Response to Dr. Westoff

We very much appreciate Dr. Westoff for his valuable comments that helped us to improve the manuscript. Note: The text provided in italics will be incorporated in the revised draft.

Suggestion #1:

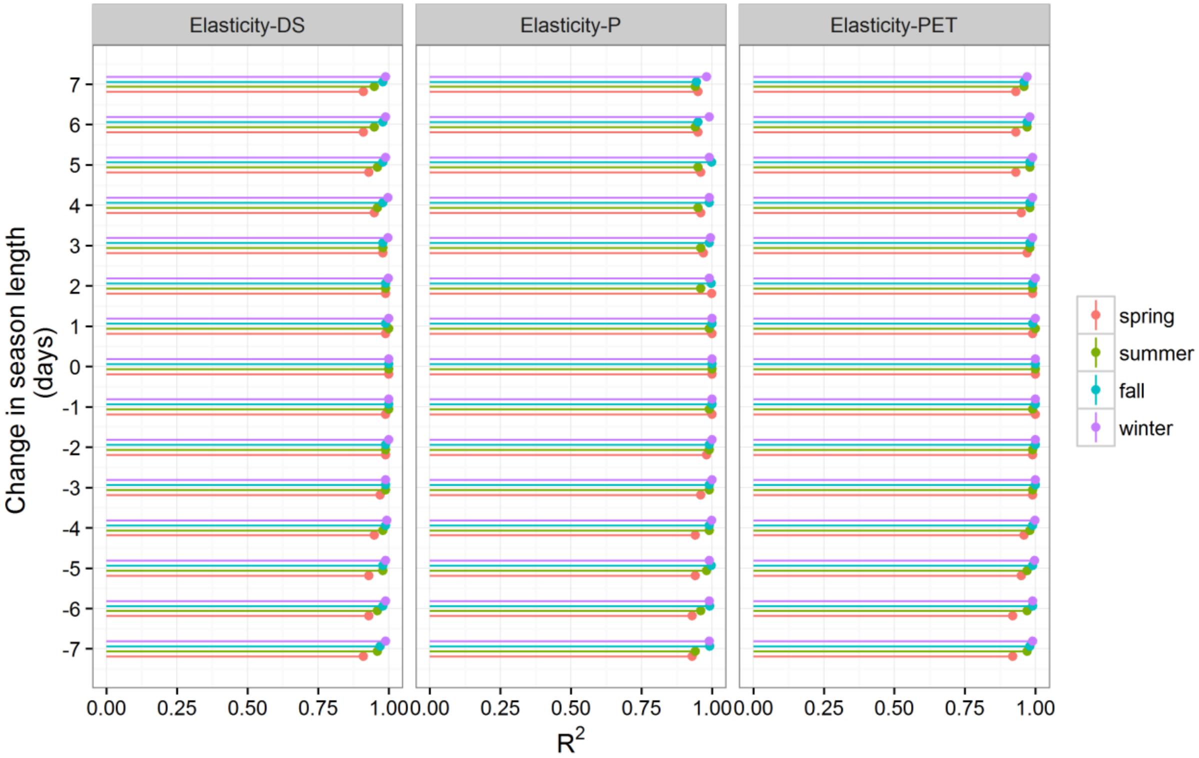
It is correct that at seasonal time scales, storage cannot be neglected, but I have some problems with how this is incorporated in Eq. (4). In this equation Q, PET and P are long term average fluxes, which are not very sensitive when long time series are one year longer or shorter. However, storage change (DS) is a state variable and is given by DS = S(t=n) – S(t=0), where n denotes the length of the time series. Because storage oscillates around zero (in a steady climate), DS is relatively large if n = x years + 6 months and small if n = x year + 0 months: In fact each year there will be a moment in time when DS is zero. This shows that DS is very sensitive to the exact length of the time series. And if it is zero, the last term in Eq (4) is divided by zero leading to infinity. A possible way to overcome this sensitivity to n may be to use the standard deviation of DS (although this may give problems on seasonal time scales since the sign of the change disappears in standard deviations).

