481000	'IA'	Boone River near Webster City	2186	Dfa	54	10
5482500	'IA'	North Raccoon River near Jefferson	4193	Dfa	54	10
5484500	'IA'	Raccoon River at Van Meter	8912	Dfa	54	10
5502040	'IL'	HADLEY CREEK AT KINDERHOOK	188	Dfa	38	10
5507500	'MO'	SALT RIVER NEAR MONROE CITY	5776	Dfa	32	10
5515500	'IN'	KANKAKEE RIVER AT DAVIS	1391	Dfa	54	10

5517000	'IN'	YELLOW RIVER AT KNOX	1127	Dfa	54	10
5517500	'IN'	KANKAKEE RIVER AT DUNNS BRIDGE	3502	Dfa	54	10
5518000	'IN'	KANKAKEE RIVER AT SHELBY	4608	Dfa	54	10
5520500	'IL'	KANKAKEE RIVER AT MOMENCE	5941	Dfa	53	10
5526000	'IL'	IROQUOIS RIVER NEAR CHEBANSE	5416	Dfa	50	10
5542000	'IL'	MAZON RIVER NEAR COAL CITY	1178	Dfa	47	10
5552500	'IL'	FOX RIVER AT DAYTON	6843	Dfa	53	10
5554500	'IL'	VERMILION RIVER AT PONTIAC	1500	Dfa	53	10
5555300	'IL'	VERMILION RIVER NEAR LEONORE	3240	Dfa	29	10
5555500	'IL'	VERMILION RIVER AT LOWELL	3310	Dfa	23	10
5569500	'IL'	SPOON RIVER AT LONDON MILLS	2776	Dfa	52	10
5570000	'IL'	SPOON RIVER AT SEVILLE	4237	Dfa	52	10
5582000	'IL'	SALT CREEK NEAR GREENVIEW	4672	Dfa	53	10
5584500	'IL'	LA MOINE RIVER AT COLMAR	1696	Dfa	53	10
5585000	'IL'	LA MOINE RIVER AT RIPLEY	3349	Dfa	53	10
5592500	'IL'	KASKASKIA RIVER AT VANDALIA	5025	Dfa	53	10
5593000	'IL'	KASKASKIA RIVER AT CARLYLE	7042	Dfa	52	10
6191500	'MT'	YELLOWSTONE RIVER AT CORWIN SPRINGS	6794	Dfc	54	10
6192500	'MT'	YELLOWSTONE RIVER NEAR LIVINGSTON	9197	Dfc	54	10
6225500	'WY'	WIND RIVER NEAR CROWHEART	4898	Dfb	54	10
6334500	'SD'	LITTLE MISSOURI R AT CAMP CROOK	5102	BSk	45	10
6340500	'ND'	KNIFE RIVER AT HAZEN	5802	Dfb	53	10
6359500	'SD'	MOREAU R NEAR FAITH	6889	BSk	54	10
6426500	'WY'	BELLE FOURCHE RIVER BELOW MOORCROFT	4377	BSk	40	10
6441500	'SD'	BAD R NEAR FORT PIERRE	8047	BSk	53	10
6454500	'NE'	NIOBRARA RIVER ABOVE BOX BUTTE RESERVOIR	3626	BSk	46	10
6480000	'SD'	BIG SIOUX RIVER NEAR BROOKINGS	10096	Dfb	48	10
6600500	'IA'	Floyd River at James	2295	Dfa	54	10
6606600	'IA'	Little Sioux River at Correctionville	6475	Dfa	54	10
6607200	'IA'	Maple River at Mapleton	1733	Dfa	54	10
6609500	'IA'	Boyer River at Logan	2256	Dfa	54	10
6799500	'NE'	LOGAN CREEK NEAR UEHLING	2629	Dfa	53	10
6808500	'IA'	West Nishnabotna River at Randolph	3434	Dfa	53	10
6810000	'IA'	Nishnabotna River above Hamburg	7268	Dfa	54	10
6811500	'NE'	LITTLE NEMAHA RIVER AT AUBURN	2054	Dfa	52	10
6813000	'MO'	TARKIO RIVER AT FAIRFAX	1316	Dfa	42	10
6815000	'NE'	BIG NEMAHA RIVER AT FALLS CITY	3471	Dfa	53	10
6817000	'IA'	Nodaway River at Clarinda	1974	Dfa	54	10
