Transportation Research Part D 82 (2020) 102159

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Forecasting the impacts of climate change on inland waterways

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ARTICLE INFO

Keywords:
Inland waterways
Climate change
Droughts
River discharges
Low water levels
Impacts on transport

ABSTRACT

Inland waterways are vulnerable to climate change as river navigation depends on water levels. Droughts can severely disrupt inland navigation services by reducing water levels either to completely non-navigable ones or to levels that oblige operators to reduce vessel load. We analyse the impacts of droughts induced by climate change using projections of river discharge data provided by eleven different climate model runs. We consider location specific characteristics by focusing the analysis on four specific locations of the Rhine and the Danube where a substantial part of the total freight activity in the European Union (EU) takes place. For the majority of the cases and scenarios considered, a decrease of the number of low water level days is projected, leading to fewer drought related disruptions in the operation of the inland waterway transport system. Although the uncertainties from the climate projections should not be neglected, the navigation sector could benefit from global warming which means that European inland waterways might be one of the few sectors where climate change can have negligible, or even positive, impact. The average economic benefit, for the cases considered, from the decrease of low water levels by the end of the century is projected to be almost €8million annually.

1. Introduction

Inland Waterways (IWW) play a significant role in freight transportation in Europe. The freight activity by IWW between EU Member States is only slightly smaller to that carried out by rail and one third of the corresponding figure by road. IWW are considered to be a very reliable mode, but can be more vulnerable to climate change than road or rail because of the reliance of river navigation on water levels and the limited flexibility of the European inland waterways network. Extreme weather events affecting IWW include floods during which water levels exceed the maximum permitted ones and droughts due to which water levels become critically low imposing limitations to navigation services (Jonkeren et al., 2007).

Besides the water levels, the formation of ice can also be disruptive to the operation of IWW especially in slow flowing rivers; for example shipping on the Danube was interrupted for several days during the winters of 2005 and 2006 due to ice formation (Scholten and Rothstein, 2016). However ice has limited effects in terms of duration or frequency, which are expected to be reduced further due to the projected increase of temperatures in the (mid- and long-term) future.

Higher than normal water levels can affect IWW navigation especially when they exceed a critical limit as determined by infrastructure while stronger and adverse currents can increase the likelihood of accidents currents and travel times. The impacts of the latter would be impossible to consider as we do not have projections on currents while, regarding the former, floods are considered to have less severe impacts on IWW transportation than droughts because of their relatively shorter duration (Hendrickx and

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https://doi.org/10.1016/j.trd.2019.10.012

Breemersch, 2012; Scholten and Rothstein, 2016; Jonkeren et al., 2007). In addition, droughts can severely disrupt inland navigation services by reducing water levels either to completely non-navigable ones or, more frequently, to levels at which operators are forced to reduce the vessels' load factors. The analysis of the daily variation of the discharge data over the modelled period shows that the lower limit of water levels tends to be exceeded more frequently than the higher one. This indicates that low discharge levels are expected to be more disruptive to IWW traffic than high ones.

Droughts and as a result low water levels, may disrupt IWW activity by imposing restrictions to the amounts of loads transported, increasing the number of vessels to compensate reduced load factors or increasing travel times when vessels stop and wait for the water levels to rise again. Furthermore, a possible reaction of the market to disrupted navigation services might be shifting to more resilient to climate change (but more environmentally harmful in terms of carbon emissions per tonne of cargo) modes such as road. Jonkeren et al. (2011) found in their study which focused on the impacts of climate change on the river Rhine that the effect of low water levels on modal split is limited. They estimated that the majority of the freight lost in IWW will be transported by road transport (around 70%) with negative impacts on the environment (higher emissions) and further loading of an already congested road network.

Our main objective in this paper is to assess the economic implications of climate change for inland waterways transport by taking into account the uncertainty associated with climate projections. We focus on the impacts of droughts on four key ports on the Rhine and the Danube. We use high resolution projections of future water discharges based on different long term climate model runs. Our method allows the estimation of the number of days for which the water levels at each point examined will be below the threshold determined for each type of ship and quantifies the cost or benefit compared to the historical frequencies of such events.