Author reply: Yes, we do agree that at annual scale (equation 4), the DS may tent to zero. In this article, we have hypothesized that, if DS is zero, then we can always go back to equation 2 (two parameter equaltion), which is defined for situations were DS is zero. But, the assumption of DS =0 is not always valid. For example, in regions were the anisotropy ratio (Vertical hydraulic conductivity/Horizontal hydraulic conductivity) is not negligible, the ground water losses do occur, indicating that DS ≠0 (Wang, 2014). However, we do agree that the DS is calculated as a residual (P-Q-AET) and likely to have uncertainties due to usage of data from different sources. So, this may result in either underestimation or overestimation of storage change than it is derived in this article. Hence, until more information is available, this can be deemed as a hypothesis that remains to be tested. However, in this study we do neglect the regions for which DS =0 at all scales. But, when it comes to seasonal scales, the DS would theoretically not be zero since, in a particular season; water balance would contain deficits or excesses depending on occurrence of rainfall events and change in temperature.

Suggestion #2:

The seasons are defined as 3 month averages, which is indeed a logical thing to do. However, I am missing a sensitivity analysis on the effect of changing these three month averages with a couple of days or weeks. Also, how do the separation of the seasons correspond to the (start of the) hydrological year of each catchment.

Author’s reply: This is an interesting suggestion. To investigate the effect of length on seasonal elasticities, we decreased (increased) the length of each season by decreasing (increasing) the number of days from each season and calculated the seasonal elasticities. Then we calculated the coefficient of determination (R^2) between elasticities computed with original season lengths and the increased (decreased) season lengths. We limited our modified season lengths to original season length ±7 days. As anticipated, the R^2 decrease with increase (decrease) in season lengths. However, the least R^2 value obtained was 0.93 in the case of PET elasticity in spring. The average R^2 for the elasticities is around 0.99 indicating that small changes in season length may not have significant impact for elasticity estimation.



The United States Geological Survey defines Hydrologic year as the time period between October 1st of one year and September 30th of the next year. However, in our article we have considered seasons as a three month average usually considered in a majority of seasonal studies.

Suggestion #3:

A thorough discussion is missing: Especially about the meaning of all the seasonal elasticities: Why is it useful to know them, what do they say about the hydrology of a certain catchment, how sensitive are they to measurement errors, what is the influence on snow, etc. Please couple back to the (in my opinion main-) goal of the paper, which is listed on page 3, Line 1: “[it] would serve the purpose of understanding the climate and physical controls”.

Author’s reply: Thank you for the suggestion. We have incorporated required suggestion in the revised draft. In addition to those, we have added the following text to increase the discussion part to couple back to goal of the paper in explaining the climate and physical controls of streamflow.

“Overall, the low values of stream flow elasticities due to PET have highlighted the fact that PET play less role (Also, less number of statistically significant streamflow elasticities due to PET) in influencing the annual streamflow (Zhao et al., 2009, 2010; Wang et al., 2011). However, PET which is an indirect measure of temperature does indicate lower PET would result in higher precipitation elasticity (Fu et al., 2007). In addition to that, we observed that the modified elasticity model clearly strengthens the inter-relationship between precipitation, potential evapotranspiration, stream flow and storage changes. This would eventually point to a prominent role of storage changes in the generation of streamflow at annual scales as concluded in other studies (Wang et al., 2009; Gonzalo and Fan et al., 2012; Huntington and Niswonger, 2012). Hence, neglecting these changes would result in either underestimation or overestimation of precipitation and PET elasticities. Moreover, in the situation where DS = 0, we can always go back to equation 2 which neglects the effect of DS on annual streamflow. However, even though the trivariate elasticity model performs better than the bivariate model, we can see that DS is calculated as a residual (P-Q-AET) and likely to have uncertainties due to usage of data from different sources. So, this may result in improper assessment of storage change. Hence, until high quality information with minimum uncertainty in the data sources is obtained, this has to be viewed as a hypothesis that remains to be tested.”