6817500	'MO'	NODAWAY RIVER NEAR BURLINGTON JCT	3212	Dfa	34	10
6820500	'MO'	PLATTE RIVER NEAR AGENCY	4558	Dfa	54	10
6847000	'NE'	BEAVER CREEK NEAR BEAVER CITY	4273	Dfa	46	10
6860000	'KS'	SMOKY HILL R AT ELKADER	9207	Dfa	53	10

6868000	'KS'	SALINE R NR WILSON	4921	BSk	15	7
6869500	'KS'	SALINE R AT TESCOTT	7304	Dfa	54	10
6883000	'NE'	LITTLE BLUE RIVER NEAR DEWEESE	2549	Dfa	45	10
6884400	'KS'	L BLUE R NR BARNES	8609	Dfa	43	10
6885500	'KS'	BLACK VERMILLION R NR FRANKFORT	1062	Dfa	48	10
6888500	'KS'	MILL C NR PAXICO	818	Dfa	48	10
6890500	'KS'	DELAWARE R AT VALLEY FALLS	2388	Dfa	18	9
6892000	'KS'	STRANGER C NR TONGANOXIE	1052	Dfa	54	10
6894000	'MO'	LITTLE BLUE RIVER NEAR LAKE CITY	477	Dfa	53	10
6897500	'MO'	GRAND RIVER NEAR GALLATIN	5827	Dfa	54	10
6898000	'IA'	Thompson River at Davis City	1816	Dfa	54	10
6899500	'MO'	THOMPSON RIVER AT TRENTON	4325	Dfa	54	10
6908000	'MO'	BLACKWATER RIVER AT BLUE LICK	2901	Dfa	54	10
6913500	'KS'	MARAIS DES CYGNES R NR OTTAWA	3237	Dfa	54	10
6914000	'KS'	POTTAWATOMIE C NR GARNETT	865	Dfa	53	10
6928000	'MO'	GASCONADE RIVER NEAR HAZLEGREEN	3237	Dfa	23	10
6933500	'MO'	GASCONADE RIVER AT JEROME	7356	Dfa	54	10
7029500	'TN'	HATCHIE RIVER AT BOLIVAR	3833	Cfa	34	10
7049000	'AR'	WAR EAGLE CREEK NEAR HINDSVILLE	681	Cfa	18	9
7052500	'MO'	JAMES RIVER AT GALENA	2556	Cfa	54	10
7056000	'AR'	BUFFALO RIVER NEAR ST. JOE	2147	Cfa	54	10
7057500	'MO'	NORTH FORK RIVER NEAR TECUMSEH	1453	Cfa	54	10
7067000	'MO'	CURRENT RIVER AT VAN BUREN	4318	Dfa	54	10
7068000	'MO'	CURRENT RIVER AT DONIPHAN	5278	Dfa	54	10
7069500	'AR'	SPRING RIVER AT IMBODEN	3064	Cfa	46	10
7144200	'KS'	L ARKANSAS R AT VALLEY CENTER	3437	Dfa	54	10
7144780	'KS'	NF NINNESCAH R AB CHENEY RE	2038	Dfa	37	10
7147070	'KS'	WHITEWATER R AT TOWANDA	1103	Dfa	40	10
7147800	'KS'	WALNUT R AT WINFIELD	4869	Dfa	54	10
7152000	'OK'	CHIKASKIA RIVER NEAR BLACKWELL	4815	Cfa	54	10
7163000	'OK'	COUNCIL CREEK NEAR STILLWATER	80	Cfa	45	10
7172000	'KS'	CANEY R NR ELGIN	1153	Cfa	54	10
7177500	'OK'	BIRD CREEK NEAR SPERRY	2344	Cfa	54	10
7183000	'KS'	NEOSHO R NR IOLA	9889	Dfa	54	10
7186000	'MO'	SPRING RIVER NEAR WACO	3015	Cfa	54	10
7197000	'OK'	BARON FORK AT ELDON	795	Cfa	53	10
7211500	'NM'	CANADIAN R NR TAYLOR SPRINGS	7381	BSk	37	10
7221000	'NM'	MORA RIVER NR SHOEMAKER	2859	BSk	48	10
7222500	'NM'	CONCHAS RIVER AT VARIADERO	1355	BSk	48	10
7243500	'OK'	DEEP FORK NEAR BEGGS	5227	Cfa	54	10
7252000	'AR'	MULBERRY RIVER NEAR MULBERRY	966	Cfa	46	10
