Summary: This paper uses a hydrological model, a dynamic agent based model and present and past input/forcing data for these model and comes up with a virtual water trade analysis under climate variability for the Roman world around 200 A.D. Comments: I read this article with great enthusiasm. Virtual water trade is an important topic, especially in context of socio-hydrology and water footprint assessment. Yet I have several concerns with the underlying methodology. Following are my comments:

The reviewer has a number of central points which we address first. After we provide a point by point response to each of the reviewer's specific comments.

The authors do not make a clear distinction between socio-hydrology, which is the science of people and water that studies two-way feedbacks between humans and water systems, and water resource management. The two-way feedbacks between society and hydrology are not captured as one would expect from a socio-hydrology paper.

Socio-hydrology is a 'science that is aimed at understanding the dynamics and co-evolution of coupled human-water systems' whereas integrated water resources management uses a scenario-based approach to understand these interactions (Sivapalan et al., 2012). Our study uses historical reconstructions of Roman trade networks, agricultural land cover and population distribution with dynamic models to understand the impact of spatial and temporal variability in water resources on the Roman civilisation. We also examine the impact that urbanisation and population growth, which arose as a result of Roman water resource management practices, had on their water resources. However, we do not model the feedbacks between the two (as proposed by Liu et al., (2014) and Elshafei et al., (2014) for example); rather we apply a scenario-based approach. We have good reasons for modelling the system in the way we have, which we outline in our response to reviewer 2's second central point. Given that this research is focused on the Roman civilisation, our paper falls in between the definitions of historical socio-hydrology and water resource management.

We have provided a more comprehensive literature review in the introduction section of the revised paper that covers the topics of socio-hydrology, historical socio-hydrology and water resource management (e.g. Davies and Simonovic, 2011; Elshafei et al., 2014; van Emmerik et al., 2014; Kelly (Letcher) et al., 2013; Konar et al., 2013; Liu et al., 2014; Shi et al., 2014; Sivapalan et al., 2012; Suweis et al., 2013). We have endeavoured to explain how this paper fits within the context of those three sub-disciplines of hydrology. In addition, reviewer 1 challenged us to illustrate the wider implications of this paper. To that end we have added a paragraph in the discussion of the revised manuscript in which we discuss the wider implications of our research on Roman water resource management. We provide a conceptual model that illustrates the general implications of our research for present-day understanding of the interactions between VW trade and sustainable water resource use (Reviewer 1, Figure 4).

There is a mismatch between the complexity of the very detailed underlying hydrological model and a simple VW trade model.

The trade network used contains 649 nodes and 1,371 links based on a wealth of historical and archaeological data. As far as we know it is the most detailed trade network reconstruction for the ancient world. It is also comparable in detail, if not more detailed than trade networks described for present day VW trade. For example, Konar et al. (2011) described VW trade for the entire globe using 166 nodes and 6033 links. In a later paper Konar et al. (2013) simulated global VW trade under future climate change using a VW trade network containing 92 nodes and a hydrological model at 0.5 degree resolution. At a global scale and with only 92 nodes, a 0.5 degree hydrological model is likely sufficient to identify differences in VW status among trading regions. However, at the regional scale that our analysis was focused and with 649 nodes, if we used a coarser hydrological model many neighbouring nodes would have identical VW values as they would occupy the same cell of the hydrological model. In addition, we would fail to capture the important heterogeneity in the Mediterranean arising from differences in elevation, soil, surface water availability, climate and so on. Our use of a 5' hydrological model uncovered some of the most important findings in our paper such as that grain yields were likely temperature rather than water limited in most of the Mediterranean, the stability of yields differed between the East and Western Mediterranean as well as between irrigated and rainfed agriculture. In addition, using a detailed hydrological model provided a more accurate estimation of discharge and thus a realistic constraint of the available water available for irrigation.