“Overall, as previously put forth by numerous studies in case of annual water balances, precipitation has higher magnitude elasticity values than compared to both PET and Storage changes even at seasonal scale. Considerable seasonality of rainfall elasticity is observed in most of the MOPEX basins in USA. However, the catchments in eastern USA exhibit contrasting features of less rainfall seasonality more seasonal behavior in streamflow (Supplementary figures). This suggests a prominent role of DS and PET in streamflow seasonality since human influence is considered minimal in the eastern region (Wang and Hejazi, 2011). Another observation worth mentioning, is the lag exhibited by the catchments in western USA in terms of precipitation elasticity. There appears to be a precipitation plus snowfall excess during fall and streamflow excess during spring. Whereas, during winter, the precipitation plus snowmelt is in phase with streamflow (Berghuilius 2014). This might be the reason for the higher elasticities during winter. However, this result should be interpreted with caution, since the western USA

has significant human induced changes on streamflow characteristics (Wang and Hejazi, 2011). Also, the storage change have shown considerable seasonal elasticity values. The seasonal DS elasticities indicate that ground water storage act as a natural reservoir and subsequently supply and store the streamflow during various seasons. For example, during summer when the temperatures are high and water requirement is more, ground water supplies water to the streamflow resulting in a positive elasticity in most of the MOPEX basins. Whereas, in winter and spring the soil gets recharged leading to negative elasticity values. However, we observed that in western USA, the negative elasticity magnitude increases during winter unlike the rest of US MOPEX basins. This may be mainly because groundwater contribution to streamflow is inversely correlated to snowmelt runoff (Huntington and Niswonger, 2012). Hence, it possibly has high negative elasticity values when the snow accumulates in winter. Whereas, when the snowmelt runoff starts in the spring it starts contributing to streamflow indicating positive elasticities."

"It is interesting to see how the hydroclimatic variables relationship changes with each season. For example, during summer there exists a stronger association of rainfall magnitude and less predominant association of streamflow with elasticities than in other seasons. During summer, due to relatively high temperatures and inadequacy of available water as streamflow, the catchments become water limited leading to be more dependent on rainfall as a source of water. This behavior is more prevalent in storage changes elasticity. Also, it is obvious that the elasticities are more governed by the magnitudes of streamflow in most of the other cases. But, the linear associations suggest that the streamflow is inversely proportional to precipitation and potential evapotranspiration elasticities. Usually, if the catchments with high streamflow are highly elastic in nature, even minimal amount of rainfall would result in high streamflow hampering efficient disaster and water management activities. Hence, this inverse relationship which is achieved either through artificial/natural storage facilities is beneficial to water management. In the case of elasticity due to storage changes, during the seasons of fall and winter when the elasticities have negative values, there exist a positive linear relationship with streamflow achieving a similar goal of efficient water management practice. However, we suspect that this might not be a natural behavior of a catchment, significant human interference might have created this behavior(Wang and Hejazi, 2012, *Ye et al., 2015). Also, there exists a significant inter-relationship between the hydroclimatic variables and determined elasticities. For example, the seasonal magnitudes of DS effects PET elasticity as well as precipitation elasticity in most of the seasons. Same conclusion can be arrived in other cases too.*

The aridity index, which is a possible indicator of catchment climate (higher the aridity index, drier is the catchment) (Jones et al., 2012) also has significant association with climate *elasticites. The negative correlations in the case DS elasticities, indicate that the dry catchment have higher DS elasticities. Hence, drier catchments have the capacity to store streamflow during wet seasons and aid in streamflow generation during dry seasons. An in-depth analysis of this could further help in investigating the discharge and recharge mechanisms of the available MOPEX basins. Similarly, interpretations can be made in terms of precipitation elasticity for positive correlations. In addition to that, AI plays a more significant role in spring season, indicating that the elasticities are more susceptible to catchment climate conditions in that season. Similarly, the evaporative index which is an indirect gauge of the physical properties of catchments [Jones et al., 2012] has significant associations peaking in the spring season. For example, this relationship articulates that an increase in evaporative index is accompanied by an increase in precipitation elasticity indicating that the catchments with more physical control on streamflow generate more streamflow even for small events of rainfall. This analysis complements many studies which have linked the catchment properties at different scales to streamflow dynamics (Chiverton et al., 2015; Ann vann loon et al., 2015; Gaal et al., 2012; Ye et al., 2015). However, we do not want to stress on a single dominant factor affecting the streamflow elasticities, since there appears to be a strong interplay between elasticites and all the considered catchment properties with substantial seasonal variations."*

Specific comments #1: I do agree with the comment posted by Wouter Berghuijs:

Author's reply: We have addressed these issues; Please have a look at them.

