Faculty of Geosciences
Copernicus Institute of Sustainable Development
Department of Environmental Sciences

Universiteit Utrecht

A Virtual Water Network of the Roman World

B. J. Dermody[1], Rens P.H. van Beek[2], Elijah Meeks[3], Kees Klein Goldewijk[1,4], Walter Scheidel[5], Y. van der Velde[6], M. F. P. Bierkens[2], M. J. Wassen[1] and S. C. Dekker[1]

1. Utrecht University, Department of Environmental Sciences, Copernicus Institute, the Netherlands
2. Utrecht University, Department of Physical Geography, the Netherlands
3. Stanford University Library, USA
4. Netherlands Environmental Assessment Agency, De Bilt, the Netherlands
5. Stanford University, Department of Classics, USA
6. Wageningen University, Department of soil, geography and landscape, the Netherlands

Overview

Water resource management through irrigation and virtual water trade has enabled societies throughout history to persist in regions with insufficient water resources. The Roman civilisation were one of the most impressive exponents of water resource management in preindustrial times. To understand Roman water management in response to urbanisation and climate variability, a virtual water redistribution network for the Roman World was developed.

Methodology

- Virtual Water (based on wheat yields) was calculated in PC Raster Global Water Balance Model (PCR-GLOBWB) (van Beek et al., 2011) at 5' horizontal resolution based on 52 years of climate forcing
- Cropland fractions were assigned according to the Historical Database of the Global Environment (HYDE) (Klein Goldewijk et al., 2011). Irrigated agricultural fractions were assigned based on the MIRCA dataset (Portmann et al., 2008). Natural landcover was based on the Olson classification (Olson, 1994a and 1994b).
- Virtual water surplus and deficits were calculated per 5' cell based on an annual wheat demand of 200kg per person. Population was based on HYDE with corrections for the largest cities based on Chandler's (1987) reconstructions of urban growth.
- The surplus and deficits in virtual water were abstracted to Orbis, the Stanford Geospatial Network of the Roman World (Scheidel, 2013) to form virtual water rich and virtual water poor nodes
- The yearly redistribution of virtual water from VW rich to VW poor nodes was simulated in Netlogo. We examined the response of the virtual water network to climate variability and changing demand arising from urbanisation

