Reference: hess-2020-501

"Aquifer recharge in the Piedmont Alpine zone: Historical trends and future scenarios"

Dear Editor,

please find enclosed a point-by-point response to the comments and issues, with a detailed list of the changes which we applied. The original comments are shown in italics.

We have changed extensively the paper according to the comments raised by the reviewers and the Editor, in particular revising and extending, also including new references, the introduction, methodology and conclusions, integrating our results with information from the literature, underlying the scientific novelty of the paper and its relevance for an international audience.

We provide a copy of the manuscript with all changes tracked in red.

We thank the reviewers for their constructive comments which helped us to improve this work and we hope that it can now be considered for publication in HESS.

With best regards,

Elisa Palazzi

on behalf of the first author and all co-authors

EDITOR COMMENTS:

1) *Reviewer #1 thinks that this study serves the local policy very well but the methodology presented is not very novel. Reviewer #1 encourages the authors to better integrate the study results with the existing literature, with the aim of making it more relevant internationally and better bringing out its novelty. I concur with this assessment.*

In the response the authors state that they are planning to revise the Introduction section, but I suggest they also, and even more so, integrate the methods and results with the existing literature. This is an internationally journal, so the papers not to be relevant for an international audience.

I would encourage the authors to revise their manuscript along the lines they proposed and, importantly, make the paper more relevant internationally as suggested by reviewer #1. Please list in detail the changes you have made, including in addressing the latter point.

We have welcomed the suggestions by reviewer #1 and by the Editor and we further revised the paper extending the abstract, introduction, methodology, results and conclusions sections, and adding references to the relevant literature, as detailed below:

INTRODUCTION

The manuscript deals with the characterization of future groundwater resources availability in a study area located at the bridge between two climate hot-spot regions: the Alps and the Mediterranean area. In this area water resources are subject to multiple anthropogenic pressures and climate change is expected to exacerbate the competition between different users. [lines 65-68; lines 141-143]

The methodology developed in this study, a stakeholder-driven interdisciplinary research study, could be applied also in other areas of the world and our results will be useful to characterize future groundwater resources availability in other border areas between Mediterranean and continental climate. [lines 141-145]

The outcomes of this study are in-line with the existing literature, confirming the strong spatial variability of the precipitation field over northern Italy (Blöschl, 2019; Gudmundsson et al., 2017 and Libertino et al., 2019). We found that precipitation over Dora Riparia valley (one of the water catchments considered in our study) shows a decline, confirming a different behaviour compared to the rest of north-western Italy [lines 68-73].

In this study we addressed the following research questions, relevant also for applications in other regions of the world:
a) What is the role of AET and precipitation trends in determining significant trends in the water balance?
b) How different are water balance trends in three different portions of the mountain area, namely a drier west-east oriented area, a wetter area, and a mostly irrigated agricultural area?
c) To what extent are the spatial variability and trends observed in the past 60 years expected to undergo changes during the next 30 years? [lines 129-135]

All these research questions are now introduced in the introduction.

METHODOLOGY

The background about previous studies (Smerdon 2017; Epting et al., 2021; Li et al., 2015, Taylor et al. 2013) provided in the Introduction justifies the use of precipitation and of AET as the largest source of recharge variability. Also, the added literature highlights the importance of the spatial and temporal variability in recharge-related studies and illustrates how groundwater recharge projections are related to projections of precipitation, irrigation and snowpack reduction [lines 92-110].

In such a framework, the widespread use of irrigation in most parts of the Po Valley plain needs to be correctly represented. In managed agrosystems, changes in surface energy budgets are associated with enhanced soil moisture from irrigation (Taylor et al. (2013). Irrigation practices, especially for highly water-demanding crops such as maize, can increase the *AET* term of the water balance [lines 240-243, lines 252-257]. These water-demanding crops are quite widespread in the study area and therefore a novel procedure reproducing agricultural irrigation techniques was implemented in the soil-water model. This module is based on previous research in three farms (Canone et al., 2015, 2016), reproducing farmers' decision rules, and tuned in order to obtain irrigation events similar to the observed ones [lines 252-257].