Specific comments # 2:

Section 3.4: The description of all results reads as a long list of numbers. I suggest highlighting the meaning of the individual results and instead of stating that a certain region (e.g. western part of USA) has a certain elasticity, cluster these results in more hydrological terms, such as e.g. the snow dominated catchments have an elasticity of .

Author's reply:

We have made the suggested changes throughout the revised manuscript.

Specific comments # 3:

P9, L12-13: “this increase ... the same season”. This is a strong statement: is there any proof for this?

Author’s reply:

This is a very relevant comment which requires a dedicated and separate study. However to support our findings we are including the following discussion in the revised manuscript

“*In previous studies also, certain catchments have shown positive streamflow elasticities due to potential evapotranspiration [Andréassian et al., 2015, Yang et al., 2014]. The positive PET elasticity may be caused by the local climate feedback. According to previous studies (e.g., (Koster et al. 2004; Guo et al., 2006 Mei and Wang, 2011), the central USA has strong land-atmosphere coupling strength. The PET plays an important role in the linkage of soil moisture and precipitation in the land-atmosphere interactions. Based on the positive land-atmosphere interactions, the increased soil moisture would lead to a cascading effect of increase of temperature (indirectly PET) and precipitation. The increased precipitation would therefore lead to the increase of Streamflow. In this notation, the PET has a positive relationship with precipitation, which would lead to a positive PET elasticity. The positive PET elasticity are within these hotspots in summer season”.*

Specific comments # 4:

P12, L12-13: “This suggests ... of the basins”. This is a strong statement: is there any proof for this?

Author’s reply:

We have revised the manuscript, which was also suggested by Dr. Berghuijs. We have made the following changes at appropriate locations in the revised manuscript.

“ Studies [Sankarasubramanium et al., 2001; Chiew, 2006; Fu et al., 2011; Sun et al., 2013] estimated that the there exists a nonlinear relation between the annual elasticities and the considered hydroclimatic variables. Expecting a similar behaviour at seasonal scale, we quantify the strength of association, using both linear and nonlinear association metrics. For the purpose of estimating the linear and nonlinear associations we considered the seasonal precipitation (P), Storage Changes (DS), Potential evapotranspiration (PET), Aridity Index (AI) and evaporative index (EI). Even though we have estimated the elasticities based on seasonal variations in P, Q and DS, we want to further explore the relationship between seasonal magnitudes of these variables and the calculated elasticites. In addition to that, aridity

index (AI) and evaporative index (EI) which are indicators of catchment (climate) and physical characteristics can explore the seasonal control of catchment properties on elasticities. Hence, we aggregate P, Q, DS, PET and AET at seasonal scales and calculate their averages over the study period. From those averages, seasonal AI and EI are estimated as PET/ (P-DS) and AET/ (P-DS) respectively (Chen et al, 2012). We estimated the linear association based on Pearson correlation coefficients and estimated the level of significance based on p values derived from two sided permutation test of 999 replicates (Helsel and Hirsch, 1992). Several nonlinear association metrics like mutual information (MI)(Cover and Thomas , 1991), Maximal information coefficient (MIC)(Reshef DN, et al. 2011), Hoeffding distance [Hoeffding, 1948] and distance correlation [Szekely and Rizzo, 2009] are prevalent in literature. Among these measures, distance correlation coefficient is easier to implement and has comparatively better statistical power [Kinney and Atwal, 2014], which is used in this study. As this metric is new to field of hydrology, we present the derivation in the following text.