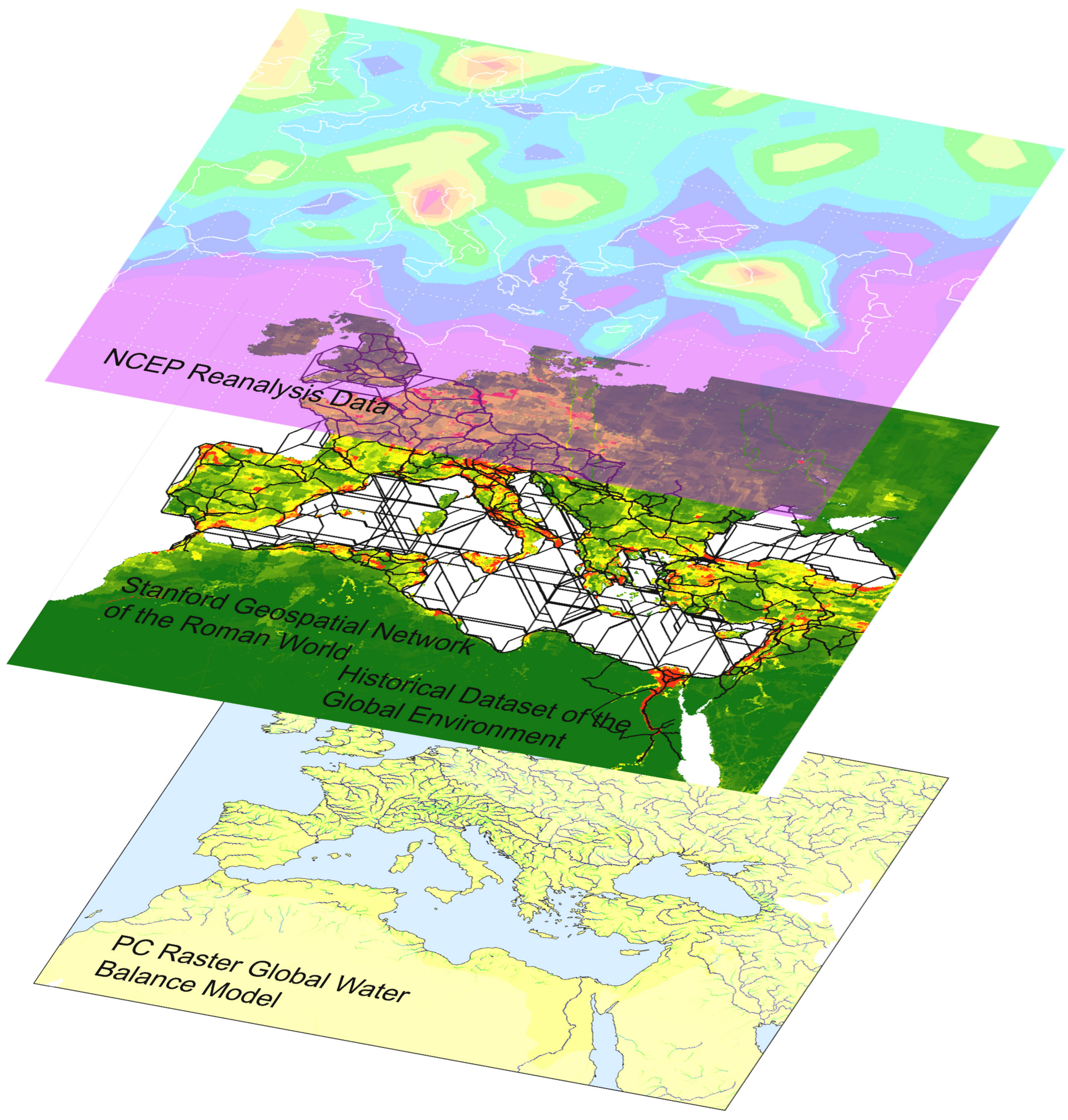

Figure 1. The component layers of our Virtual Water Network of the Roman World. .*Not shown*: the MIRCA dataset of global monthly rainfed and irrigated crops, Chandler (1987) estimates of urban population growth, Olson classification of natural landcover (Olson, 1994a and 1994b).

Conclusions

1. The majority of the Mediterranean is temperature-limited for winter wheat production (Fig.3) Thus conditions were likely optimal for grain production during the warm, Roman climatic optimum
2. Irrigation and virtual water redistribution provided the Romans with high resilience to climate variability (Fig. 4 and 5)
3. Virtual water redistribution during the Roman Period contributed to urbanisation as the import of water resources allowed cities to overshoot their ecohydrologically-controlled carrying capacities. (Fig. 5) This urbanisation likely reduced the redundancy of water resources in the Mediterranean region and led to an average increase in import distance and cost (Fig. 6).
4. Increases in import distance and cost are not evenly distributed with higher degree nodes experiencing greater increases in import costs as demand increases compared with low degree nodes (Fig. 6)

Results: yield calculation

1. Yields highest in Egypt, Southern Spain, Po Valley, the Fertile Crescent and Thrace (Fig. 2)
2. In most of the Mediterranean winter wheat is temperature limited rather than water limited (Fig. 3).
3. Year to year stability in yields are highest in the Eastern Mediterranean and North Africa. France and Spain have relatively low yield stability (Fig. 4)