In terms of how we modelled Roman VW trade, there is significant historical evidence that the principal constraint on trade in the ancient world was a struggle against distance, something which Orbis captures. Historical evidence indicates that urban centres ensured a stable supply of grain by means of tributary donations (tax in kind). There was likely a parallel free market economy, but municipal urban grain supplies were thought to be too important to be risked on the free market and were ensured using more hierarchical methods (Erdkamp, 2005; Rickman, 1980). Therefore we calculated VW trade based on VW poor regions (urban centres) demanding grain from the nearest VW rich region (agricultural regions) in the network: analogous to a tax in kind trade system constrained by the 'struggle against distance'. In the revised manuscript we have expanded on our explanation of how we simulated VW redistribution and the reasons we believe this is appropriate for the Roman period (see reviewer 2, comment 7 for further details).

1. The paper appears to have been condensed from another version. This process appears to have been rushed through. Selective examples include reference to figure 4 (line 25, page 6573)when they meant figure 3, reference to Wilensky, 2010 that does not exist in the reference list, reference to a dynamical agent-based network which this referee was not able to find, insufficient explanation of this agent based model itself, passing reference to socio-hydrology without further exploring how this paper fits into or complements recently published literature on socio-hydrological modelling, in particular historical socio-hydrology, etc.

We have endeavoured to eliminate all typos from the paper.

Also in response to reviewer 1 we have provided a more intuitive schematic of how the Virtual water redistribution model was generated (Reviewer 1, Figure 1 and 2). In addition we have expanded our explanation of how the agent-based trade model operates (see reviewer 2, comment 7 for more detail).

2. The authors do not make a clear distinction between socio-hydrology, which is the science of people and water that studies two-way feedbacks between humans and water systems, and water resource management.

We have addressed this point in our general response to reviewer 2.

The authors mention "emergence" of complex socio-hydrological responses to climate variability but none are found in the manuscript

Nodes in our model are individual agents and we assign them with the same decision rules based on their VW status (VW rich, VW poor or VW neutral). Therefore, although the virtual water trade patterns we show are emergent from these decision rules, the model does not contain randomness and complex behaviour that occurs when agents have varying and adaptive decision rules. We believe that the following sentence may have contributed to giving reviewer 2 inaccurate expectations of the paper: 'Using an agent-based dynamic VW redistribution network with the hydrological model PCR GLOBWB, allows us to explore complex emergent socio-hydrologic responses to climate variability and population growth.' To avoid other readers also developing inaccurate expectations, we have removed the sentence from the revised manuscript.

3. It is not clear which agricultural commodity is facilitating the virtual trade of water. References to trade in grain have appeared in several places.

In the revised paper we have clarified that Virtual Water trade is based on the trade in grain, specifically winter wheat.

4. The modeling effort appears to be disproportionate in resolution/complexity. The authors model the hydrology using a 3 (or 4 layer land surface model, not clear) and landcover resolved at 30" resolution.

We have responded to this point in our general response. PCR-GLOBWB is a three layer hydrological model (2 soil layers and 1 groundwater reservoir).

A "suitability" algorithm is even used to downscale HYDE data set that probably been derived from proxies using GLCC. The authors also fail to justify why the suitability algorithm is a suitable algorithm to downscale HYDE data set.

The Romans preferred low lying, gently sloping land for agriculture owing to the mobility of the soils on hill slopes balanced with the ease of working on gentle slopes (van der Leeuw, 1998). Therefore we gave precedence to regions with shallow slopes when defining our agricultural regions. We have added this justification in the methods section of the revised paper.

No details of how HYDE dataset has been reconstructed is provided. This perhaps is an overkill, given the uncertainties in HYDE is data set.

The discussion paper is already quite long. Given that detailed descriptions of HYDE, PCR-GLOBWB and Orbis are published elsewhere we regarded it as the best to point readers towards those publications if they wished to know the details of how they were generated.

No underlying assumptions have been provided by the authors to gauge its value in analyzing the VW trade in the Roman world.