For computing the distance correlation measure between two random variables (X, Y), we first compute the pairwise distances matrices ($a_{i,j}$) *and* ($b_{i,j}$) *as*

$$a_{i,j} = \left\| X_i - X_j \right\| \tag{1}$$

$$b_{i,j} = \left\| Y_i - Y_j \right\| \tag{2}$$

where i, j = 1,2,3,4,5,….n and $\|.\|$ *denotes the Euclidean (in our case) distance. Now, we center these distances matrices as shown below*

$$A_{i,j} = a_{i,j} - \bar{a}_{i.} - \bar{a}_{.j} + \bar{a}_{..} \tag{3}$$

$$\mathrm{B}_{i,j} = b_{i,j} - \bar{b}_{i.} - \bar{b}_{.j} + \bar{b}_{..} \tag{4}$$

where, $\bar{a}_{i.}, \bar{b}_{i.}$ *are the* i^{th} *row means,* $\bar{a}_{.j}, \bar{b}_{.j}$ *are the* j^{th} *column means,* $\bar{a}_{..}, \bar{b}_{..}$ *are the overall mean of the* ($a_{i,j}$) *and* ($b_{i,j}$) *matrices, respectively. Then, we estimate the square of distance covariance as the arithmetic average of the products* $A_{i,j}$ *and* $B_{i,j}$.

$$dCov_n^2(X,Y) = \frac{1}{n^2} \sum_{i,j=1}^{n} A_{i,j} . B_{i,j} \tag{5}$$

Similarly, we estimate the distance variance as

$$dVar_n^2(X) = dCov_n^2(X,X) = \frac{1}{n^2} \sum_{i,j=1}^{n} A_{i,j}^2 \tag{6}$$

Finally, the distance correlation is obtained as

$$dCor(X,Y) = \frac{dCov(X,Y)}{\sqrt{dVar(X) \times dVar(Y)}} \qquad (7)$$

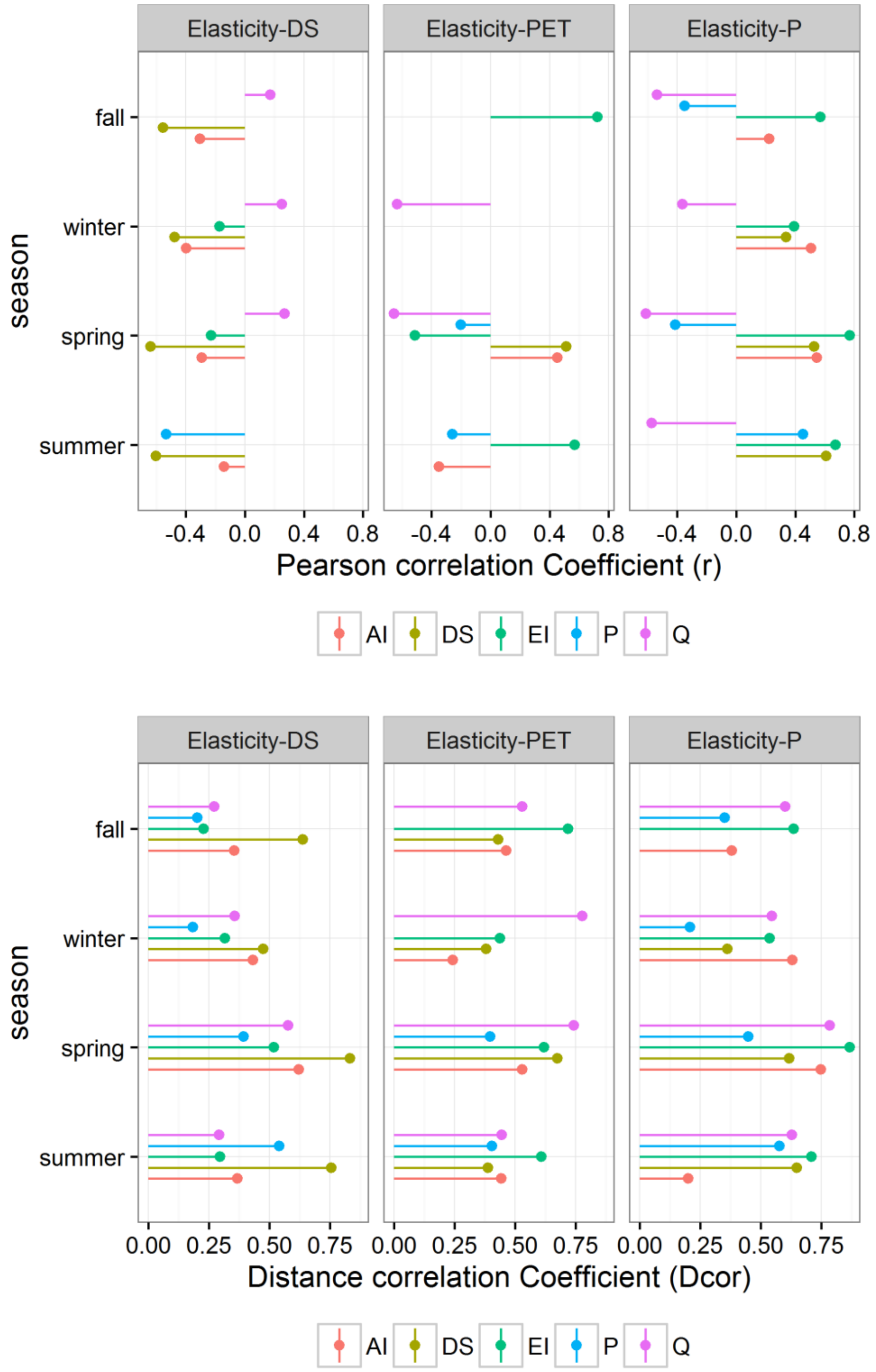
The significance of the calculated correlation is estimated by one sided permutation test of 999 replicates. In both the linear and nonlinear cases, only relations which satisfy the 95% significance level ($p<0.05$) are presented. "