RESULTS

Observed data (historical data from 1959 to 2017)

The outcomes of this study are in-line with the existing literature, confirming the statistically significant positive trends of maximum temperature over the whole study area [lines 387-388, lines 392-393], and the strong spatial variability of the observed precipitation field over northern Italy (Blöschl, 2019; Gudmundsson et al., 2017 and Libertino et al., 2019) [lines 423-425].
Moreover, as reported in Blöschl (2019), it can be observed that the precipitation field over Dora Riparia valley (one of the water catchments considered in our study area) shows a significant negative trend, confirming a different behaviour compared to the rest of north-western Italian region. This is the driest part of the study area (i.e. the western part of the area), where the decrease

in precipitation combines with increasing evapotranspiration, thus leading to a significant negative drainage trend [lines 425-431].

The evaluation of temporal variability of precipitation is part of the international debate on Alpine precipitation variability as in Haslinger et al (2021) [lines 409-414].

In our paper, AET trends are positive over the whole study area, and statistically significant in 14 out of 23 catchments. This finding is in line with the results of Blyth et al. (2018), who estimated AET using a land surface model in Great Britain under similar conditions. That paper analysed a similar time period as in our paper, considering a region where precipitation is not out of phase with the vegetation growing season, similarly to our study area. However, the finding of an increase in AET is not obvious. For example, Pangle et al. (2014), using the data from a mesocosm experiment, found a decreasing trend of AET, highlighting that the hydrological response to climate warming can be attenuated where precipitation is out of phase with the vegetation growing season. In a more theoretical study, Fatichi and Ivanov (2014) found AET to be quite unaffected by the imposed climate fluctuations, using input data from four very different sites [lines 393-403].

Drainage shows negative but mostly non-significant trends, with significant decreasing trends only in the western part of the region (Dora Riparia catchment), where they combine with positive evapotranspiration trends. Increasing AET trends in the southern irrigated areas (a map representing the spatial distribution of annual AET has been added, in the revised paper see Figure 4) do not lead to a significant drainage decrease, because the precipitation field does not show a significant negative trend. Therefore, in our study area, precipitation plays a major role in affecting drainage trends [lines 423-432].

Mid-century projections of drainage

We used an ensemble of climate models to perform drainage projections, finding a large inter-model variability, as in Crosbie et al. (2013) and in Persaud et al. (2020). Moreover, a much less clear pattern in the spatial variability is found in the model projections compared with the historical data trend evaluations [lines 493-494].

Driven by the precipitation field, which does not show unique or significant trends, we find a slight drainage increase with higher precipitation amounts, decreasing trends with higher daily maximum temperature and, above all, a strong interannual variability [lines 467-471], as already reported by Stoll et al. (2011) in their recharge projections in a catchment in northern Switzerland [lines 513-514]. Changes in long-term drainage were already identified by Konapala et al. (2020), who highlighted the limitations in the ability of current generation coupled climate models to capture the key drivers of persistent weather extremes [lines 514-515].

CONCLUSIONS

Assessing the impacts of climate change on groundwater resources represents a priority in water management, besides being an important scientific challenge. In this study a stakeholder-driven research study was carried out to quantify the role of groundwater on an area characterized by a very large spatial variability of precipitation, due to the proximity of high mountains and of the sea [lines 517-522], located at the bridge between two climate hot-spot regions (the Alps and the Mediterranean area) and where multiple anthropogenic pressures act on groundwater resources [lines 555-558].

This study aims to support better informed management, infrastructural and supply decisions in the considered study area, with a methodology that could be extended also to other areas of the world [lines 549-550]. Our results could help in better understanding future groundwater behaviour in other regions at the bridge between Central and Southern Europe [lines 559-562].

Regarding drainage, our analysis revealed a very strong interannual variability in the historical period, as well as remarkable geographical differences [lines 534-537] that are not evident in the model projections [lines 547-548]. In the analysis of historical observations, the western part of the study area (Dora Riparia catchment) shows significant negative trends, due to the combination of decreasing precipitation trends together with positive evapotranspiration trends [lines 540-542]. In this area a new drinking-water aqueduct (70 km long and 180 million cost) was built to provide water from an existing hydroelectric reservoir located at an elevation of 1600 m asl, preventing the continuous pumping from the Dora Riparia aquifer. A complementary hydraulic research was performed by the Polytechnic of Torino (Fellini et al., 2018) [lines 550-555].

Finally, the outcomes of this paper reinforce the findings of two different precipitation regimes over Europe, the Mediterranean and the continental one. Both can be found in our study area and the Dora Riparia valley seems to represent a transition between them [lines 561-563].

> *2) Reviewer #2 has a number of more minor points which, I think, the authors addressed well in their response.*

Thank you.