We explain in the introduction of the discussion paper how the Roman grain trade operated. We have expanded on this in the methods section of the revised paper and clearly stated the assumptions upon which our trade algorithm is based (see reviewer 2, comment 7 for further details).

Present day climate forcings for the study have also been used.

We state in the discussion paper that it is estimated that temperatures during the Roman period were similar to the mean Northern Hemisphere temperature between 1961 and 1990 (Ljungqvist, 2010). In addition, Dermody et al. (2012) estimate that average precipitation rates during the Roman Period were likely similar to present day. Since we are interested in examining how the Romans managed their water resources under climate variability it was regarded that current-day climate forcing was therefore appropriate to understand this.

It is hard to believe that such detailed modeling can compensate for the uncertainties present in the reconstructed HYDE dataset or for that matter Orbis network structure data set.

Of course reconstructions of past human systems such as Orbis and HYDE contain uncertainties, just as reconstructions of past climate contain uncertainties. However, it is our assessment that using physical models such as the hydrological model used here allows us to refine theories about past civilisations based on what was possible given the constraints of the physical environment. In addition, by using the historical information we can compare the outcomes of our models to what happened in reality and thus determine if the assumptions and processes captured in our models are valid. In this way physically based models and historical reconstructions are complementary. The wealth of information we can learn about how human societies (Cornell et al., 2010; Costanza et al., 2007) increased their vulnerability or resilience to climate makes living with a certain amount of uncertainty worthwhile in our estimation. For example, a great deal of what we know about the climate system derives from paleo reconstructions that contain large amounts of uncertainty.

The VW deficits that the authors calculate can as well be estimated using very simple mass balance models. This mismatch between model complexity and information availability casts doubts on the conclusions drawn.

We used a complex and detailed hydrological model because it captures the heterogeneous response of grain yields in the Mediterranean region to climate based on the physical constraints of the Mediterranean environment. That method uncovered some of the most important findings in our paper such as that grain yields were likely temperature rather than water limited in most of the Mediterranean, the stability of yields differed between the East and Western Mediterranean as well as between irrigated and rainfed agriculture. We doubt whether such findings would come out of a simple mass balance model, as simple models capture a researchers understanding of the system rather than the complex and heterogeneous physical constraints of the system. In addition, the use of a detailed hydrological model provided a more accurate estimation of discharge and thus a realistic constraint of blue water availability for irrigation.

5. To continue on point 4, the authors use MIRCA dataset to divide cropland into rainfed and irrigated. They then use the complex hydrological model to estimate how much of blue water demand can be met. Using HYDE population data set, the authors then estimate the food deficit (and hence VW deficit). The authors failed to realize that MIRCA dataset refers to a

period of 1998-2002 and heavily depends on existing agriculture infrastructure (Area Equipped for Irrigation, AEI). Linear transfer of AEI figures from present to the past is erroneous and connects to another comment that appears later. Further unvalidated output of the complex hydrological model is used to estimate how much of blue water demand is met, assuming AEI can be linearly interpolated.

It was perhaps not clearly defined how we prescribe irrigation in the model. In the revised paper we have updated our model schematic to make this more intuitive and expanded on our explanation in the methods section (see Reviewer 1, Figure 1). To clarify, the present day area where irrigation takes place as outlined by MIRCA represents an upper limit of regions where irrigation is possible. We then limit the irrigated areas to regions where MIRCA and HYDE 200 AD cropland reconstructions overlap. Irrigation in these regions is then further limited to the catchment area within the 2m bank overflow of a river. The amount of irrigation in the regions we define as having irrigation potential is constrained by river discharge, calculated by the detailed hydrological model. Yields in rainfed and irrigated regions are also limited by the available work force for harvest.

6. Available area under irrigation requires infrastructure. Depending on the scale of irrigation, infrastructure development requires relatively heavy investments and often central planning. This in turn tends to go hand in hand with institutional development of societies, often nonlinearly. Linear transfer of AEI from present to past is therefore misguided and ignores the relevant two way feedbacks between humans and their water system in the Roman world.