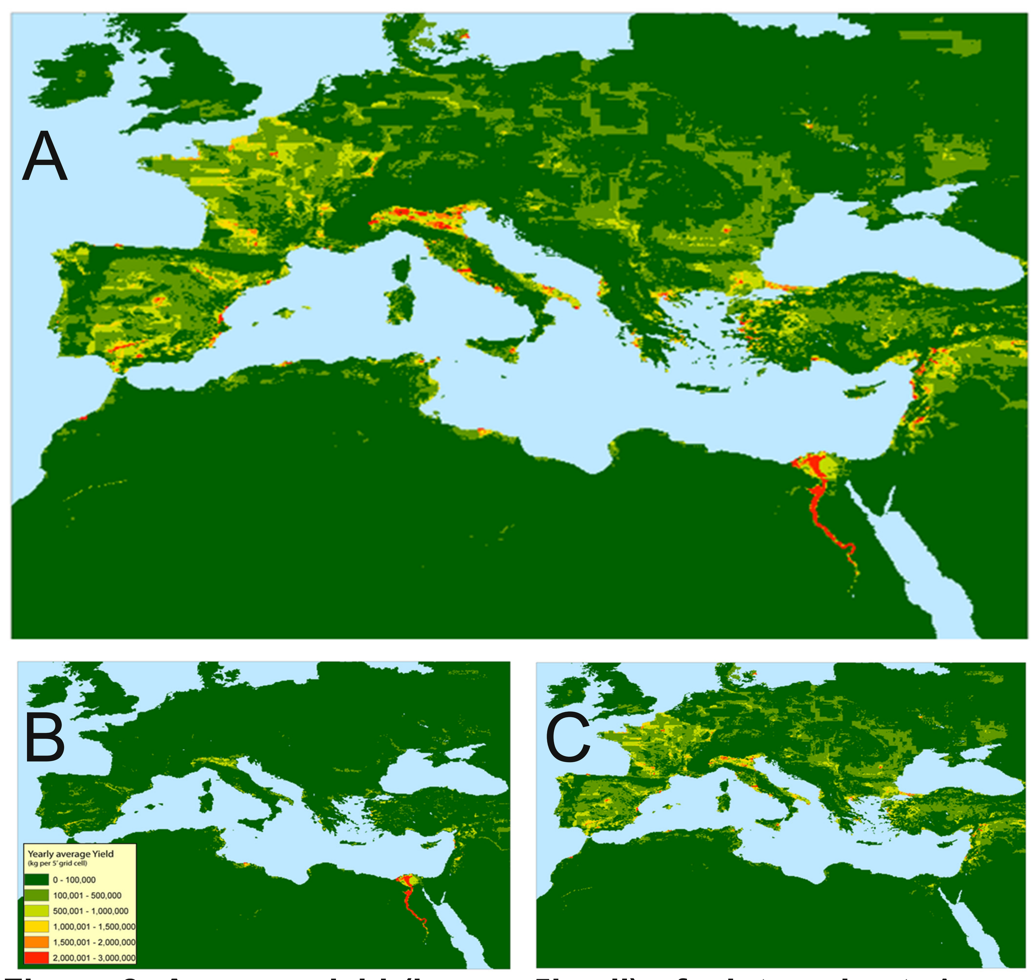

Figure 2. Average yield (kg per 5' cell) of winter wheat. Average winter wheat yield calculated in PCR GLOBWB and based on 52 years of climate forcing (A). The yields from irrigated (B) and rainfed (C) agriculture are shown separately. Yields were underestimated in parts of North Africa and Sicily based on historical evidence of grain exports from these two regions.

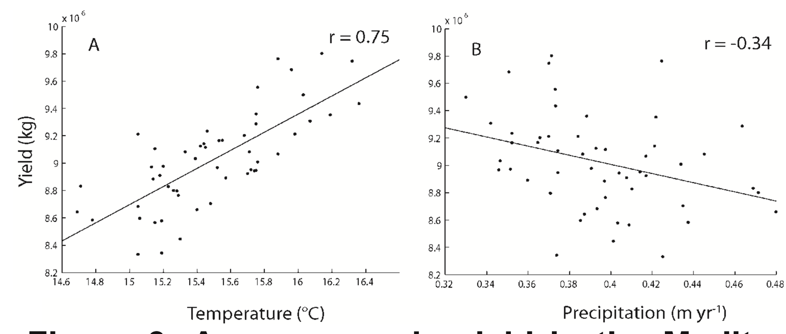

Figure 3. Average yearly yield in the Mediterranean plotted against temperature and precipitation. Wheat yields increase under increasing temperature and decrease under increasing precipitation