The estimation of the economic impacts of climate change is of high importance for policy-makers and can influence decisions regarding relevant investments. We estimate a moderate but positive impact on the majority of the cases considered as a result of a decrease of low water levels. Furthermore, this exercise highlights the importance of multiple factors including spatial detail when estimating the impacts on transport. Assessing the impacts of climate change is a particularly challenging task and one of the reasons is uncertainty. Particularly for measuring the impacts of climate change on transport, uncertainty is very distorting because the level of detail (including spatial resolution) required to measure vulnerability is difficult to be matched by the level of detail at which climate projections are commonly produced. In order to address the issue of uncertainty, the economic impacts of droughts on IWW are estimated using eleven different climate model runs while a hydrological model is used to produce river discharge projections.

This study was completed in the context of PESETA III project (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis)[1] in which other transport sectors considered include seaports (Christodoulou et al., 2018) and airports. The economic impacts of droughts are quantified by focusing on the impacts of change of transport activity in terms of cargo transported or, better, cargo transportation potential of a given fleet. The impacts of climate change on IWW are estimated by combining physical impacts with activity data on the IWW network.

2. Measuring the impacts of droughts on inland waterways

Droughts and resulting low water levels affect the operation of IWW. Water levels are directly related to discharges and the riverbed morphology at a specific part of the river, which means that the relationship between water levels and discharges has to be location specific. The morphology of the riverbed changes over time and as a result water levels are difficult to compare over long time-periods. Hence, discharges are commonly used for relevant types of analysis instead of water levels (Nilson et al., 2012).

In this study, we combine daily discharge values with information on the relationship between water levels and discharges[2] in order to identify critical discharge levels. Depending on each scenario's expected frequency of low water levels, we estimate the impacts on transport activity and relevant costs for different scenarios. The relation between water levels and discharges might change – even drastically in some cases – over time while it can be affected by human interventions. The U.S. Geological Survey estimated for the Mississippi and Missouri rivers more than two meters changes of the waters levels corresponding to the same discharges during the last two centuries.[3] However, even in the same river there might be opposite trends in different locations while even in the same locations, the changes might fluctuate from positive to negative over the years (Pinter et al., 2006). Considering that relevant trends are not necessarily consistent but also the scope of this study, a constant relationship between water level and discharges is used to estimate the impacts of projected discharges ceteris paribus.

We focus on four critical points on the Rhine and Danube rivers which account for a large part of the total activity on the IWW network. Only the Rhine accounts for around 70% of the total IWW transport activity of the former EU15 member states (Jonkeren et al., 2007). The four points were selected based on a combination of criteria including their importance as freight nodes, the effect of low water levels and the availability of data. The selected points are the following: Wildungsmauer (Danube), Hofkirchen (Danube), Ruhrort (Rhine) and Kaub (Rhine). The same points were also analysed in the ECCONET project (Beuthe et al., 2014; Hendrickx and Breemersch, 2012, Holtmann et al., 2012) while Kaub is referred to as a key bottleneck of Rhine in several studies (Jonkeren et al., 2007, 2011, 2014; Beuthe et al., 2014). Jonkeren et al (2011) argue that they "have chosen Kaub as a reference point, because it is here that restrictions related to low water levels are most severe. For the barge trips that pass Kaub, the water level at Kaub is the critical point for the maximum possible load factor and thus also for the costs (or price) per tonne transported."

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[1] https://ec.europa.eu/jrc/en/peseta-iii.

[2] E.g. ELWIS, 2016; Scholten and Rothstein, 2016; https://www.pegelonline.wsv.de/gast/start

[3] https://www.umesc.usgs.gov/aquatic/jwlosinski_5001295.html.