We agree wholeheartedly with the reviewer that highly complex social and environmental factors went into deciding where investment in irrigation infrastructure took place. However, by using historical reconstructions we incorporate many of those complex factors without explicitly modelling them. In addition, we use physical models to constrain the irrigated as outlined in the previous response. Nonetheless, the evidence we have indicates that they were masters of water resource management and built irrigation infrastructure throughout the Mediterranean region (Barker, 1996; Wilson, 1997). We can never know for sure where and to what extent the Romans irrigated throughout the Mediterranean region. Nonetheless, we feel that by limiting the irrigation regions according to historical reconstructions of land cover and population at 200 AD (HYDE) as well as physical environmental constraints (river discharge and 2m bank overfall) we have at least identified the regions that were likely optimal and thus most likely used for irrigation from surface water during the Roman Period.

7. How VW redistribution is calculated is missing. I will therefore assume that one starts with the most VW poor, allocate VW from VW rich nodes ordered by their edge costs, update the VW deficits and repeat the same with the second most VW poor and so on. If this is the case or it be any other algorithm, no rationale has been provided why agricultural trade will happen in this fashion. Why should the VW rich nodes trade with the closest (in edge cost sense) VW poor node. At present there is no reason to believe that "struggle against distance" is an appropriate mechanism for VW trade.

In the revised manuscript, we have expanded on our description of how we simulate VW trade. In the same section we have clarified why demand-driven, cost-distance based VW trade is an appropriate mechanism for the Roman period. To expand on that point here, we have mentioned in the discussion paper that the struggle against distance is a robust pattern in current trade in bulk goods and historians who have given their careers to studying ancient civilisations have determined that it was the main limit to trade in the ancient world also (Braudel, 1995; Scheidel, 2013). For example, the Roman scholar Arnold H. M. Jones (1986) calculated based on Diocletian's Edict on Maximum Prices that it was less costly to ship grain from one end of the Mediterranean to the other than 75 miles over land.

Roman scholars have concluded that the grain trade was under greater control by state and city authorities compared with trade in other goods (Rickman, 1980). Evidence indicates that urban centres ensured a stable supply of grain by means of tributary donations (also known as tax in kind) as well as the granting of privileges to certain traders to ensure reliable supplies. Although, much of our evidence about the grain trade relates to the city of Rome, it is likely that other major cities used similar methods to ensure grain supplies. There was likely a parallel free market economy, but municipal urban grain supplies were considered too important to be risked on the free market and were ensured using more hierarchical methods (Rickman, 1980).Therefore we calculated VW trade based on VW poor regions (urban centres) demanding grain from the nearest VW rich region (agricultural regions) in the network: analogous to state-controlled, tax in kind trade system constrained by the struggle against distance.

Building up our methodology in a logical and transparent way such as outlined allows us to refine hypotheses on Roman water resource management. We can then compare our model output with what we know from historical sources and make conclusions about why the two may be different. In this paper we have concluded that information transfer was the principal reason for the difference between our modelled trade patterns and those of the Roman period. This is something we are enthusiastic to explore in the future by adding more complex decision rules to our agent-based model.

8. Continuing further on point 7, the VW network structure does not appear to evolve over time.

The network does not evolve over time. This is a snapshot of the Roman trade network in 200AD. The advantage of using historical reconstructions is that we can constrain our modelling framework based on what happened in the past, albeit with the uncertainties that reconstructions of the distant past hold.

No support has been provided for the assumption that all the edges of the Orbis network were active around 200AD. Perhaps the VW redistribution algorithm may also activate or deactivate certain edges based on the distribution of VW deficits but it preserves the structure of the network.