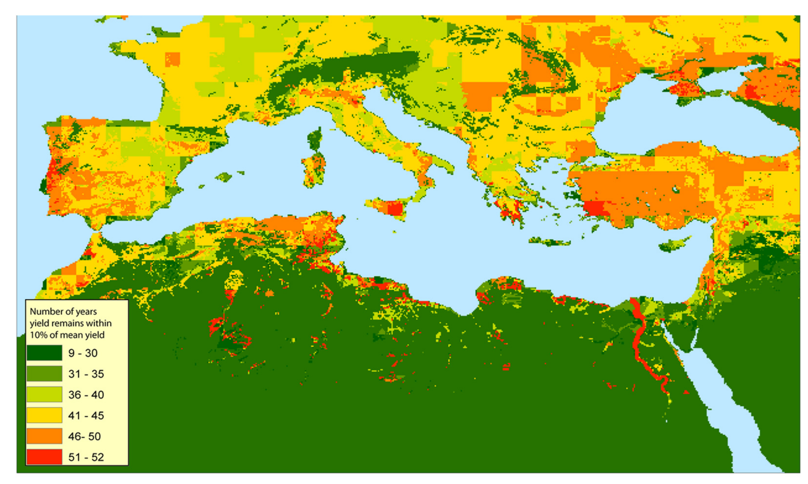

Figure 4. The stability yields over time. The map shows in how many years the total annual yield in each cell remains above 90% of the average yield for the same cell calculated over 52 years of climate forcing. In the Nile Valley, yields remain within 90% of the average yield in all years, meaning that yields are exceptionally stable. Regions of Northern Spain and Northern France are relatively unstable with yields dropping below 90% at least 40 out of 52 years.

Results: virtual water redistribution

1. Virtual water flows are largest between Spain and Rome with large flows also within Egypt, along the western coast of Turkey, along the Southern Italian coast and between Egypt and Southern Italy
2. Rome is by far the largest importer of virtual water, whilst Egypt and Spain are the largest exporters
3. Import costs decrease with increasing node degree as neighbouring nodes are more slowly depleted
4. Under increasing demand, import distances and costs increase more rapidly for higher degree nodes compared with lower degree nodes