7261000	'AR'	CADRON CREEK NEAR GUY	438	Cfa	46	10
7288500	'MS'	BIG SUNFLOWER RIVER AT SUNFLOWER	1987	Cfa	42	10
7289500	'MS'	BIG BLACK RIVER AT PICKENS	3867	Cfa	23	10
7307800	'TX'	PEASE RIVER NR CHILDRESS	7133	BSk	34	10
7340000	'AR'	LITTLE RIVER NEAR HORATIO	6895	Cfa	46	10

7346000	'TX'	BIG CYPRESS CREEK NR JEFFERSON	1834	Cfa	33	10
7346050	'TX'	LITTLE CYPRESS CREEK NR ORE CITY	992	Cfa	37	10
7346070	'TX'	LITTLE CYPRESS CREEK NR JEFFERSON	1748	Cfa	48	10
7348000	'LA'	TWELVEMILE BAYOU NEAR DIXIE	8125	Cfa	43	10
8032000	'TX'	NECHES RIVER NEAR NECHES	2966	Cfa	54	10
8033500	'TX'	NECHES RIVER NEAR ROCKLAND\	9417	Cfa	54	10
8055500	'TX'	ELM FORK TRINITY RIVER NR CARROLLTON	6369	Cfa	54	10
8085500	'TX'	CLEAR FORK BRAZOS RIVER AT FORT GRIFFIN	10329	Cfa	54	10
8095000	'TX'	NORTH BOSQUE RIVER NR CLIFTON	2507	Cfa	52	10
8103800	'TX'	LAMPASAS RIVER NR KEMPNER	2119	Cfa	37	10
8146000	'TX'	SAN SABA RIVER AT SAN SABA	7889	Cfa	45	10
8150000	'TX'	LLANO RIVER NR JUNCTION	4805	Cfa	45	10
8150700	'TX'	LLANO RIVER NR MASON	8410	Cfa	24	10
8167500	'TX'	GUADALUPE RIVER NR SPRING BRANCH	3406	Cfa	54	10
8171000	'TX'	BLANCO RIVER AT WIMBERLEY	919	Cfa	54	10
8171300	'TX'	BLANCO RIVER NR KYLE	1067	Cfa	46	10
8172000	'TX'	SAN MARCOS RIVER AT LULING	2170	Cfa	54	10
8189500	'TX'	MISSION RIVER AT REFUGIO	1787	Cfa	54	10
8205500	'TX'	FRIO RIVER NR DERBY	8881	Cfa	53	10
8340500	'NM'	ARROYO CHICO NR GUADALUPE	3600	Cfb	37	10
9132500	'CO'	NORTH FORK GUNNISON RIVER NEAR SOMERSET	1362	Cfb	54	10
9251000	'CO'	YAMPA RIVER NEAR MAYBELL	8832	Cfb	54	10
9430500	'NM'	GILA RIVER NEAR GILA	4828	Cfb	54	10
9431500	'NM'	GILA RIVER NEAR REDROCK	7327	Cfb	39	10
9442692	'NM'	TULAROSA RIVER ABOVE ARAGON	243	Cfb	30	10
9444500	'AZ'	SAN FRANCISCO RIVER AT CLIFTON	7164	Cfb	54	10
9497500	'AZ'	SALT RIVER NEAR CHRYSOTILE	7379	BSk	54	10
10296000	'CA'	W WALKER R BL L WALKER R NR COLEVILLE	466	Csa	53	10
10296500	'CA'	W WALKER R NR COLEVILLE	647	Csa	44	10
10301500	'NV'	WALKER R NR WABUSKA	6734	Csa	53	10
10309000	'NV'	EAST FORK CARSON RIVER NEAR GARDNERVILLE	922	Csa	53	10
10312000	'NV'	CARSON RIVER NEAR FORT CHURCHILL	3372	Csa	53	10
11025500	'CA'	SANTA YSABEL CREEK NEAR RAMONA	290	Csa	54	10
11080500	'CA'	EF SAN GABRIEL R NR CAMP BONITA	219	Csa	30	10
11138500	'CA'	SISQUOC RIVER NEAR SISQUOC	728	Csa	51	10
11210500	'CA'	KAWEAH R NR THREE RIVERS	1344	Csa	12	6
11213500	'CA'	KINGS R AB NF NR TRIMMER	2466	Csa	33	10
11222000	'CA'	KINGS R A PIEDRA	4385	Csa	10	5