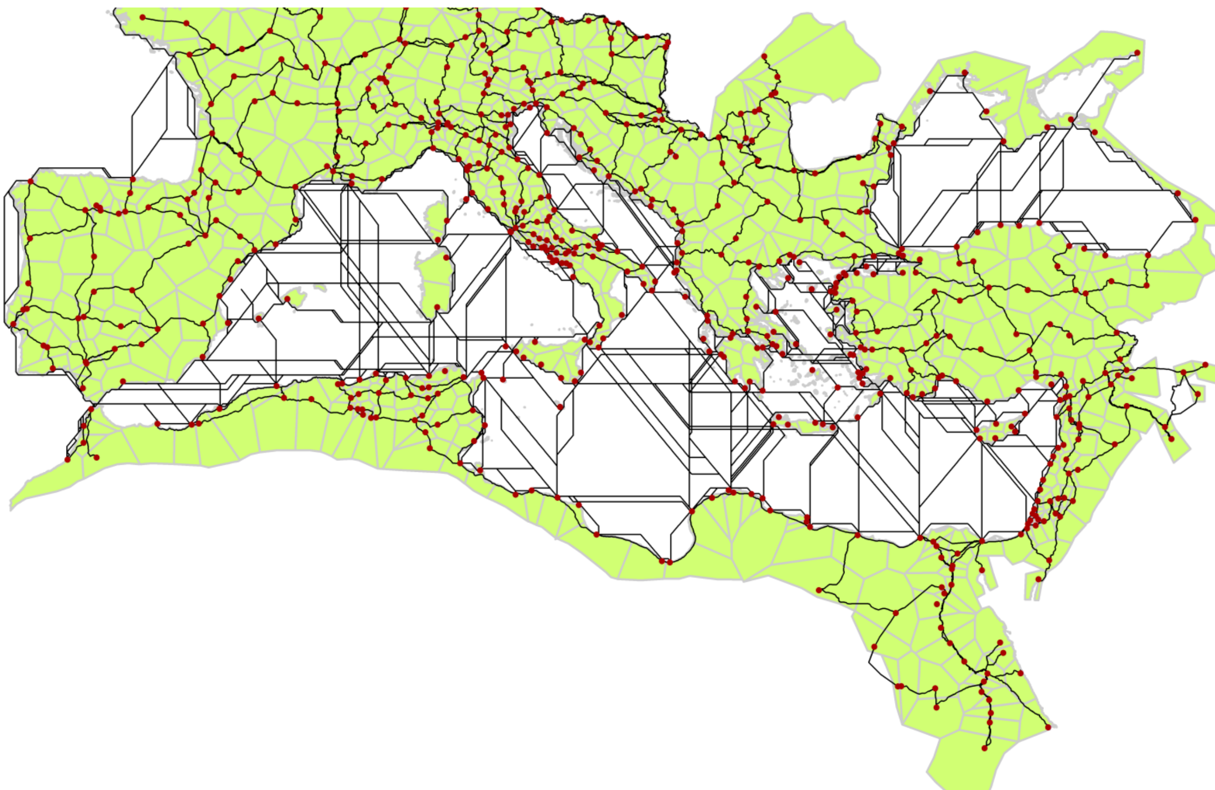
As mentioned, the details of the Orbis network have been published previously and those publications contain details of how the network was generated and the uncertainties, assumptions etc. contained within. Therefore, we did not regard it as necessary to go into those details here. However, we have added the following sentences to the methods section for clarity: Orbis broadly reflects the transport network in the Roman Empire around 200 AD. All links are confirmed as Roman era transport routes although we cannot be certain that all were active in 200 AD. Orbis should be taken in the spirit for which it was intended, which is to outline the dramatic contrasts between terrestrial, fluvial, and maritime transportation expenses and the patterns they imposed on the flow of goods within the Roman Empire.

Without the flexibility to adapt the structure, one is unable to see how the presented paper allows us to explore complex emergent sociohydrological responses. In fact, not knowing whether all the edges of Orbis were active during the period under study, one may even overestimate the resilience provided by the VW network.