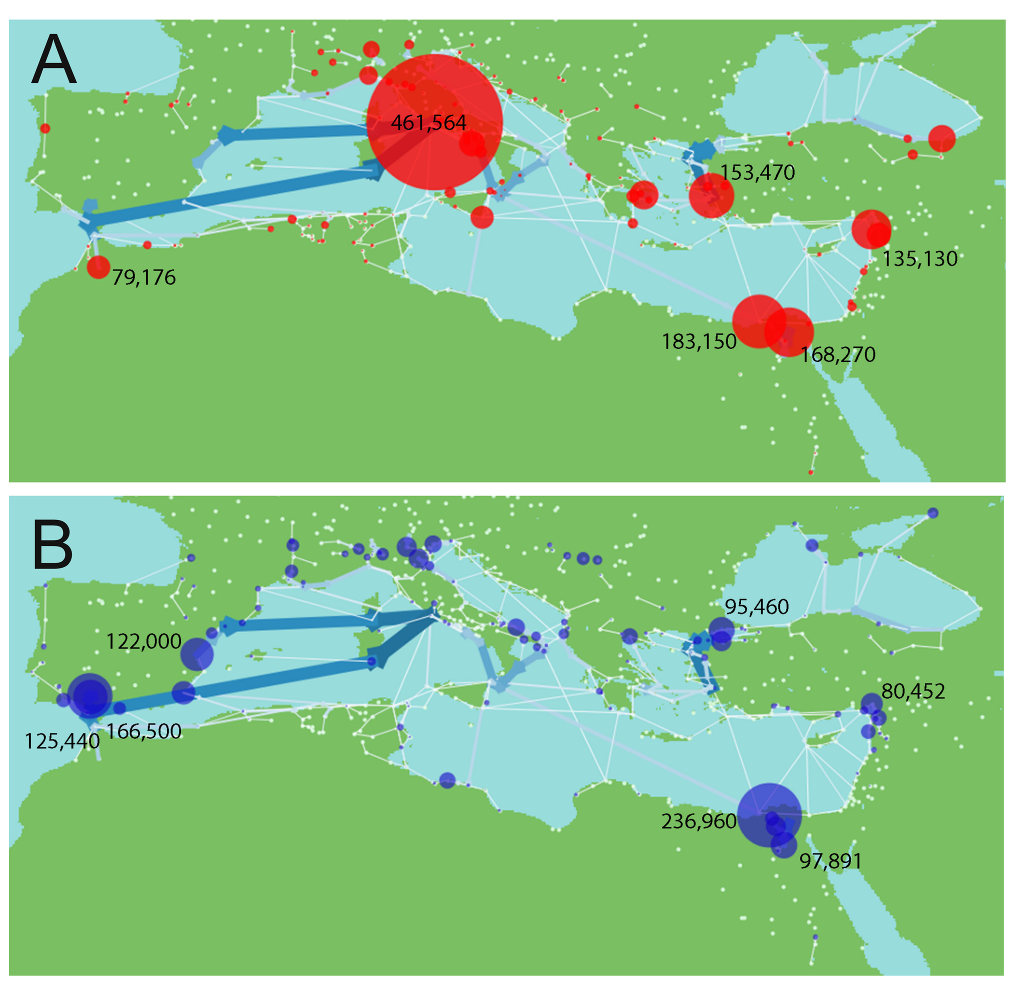

Figure 5. Virtual water Imports and exports. The relative amount of VW imported and exported from each node is illustrated by the size of the nodes, whilst the associated numbers show deficit (A) or surplus (B) in terms of per person population demand at a yearly consumption of 200 kg of grain. The edge colour and thickness indicates the relative volume of VW flow between nodes. Our model does not simulate the problems with information transfer in Roman times. Owing to difficulty in information transfer the Romans placed greater value on the stable harvests from Egypt , North Africa and Sicily (Fig. 4) rather than large but more variable yields from Spain

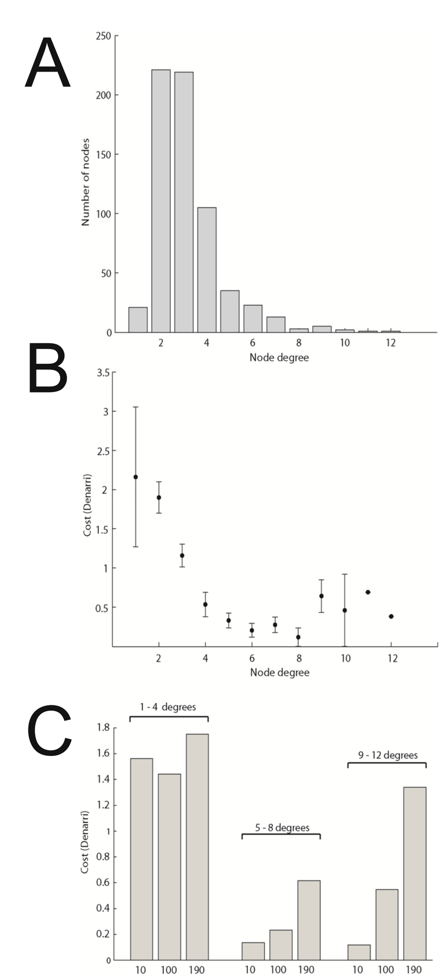

Figure 6. Virtual water import costs in relation to node degree. (A) The node degree distribution of the virtual water redistribution network. **(B)** Lower degree nodes generally have higher import costs **(C)** For nodes with 1 – 4 links, import costs remain high irrespective of the level of demand. However, for nodes with 5 – 8 links and 9 -12 links, costs increase under increasing demand.