11224500	'CA'	LOS GATOS C AB NUNEZ CYN NR COALINGA	248	Bsk	54	10
11401500	'CA'	INDIAN C NR CRESCENT MILLS	1914	Dsb	45	10
11403000	'CA'	EB OF NF FEATHER R NR RICH BAR	2655	Dsb	24	10

11413000	'CA'	N YUBA R BL GOODYEARS BAR	647	Dsb	54	10
11427000	'CA'	NF AMERICAN R A NORTH FORK DAM	886	Dsb	54	10
11497500	'OR'	SPRAGUE RIVER NEAR BEATTY	1329	Dsb	37	10
11501000	'OR'	SPRAGUE RIVER NEAR CHILOQUIN	4092	Dsb	53	10
12340000	'MT'	BLACKFOOT RIVER NEAR BONNER	5931	Dfb	54	10
12413000	'ID'	N FK COEUR D ALENE RIVER AT ENAVILLE	2318	Dsb	54	10
13186000	'ID'	SF BOISE RIVER NR FEATHERVILLE	1645	Dsb	54	10
13302500	'ID'	SALMON RIVER AT SALMON	9738	Dsb	54	10
13337000	'ID'	LOCHSA RIVER NR LOWELL	3056	Dsb	54	10
13351000	'WA'	PALOUSE RIVER AT HOOPER	6475	Dsb	51	10
14080500	'OR'	CROOKED R NR PRINEVILLE	6993	BWk	42	10
14101500	'OR'	WHITE RIVER BELOW TYGH VALLEY	1080	Dsb	41	10
14113000	'WA'	KLICKITAT RIVER NEAR PITT	3359	Dsb	54	10
14308000	'OR'	S. UMPQUA RIVER @ TILLER	1163	Csb	53	10

Table 12: Characteristics of catchments in the Australia.

Catch-ment ID	State	Station name	Area (km²)	Climate (Köppen classifi-cation)	Total length (years)	Time frame length (years)
110003	'QLD'	Barron R at Picnic Crossing	220	Cwa	73	10
112003	'QLD'	North Johnstone R at Glen Allen	173	Cfa	38	10
117002	'QLD'	Black R at Bruce Highway	260	Aw	24	10
119003	'QLD'	Haughton R at Powerline	1735	Aw	27	10
120216	'QLD'	Broken R at Old Racecourse	78	Cwa	29	10
121002	'QLD'	Elliott R at Guthalungra	270	Aw	24	10
125002	'QLD'	Pioneer R at Sarich’s	740	Cwa	25	10
129001	'QLD'	Waterpark Ck at Byfield	245	Aw	33	10
130319	'QLD'	Bell Ck at Craiglands	300	Cfa	34	10
132001	'QLD'	Calliope R at Castlehope	1310	Cfa	58	10
135002	'QLD'	Kolan R at Springfield	545	Cfa	31	10
136202	'QLD'	Barambah Ck at Litzows	640	Cfa	77	10
136315	'QLD'	Boyne R at Carters	1715	Cfa	17	8
143110	'QLD'	Bremer R at Adams Bridge	130	Cfa	16	6
145011	'QLD'	Teviot Brook at Croftby	82	Cfa	25	10
203005	'NSW'	Richmond River @Wiangaree	702	Cfa	27	10
203010	'NSW'	Leycester River @Rock Valley	179	Cfa	32	10
203030	'NSW'	Myrtle Creek @Rappville	332	Cfa	22	10
204016	'NSW'	Little Murray River @North Dorrigo	104	Cfa	34	10
204019	'NSW'	Nymboida River @Bostobrick	220	Cfa	17	8
204026	'NSW'	Bobo River @Bobo Nursery	80	Cfa	18	9
204030	'NSW'	Aberfoyle River @Aberfoyle	200	Cfb	20	10
204031	'NSW'	Mann River @Shannon Vale	348	Cfb	18	9
204033	'NSW'	Timbarra River @Billyrimba	985	Cfb	36	10
204034	'NSW'	Henry River @Newton Boyd	389	Cfb	22	8