We have removed the previous discussion and provided a revised discussion based on our new findings, as discussed below.

"This analysis allows for a quantitative investigation of relations between the seasonal elasticities and catchment climate properties and gives an understanding of the possible governing factors. Figure (shown below), shows the statistically significant linear (top panel) and nonlinear correlations (bottom panel) between the considered the seasonal hydroclimatic variables and elasticities. We excluded high elasticity values greater than 10 and lesser than -5 in this analysis which may be unrealistic due to uncertainity in the data sources by visual examination of the scatterplots provided in the supplementary information. As we expected, there does exist significant nonlinear associations between elasticities and considered catchement properties. Hence, we base most of our discussions in this text on the nonlinear associations presented in the figure, but sometimes refer the linear association for determining the directionality of the relationships.

It is interesting to see how the hydroclimatic variables relationship changes with each season. For example, during summer there exists a stronger association of rainfall magnitude and less predominant association of streamflow with elasticities than in other seasons. During summer, due to relatively high temperatures and inadequacy of available water as streamflow, the catchments become water limited leading to be more dependent on rainfall as a source of water. This behaviour is more prevalent in storage changes elasticity. Also, it is obvious that the elasticities are more governed by the magnitudes of streamflow in most of the other cases. But, the linear associations suggest that the streamflow is inversely proportional to precipitation and potential evapotranspiration elasticities. Usually, if the catchments with high streamflow are highly elastic in nature, even minimal amount of rainfall would result in high streamflow generation, which might impact existing flood and water management activities. Hence, this inverse relationship which is achieved either through artificial/natural storage facilities is beneficial to water management. In the case of elasticity due to storage change, when the elasticities have negative values(in fall and winter), there exist a positive linear relationship with streamflow achieving a similar goal of efficient water management. However, we suspect that this might not be a natural behavior of a catchment as significant human interference might have created this behaviour (Wang and Hezaidi, 2012; Ye et al.,2014). Also, there exists a significant inter-relationship between the hydroclimatic variables and determined elasticities. For example, the seasonal magnitude of DS affects PET elasticity *as well as precipitation elasticity in most of the seasons. Same conclusion can be arrived in other cases too.*