As we have stated we apply a scenario-based approach to answering the question of how Roman water resource management practices impacted their resilience to climate variability. By studying the Roman civilisation's relation with their water resources we can uncover whether their water management practices provided them with greater resilience or vulnerability to climate change. For example, we can ask whether the fall of the Western Roman Empire and persistence of the Eastern Roman Empire was related to their water management practices. However, if we adapt the network from what it was then we cannot ask those questions. Instead we are asking a question about some imagined past civilisation. It is useful in certain circumstances to ask these 'what if' questions. However, one of the principal advantages of using historical data is we can constrain our analysis based on historical reconstructions and compare our results with what actually happened (given the inherent uncertainties of historical reconstructions).

It is also important to note that the trade network is cost-distance based and links follow physical environmental constraints. For example, roads tend to follow the least cost distance between cities, ships take the least cost distance between ports or along rivers etc. Given the same technological conditions these constraints will remain the same, meaning that there is not so much adaptive capacity in the network as opposed to present-day air freight for example. Although the reviewer may question the struggle against distance was the major constraint to trade in bulk goods in ancient civilisations, there is a wealth of historical literature that provide convincing evidence that it was (Braudel, 1995; Scheidel, 2013).

All nodes and links are active in the study, however in figure 4 of the discussion paper the size of nodes is based on the amount of VW exported or imported and the thickness of links is based on the volume of VW that flows along them. Therefore nodes or links with little VW export, import or flow are not visible. We have provided a map of the Orbis network in the supplement of the revised manuscript so that readers have a clear impression of the network structure (Reviewer 2, Figure 1).



Reviewer 2, Figure 1. Orbis trade network structure. Trade links are plotted in black, nodes are plotted in red. City regions are based on a Theissen polygon operation between neighbouring nodes.

9. Last paragraph, page 6573 and page 6574: It is confusing that the arguments about the variation in yields with increasing temperature/precipitation are interchangeably made in space and time. Though it is based on spatial analysis averaged over 50 years of simulation.

We have endeavoured to clarify this point.

10. The argument that import cost is closely related to node degree is perhaps a consequence of the VW redistribution algorithm. One may wonder if it may even be independent of the underlying network structure.

In a cost-distance network where importing regions attempt to minimize the import distance and cost, the relation we demonstrate between node degree and cost will hold. We demonstrated the relation between cost and node degree is consistent even when link costs are randomly reassigned within the network. We have not tested whether the finding is independent of network structure but since most real-world networks and probably all trade networks follow the same skewed node degree distribution (Serrano and Boguñá, 2003) our findings are widely applicable.

In this referee's opinion, it is not something that "emerges" from the model but is a consequence of the VW redistribution algorithm itself. Given the lack of information on the VW redistribution algorithm, it is unclear whether this is indeed the case.

We have provided more details of the VW redistribution algorithm (see reviewer 2, comment 7).

We have removed the word 'emerge' or any variations of it from the manuscript. Although the patterns are emergent from agent-based decision rules, the use of the word appears to provide a misleading representation of our analysis, which was not our intention.

11. The authors have ignored the point that the network structure that existed during Roman times possibly emerged alongside the spatial distribution of affluence, labor specialization and emergence of social classes. Thus high cost edges from interior nodes existed because those nodes can afford it for one reason or the other, either because they were the ones who controlled the hubs, trade routes, inland trade routes, who controlled the political power etc. A resilience test of a socio-hydrological system in context of virtual water trade therefore does not reside in sensitivity of import costs to climate variability and population growth for a given network structure but how the network structure itself adapts to changing conditions and to what extent can it adapt. Population itself may adapt along with the network structure and it is this possibility of co-adaption of human and water system to climate variability that defines the resilience of socio-hydrological system.

Population distribution did change during the Roman period owing to the factors the reviewer mentions as well as others. As we state earlier, our analysis is based on a scenario approach using a reconstruction of the Empire in 200 AD. Based on our methodology we can diagnose what aspects of the Roman water resource management infrastructure provided resilience or vulnerability to climate variability. We can also identify which regions of the network were more vulnerable or resilient to the pressures of climate, population growth and urbanisation. By comparing our analysis with what happened later in the history of the Empire we can begin to understand whether the vulnerabilities we identify had an impact on the Roman civilisation. In this way, historical analysis allows us build and test hypotheses of socio-hydrological systems. In the revised manuscript we have clarified our motivation for carrying out our analysis in this way.