204036	'NSW'	Cataract Creek @Sandy Hill(Below Snake Creek)	236	Cfb	46	10
204041	'NSW'	Orara River @Bawden Bridge	1790	Cfa	25	8
204055	'NSW'	Sportsmans Creek @ Gurranang Siding	202	Cfa	19	9
204056	'NSW'	Dandahra Creek @Gibraltar Range	104	Cfa	23	9
204067	'NSW'	Gordon Brook @Fine Flower	315	Cfa	16	8
205002	'NSW'	Bellinger River @Thora	433	Cfa	18	6
205014	'NSW'	Never Never River @Gleniffer Bridge	51	Cfa	11	5
206009	'NSW'	Tia River @Tia	261	Cfa	57	10
206014	'NSW'	Wollomombi River @Coninside	376	Cfa	26	10
206018	'NSW'	Apsley River @Apsley Falls	894	Cfa	43	10
206025	'NSW'	Salisbury Waters Near Dangar Falls	594	Cfb	21	10
206034	'NSW'	Mihi Creek @Abermala	117	Cfb	10	5
207015	'NSW'	Hastings River @Mount Seaview	342	Cfa	15	7
208005	'NSW'	Nowendoc River @Rocks Crossing	1870	Cfa	21	8
208006	'NSW'	Barrington River @Forbesdale	630	Cfa	32	10

		(Causeway)				
208007	'NSW'	Nowendoc River @Nowendoc	218	Cfa	20	10
208009	'NSW'	Barnard River @Barry	150	Cfa	20	9
208012	'NSW'	Manning River @Woko	480	Cfa	19	7
208026	'NSW'	Myall River @Jacky Barkers	560	Cfa	13	5
209002	'NSW'	Mammy Johnsons River @ Crossing	156	Cfa	15	7
209006	'NSW'	Wang Wauk River @Willina	150	Cfa	12	6
210014	'NSW'	Rouchel Brook At Rouchel Brook (The Vale)	395	Cfa	43	10
210022	'NSW'	Allyn River @Halton	205	Cfa	27	10
210040	'NSW'	Wybong Creek At Wybong	676	Cfa	14	7
210042	'NSW'	Foy Brook At Ravensworth	170	Cfa	14	5
210048	'NSW'	Wollombi Brook @Paynes Crossing	1064	Cfa	21	7
210081	'NSW'	Pages Creek At U/S Hunter River	104	Cfa	20	7
210082	'NSW'	Wollar Creek @U/S Goulburn River	274	Cfa	10	5
210088	'NSW'	Dart Brook @Aberdeen No.2	799	Cfa	11	5
210091	'NSW'	Merriwa River At Merriwa	465	Cfa	10	5
211008	'NSW'	Jigadee Creek @Avondale	55	Cfa	10	5
211013	'NSW'	Ourimbah Creek @U/S Weir	83	Cfa	18	7
211014	'NSW'	Wyong River @Yarramalong	181	Cfa	16	5
212018	'NSW'	Capertee River At Glen Davis	1010	Cfb	12	6
212040	'NSW'	Kialla Creek At Pomeroy	96	Cfb	13	5
215002	'NSW'	Shoalhaven River At Warri	1450	Cfb	20	9
215005	'NSW'	Mongarlowe River At Marlowe	417	Cfb	16	8
215008	'NSW'	Shoalhaven River At Kadoona	280	Cfb	14	7
216009	'NSW'	Buckenbowra River At Buckenbowra No.3	168	Cfb	13	6
218002	'NSW'	Tuross River At Belowra	556	Cfb	29	10
218006	'NSW'	Wandella Creek At Wandella	57	Cfb	17	8
218007	'NSW'	Wadbilliga River At Wadbilliga	122	Cfb	24	10
219013	'NSW'	Brogo River At North Brogo	460	Cfb	21	10
219016	'NSW'	Narira River At Cobargo	92	Cfb	23	10
219017	'NSW'	Double Creek Near Brogo	152	Cfb	32	10