The aridity index (AI), which is a possible indicator of catchment &climate (higher the aridity index, drier is the catchment) [Jones et al., 2012] also has significant association with climate elasticities. The negative correlations between AI and DS elasticities indicate that the dry catchment have higher DS elasticities. Hence, drier catchments have the capacity to store streamflow during wet seasons and aid in streamflow generation during dry seasons. This study could further help in investigating the discharge and recharge mechanisms of the available MOPEX basins. Similarly, interpretations can be made in terms of precipitation elasticity for positive correlations. In addition to that, AI plays a more significant role in spring season, indicating that the elasticities are more susceptible to catchment (climate) conditions in that season. Similarly, the evaporative index which is an indirect gauge of the physical properties of catchments [Jones et al., 2012] has significant associations as well as higher magnitude in the spring season. This analysis complements many studies which have linked the catchment properties at different scales to streamflow dynamics (Chiverton et al., 2015; Ann vann loon et al., 2015; Gaal et al., 2012; Ye et al., 2015). However, we do not want to stress on a single dominant factor affecting the streamflow elasticities, since there appears to be a strong interplay between elasticites and all the considered catchment properties with substantial seasonal variations."



***<u>Figure</u>*: *The linear and nonlinear association strengths as determined by Pearson and distance correlation coefficients.[Note: In the figure, we have sorted the strength of association separately for each season and the hydroclimatic variables are represented by different colors and only statistically significant [p<0.05] correlation strengths are shown here.]*

Specific comments # 5

Conclusions: only point a) is a conclusion. Point b,c and d just summarize the 'observations'.

Author's reply: Thanks Dr. Westoff, We have changed the heading to summary and conclusions. Also, we have improved that section as follows:

"(a) The proposed three parameter streamflow elasticity model can be a better model than the two parameter elasticity model as it underestimated the stream flow elasticity due to precipitation. This is because the three parameter model was able to account for the covariation of precipitation, potential evaporation and storage change.

(b) Seasonality plays a prominent role in streamflow elasticities with more complex behaviour in western USA basins. This complex behaviour may be linked to snow cover in the selected western basins. However, a dedicated study in this direction could further strengthen this hypothesis.

(c) The stream flow elasticities show significant nonlinear associations with the MOPEX catchment properties. However, we do not want to stress on any single dominant factor affecting the streamflow elasticities, since there appears to be a strong interplay between elasticites and catchment properties with substantial seasonal variations.

(d) We have tested our hypothesis based on the assumption of significant deep ground water losses at annual and seasonal scales. However due to shortage of Actual Evapotranspiration datasets, there may be uncertainties in the results and it can be improved by evaluating with high quality observations. This can be viewed as a hypothesis that remains to be tested using high quality climate data as and when available."

Technical corrections 1)

P4, L11: To me it is not an empirical formula, but simply the definition of elasticity

Author's reply: The sentence has been changed to *"Schaake (1990) first derived the relationship between elasticity of runoff (Q) to precipitation (P) as:"*

2) For all symbols: use only one letter plus subscripts, since e.g. PET can also be interpreted as P times E times T.

Author's reply: These are conventional abbreviations used throughout the scientific literature. So, changing them might confuse the readers. However, we would first include the following statement, that "throughout the article, PET should always be interpreted as potential evapotranspiration. Similarly, DS should be interpreted as change in storage amount."

3) P7, L4: What is meant with 'irrespective of the sign'

Author's reply: We are changing the sentence to "As mentioned earlier, AIC can be used to compare the quality of a statistical models with the preferred model having the lowest absolute value"

4) P7, L22: refer to figure 5 instead of 4

Author's reply: We will make that change in the revised manuscript.

5) the paragraph "Streamflow elasticity due to Potential evapotranspiration:"starting at page 11, contains several sloppy typos. Please check carefully.

Author's reply: We will make that change in the revised manuscript.

6) add units to all axes and colour bars of the figures.

Author's reply: We will make that change in the revised manuscript.

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