As we have outlined (reviewer 2, comment 8), once we adapt the network we are no longer basing our analysis on historical reconstructions but rather some imagined version of history. That can be highly informative but we wanted to constrain our analysis to the historical data as much as possible here. However, it would be interesting in future to examine emergent behaviour within the constraints of the reconstructed trade network. For example, in the discussion paper we identified that the trade routes we identify are different from what we know from historical data about Roman trade. We proposed that this is owing to the importance of yield stability in exporting regions and inefficient information transfer in Roman times. A way to explore if that is the case would be to provide VW poor agents with decision rules that make them more inclined to import from VW rich nodes that have supplied them with sufficient grain in previous years. The emergent trade routes would take into account the stability of yields in exporting regions. If the emergent trade routes are reflective of the trade routes we know from historical sources, that would contribute to supporting our thesis that stability of yields was an important factor in determining VW redistribution in addition to the struggle against distance.

Nonetheless, it is our strong conviction that the network analysis carried out in the discussion paper allows us to draw the conclusions outlined below:

- Trade provided stable food supplies in response to interannual climate variability but also promoted population growth and urbanisation in the long term.

- Population growth and urbanisation increased the pressure on water resources and pushed the Empire closer to the boundary of its ecohydrological carrying capacity. Thus the resilience provided by trade in the short term was eroded by the population growth and urbanisation it promoted in the long term.
- The increased competition for water resources arising from urbanisation and population growth meant that import distance and cost increased as the most easily accessible water resources were exploited.
- The increase in import cost was not evenly distributed within the network with coastal hub nodes experiencing the most dramatic increase in costs.

12. Finally, the authors appear to invoke the relationships between stability and inefficient information transfer to counter the discrepancy between model simulations and historical records of the export regions of VW to Rome. The trade in grains probably occured for reasons not limited to what the agent based model of the authors prescribes. These include wage rates, opportunity cost of land and water, type of governance, trade in other commodities etc.The authors appear to have missed such critical aspects of VW trade. It is in this sense that the analysis is unbalanced: a complex hydrological model with a "suitability" algorithm to downscale HYDE but being inadequate in their modeling of VW trade. The scope of the study is to study the resilience of the socio-hydrological system to climate variability, which warrants a more complex representation of the VW trade but perhaps that is incompatible with the current complexity of the underlying land surface hydrology.

The Orbis network is based on Diocletian's Edict on Maximum prices as well as physical cost distance constraints. Given that the network is based on historical evidence and physical constraints it incorporates many of the factors the reviewer mentions. That is an advantage of using historical information to constrain such analysis. It would be impossible to model all the factors that contribute to trade dynamics. However, by basing our trade network on historical data and physical constraints we incorporate many of those factors without actually explicitly modelling them.

We have addressed the other remarks in this comment earlier.

13. There appears to be a lack of coherent structure to modeling the underlying socio-hydrological system.

We regret to read that it is the reviewer's opinion that the modelling lacks a coherent structure. We have revised the methods section of the revised manuscript based on both reviewer's comments and recommendations. We trust that these changes will clarify how the analysis was done and the motivations for carrying out the methodology in the way we did.

The authors appear to have incrementally contributed to the manuscript based on their expertise (and appear to have been guided by that and not by the research question), which probably has led to a mismatch between the resolution of land surface modeling, VW redistribution modeling and available historical information.

We can assure reviewer 2 that the research question arose first. Fortunately the principal author was able to establish collaboration among an interdisciplinary group of researchers at the forefront of the fields of hydrological modelling, Roman geography, trade and economics, past land cover reconstructions, agent-based modelling and climate in the Mediterranean during the Roman period.

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