220003	'NSW'	Pambula River At Lochiel	105	Cfb	32	10
220004	'NSW'	Towamba River At Towamba	745	Cfb	27	10
221002	'NSW'	Wallagaraugh River At Princes Highway	479	Cfb	15	7
221003	'NSW'	Genoa River At Bondi	235	Cfb	17	8
221010	'NSW'	Imlay Creek At Imlay Road Bridge	70	Cfb	12	6
221204	'VIC'	Thurra R at Point Hicks	345	Cfb	17	8
221210	'VIC'	Genoa R at The Gorge	837	Cfb	19	9
222001	'NSW'	Maclaughlin River At Dalgety Road	292	Cfb	15	7
222004	'NSW'	Little Plains River At Wellesley (Rowes)	604	Cfb	58	10
222007	'NSW'	Wullwye Creek At Woolway	520	Cfb	49	10
222009	'NSW'	Bombala River At The Falls	559	Cfb	33	10
222010	'NSW'	Bobundara Creek At Dalgety Road	360	Cfb	16	8
222011	'NSW'	Cambalong Creek At Gunning Grach	188	Cfb	16	8

222017	'NSW'	Maclaughlin River At The Hut	313	Cfb	11	5
223202	'VIC'	Tambo R at Swifts Ck	943	Cfb	38	10
224209	'VIC'	Cobbannah Ck near Bairnsdale	106	Cfb	17	8
225218	'VIC'	Freestone Ck at Briagolong	311	Cfb	18	9
226218	'VIC'	Narracan Ck at Thorpdale	66	Cfb	33	10
227202	'VIC'	Tarwin R at Meeniyan	1067	Cfb	40	10
227219	'VIC'	Bass R at Loch	52	Cfb	25	10
228203	'VIC'	Eumemmering Ck at Lyndhurst	149	Cfb	21	10
230205	'VIC'	Maribyrnong R at Bulla (DS of Emu Ck Junction)	865	Cfb	36	10
233215	'VIC'	Leigh at Mount Mercer	593	Cfb	35	10
233223	'VIC'	Warrambine Ck at Warrambine	57.2	Cfb	18	9
234200	'VIC'	Woady Yallock at Pitfield	324	Cfb	34	10
234203	'VIC'	Pirron Yallock Ck at Pirron Yallock (above HW Br)	166	Cfb	27	10
235203	'VIC'	Curdies R at Curdie	790	Cfb	36	10
236203	'VIC'	Mount Emu Ck at Skipton	1251	Cfb	37	10
236205	'VIC'	Merri R at Woodford	899	Cfb	43	10
236212	'VIC'	Brucknell Ck at Cudgee	223	Cfb	26	10
237200	'VIC'	Moyne R at Toolong	570	Cfb	43	10
237205	'VIC'	Darlot Ck at Homerton Bridge	760	Cfb	29	10
237206	'VIC'	Eumeralla R at Codrington	502	Cfb	24	10
238223	'VIC'	Wando R at Wando Vale	174	Cfb	27	10
239519	'SA'	Mosquito Creek @Struan	1130	Csb	27	10
302200	'TAS'	Swan R. @ The Grange	448	Cfb	33	10
303203	'TAS'	Coal R. @ Baden	53.2	Cfb	22	10
304201	'TAS'	Jordan R. @ Mauriceton	742	Cfb	33	10
319204	'TAS'	Pipers R. D/S Yarrow Ck.	298	Cfb	25	10
401013	'NSW'	Jingellic Creek @ Jingellic	378	Cfb	26	10
401015	'NSW'	Bowna Creek @ Yambla	316	Cfa	14	7
405226	'VIC'	Pranjip Ck at Moorilim	787	Cfa	34	10
405228	'VIC'	Hughes Ck at Tarcombe Road	471	Cfb	24	10
405229	'VIC'	Wanalta Ck at Wanalta	108	Cfb	36	10
405237	'VIC'	Seven Creeks at Euroa, township	332	Cfb	32	10
406213	'VIC'	Campaspe R at Redesdale	629	Cfb	38	10
406214	'VIC'	Axe Ck at Longlea	234	Cfb	32	10
407220	'VIC'	Bet Bet Ck at Norwood	347	Cfb	43	10
407221	'VIC'	Jim Crow Ck at Yandoit	166	Cfb	42	10
407236	'VIC'	Mount Hope Ck at Mitiamo	1629	Cfa	26	10
407253	'VIC'	Piccaninny Ck at Minto	668	Cfb	29	10
408202	'VIC'	Avoca R at Amphitheatre	78	Cfb	30	10
410044	'NSW'	Muttama Creek @ Coolac	1025	Cfa	44	10
410047	'NSW'	Tarcutta Creek @ Old Borambola	1660	Cfb	19	9
410048	'NSW'	Kyeamba Creek @ Ladysmith	530	Cfa	49	10
410067	'NSW'	Big Badja River @ Numeralla (Goodwins)	220	Cfb	32	10
410096	'NSW'	Mountain Creek @ Thomond North	160	Cfa	17	8

410111	'NSW'	Yaven Yaven Creek @ Spyglass	77	Cfb	15	7
410126	'NSW'	Demondrille Creek @ Wongabara	171	Cfa	12	6
410141	'NSW'	Micaligo Creek @ Michelago	190	Cfb	15	7
410705	'ACT'	Molonglo R at Burbong Bridge	505	Cfb	55	10
410734	'ACT'	Queanbyan at Tinderry	490	Cfb	31	10
411003	'NSW'	Butmaroo Creek At Butmaroo	65	Cfb	24	10
412063	'NSW'	Lachlan River @ Gunning	570	Cfb	35	10
412066	'NSW'	Abercrombie River @ Hadley No.2	1630	Cfb	28	10
412068	'NSW'	Goonigal Creek @Gooloogong	363	Cfa	17	5
412071	'NSW'	Canomodine Creek @Canomodine	132	Cfb	21	10
412072	'NSW'	Back Creek @Koorawatha	840	Cfa	21	10
412073	'NSW'	Nyrang Creek @Nyrang	225	Cfa	18	9
412076	'NSW'	Bourimbla Creek @Cudal	124	Cfb	16	8
412082	'NSW'	Phils Creek @Fullerton	106	Cfb	15	7
412089	'NSW'	Cooks Vale Creek @ Peelwood	142	Cfb	18	9
412092	'NSW'	Coombing Creek @Near Neville	132	Cfb	10	5
412096	'NSW'	Pudmans Creek @ Kennys Creek Road	332	Cfb	21	8
412110	'NSW'	Bolong River @ U/S Giddigang Creek	171	Cfb	17	8
415207	'VIC'	Wimmera R at Eversley	298	Cfb	34	10
416008	'NSW'	Beardy River @Haystack	866	Cfb	36	9
416020	'NSW'	Ottleys Creek @Coolatai	402	Cfa	21	7
416021	'NSW'	Frazers Creek @Ashford	804	Cfb	12	6
416022	'NSW'	Severn River @Fladbury	1100	Cfb	28	6
416023	'NSW'	Deepwater River @Bolivia	505	Cfb	23	8
416036	'NSW'	Campbells Creek @Near Beebo	399	Cfa	15	7
418005	'NSW'	Copes Creek @Kimberley	259	Cfb	27	10
418015	'NSW'	Horton River @Rider (Killara)	1970	Cfa	30	9
418017	'NSW'	Myall Creek @Molroy	842	Cfa	29	10
418020	'NSW'	Boorolong Creek @Yarrowyck	311	Cfb	10	5
418021	'NSW'	Laura Creek @Laura	311	Cfb	26	7
418024	'NSW'	Roumalla Creek @Kingstown	487	Cfb	14	5
418025	'NSW'	Halls Creek @Bingara	156	Cfa	15	7
418027	'NSW'	Horton River @Horton Dam Site	220	Cfa	26	10
418032	'NSW'	Tycannah Creek @Horseshoe Lagoon	866	Cfa	13	5
419010	'NSW'	Macdonald River @Woolbrook	829	Cfa	61	10
419029	'NSW'	Halls Creek @Ukolan	389	Cfa	22	6
419035	'NSW'	Goonoo Goonoo Creek @Timbumburi	503	Cfa	11	5
419044	'NSW'	Maules Creek At Damsite	171	Cfa	23	10
419047	'NSW'	Ironbark Creek At Woodsreef	581	Cfa	19	9
419050	'NSW'	Connors Creek At Barraba	73	Cfa	14	7
419053	'NSW'	Manilla River At Black Springs	791	Cfa	17	7
419054	'NSW'	Swamp Oak Creek @Limbri	391	Cfa	20	7
419055	'NSW'	Mulla Creek @Goldcliff	254	Cfa	13	6
419076	'NSW'	Warrah Creek @Old Warrah	150	Cfa	16	8
420003	'NSW'	Belar Creek @Warkton (Blackburns)	133	Cfa	20	10
421018	'NSW'	Bell River @Newrea	1620	Cfb	42	10

421026	'NSW'	Turon River At Sofala	883	Cfb	18	9
421036	'NSW'	Duckmaloi River @Below Dam	112	Cfb	11	5
421048	'NSW'	Little River @Obley No.2	612	Cfa	24	10
421050	'NSW'	Bell River @Molong	365	Cfb	17	8
421055	'NSW'	Coolbaggie Creek @Rawsonville	626	Cfa	16	8
421056	'NSW'	Coolaburragundy River @Coolah	216	Cfa	21	7
421066	'NSW'	Green Valley Creek At Hill End	119	Cfb	25	7
421068	'NSW'	Spicers Creek @Saxa Crossing	377	Cfa	16	8
421076	'NSW'	Bogan River @Peak Hill No.2	1036	Cfa	14	7
421084	'NSW'	Burrill Creek @Mickibri	163	Cfa	17	8
421100	'NSW'	Pyramul Creek @U/S Hill End Road	193	Cfb	11	5
426504	'SA'	Finniss River @ 4km East Of Yundi	191	Csb	22	10
502502	'SA'	Myponga River @ U/S Dam And Road Bridge	76.5	Csb	18	9
505504	'SA'	North Para River @ Turretfield	708	Csb	26	10
505517	'SA'	North Para River @ Penrice	118	Csb	18	9
505532	'SA'	Light River @ Mingays Waterhole	828	Csb	12	6
506500	'SA'	WAKEFIELD RIVER @ Near Rhynie	417	Csb	19	9
507500	'SA'	Hill River @ Andrews	235	Csb	20	10
507501	'SA'	HUTT RIVER @ Near Spalding	280	Csb	23	10
509503	'SA'	KANYAKA CREEK @ Sth Of Hawker	180	BSk	10	5
513501	'SA'	Rocky River @ Flinders Chase(Ki)	190	Csb	24	10
601001	'WA'	Young R at Neds Corner	1610	BSk	26	10
603004	'WA'	Hay R at Sunny Glen	1161	Csb	14	7
603136	'WA'	Denmark R at Mt Lindesay	525	Csb	37	10
604001	'WA'	Kent R at Rocky Glen	1108	Csb	18	9
606001	'WA'	Deep R at Teds Pool	457	Csb	21	10
608151	'WA'	Donnelly R at Strickland	807	Csb	47	10
610001	'WA'	Margaret R at Willmots Farm	442	Csb	30	10
611111	'WA'	Thomson Brook at Woodperry Homestead	102	Csb	40	10
613002	'WA'	Harvey R at Dingo Rd	148	Csb	29	10
614196	'WA'	Williams R at Saddleback Rd Br	1437	Csb	28	10
8140159	'NT'	Seventeen Mile Ck at Waterfall View	619	Aw	10	5
8200045	'NT'	South Aligator R at El Sharana	1300	Aw	10	5
8210007	'NT'	Magela Ck at upstream Bowerbird Waterhole	260	Aw	17	8