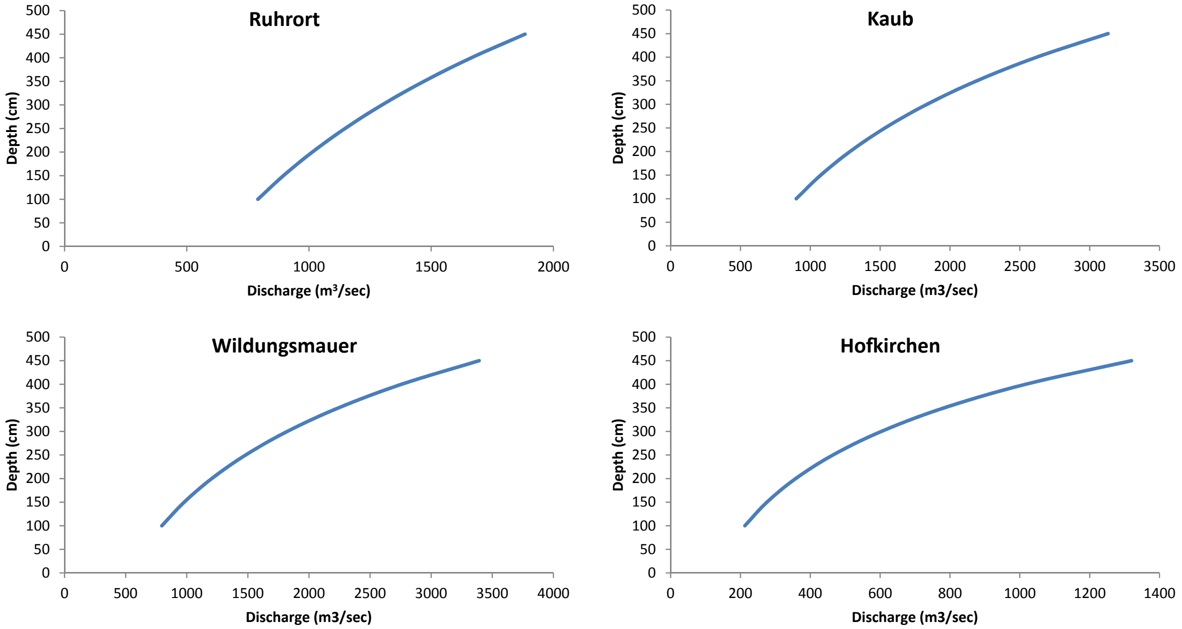

Fig. 1. Relationship between water depth and discharge for the points considered.

Low water levels affect IWW transportation by reducing the navigability of vessels. Practically, up to a certain level of water the maximum draught of the ship cannot be utilised and the ship has to be operated at limited capacity, i.e. the cargo that can be transported is reduced. As a result, more vessels have to be operated, or ships have to wait until water levels will rise, or the total amount to be transported has to be reduced in absolute values. Although the positive relationship between cargo amounts and water levels has been proven using detailed data for specific gauges, the number of ships seems to be weakly connected to water levels for both the Danube and the Rhine rivers (Scholten and Rothstein, 2016).

Furthermore, under certain demand it is expected that prices should have a negative relationship with water levels. Jonkeren et al. (2007) found that price per tonne may increase significantly during periods of low water levels, especially for vessels passing from Kaub. On the other hand, the results in Scholten and Rothstein (2016) do not clearly indicate a similar tendency. In general, market prices are affected by various factors, including seasonal demand, mode competition, direction of trip (the prices for upstream trips are higher than those for downstream trips as fuel consumption is higher), closure of a gauge for other reasons etc. The consideration of price differentiation according to water levels is beyond the scope of this study, especially taking into account the long term projections used and data restrictions. However, as will be shown later, to represent price variation a range of prices is used for the monetary cost estimation.

The most important assumptions that have been made for the estimation of the impacts of climate change on inland waterways transport are summarised in the following points:

- The estimation of the impacts of droughts is based on discharges. The correlations between water levels and discharges for the four points are shown in Fig. 1. They have been determined using data from comprehensive and reliable sources including the following ones: ELWIS (2016), BMLFUW (2012), Scholten and Rothstein (2016), Bolle and Schwab (1980), https://www.pegelonline.wsv.de and http://undine.bafg.de. ELWIS and Pegel-Online datasets/information systems are supported by the General Direction for Federal Waterways and Shipping in Germany (Wasserstrassen- und Schifffahrtsverwaltung des Bundes, Generaldirektion Wasserstarssen und Schifffahrt), BMLFUW refers to the Austrian Federal Ministry for Agriculture, Forestry, Environment and Water while the Undine information platform is supported by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety of Germany.
- The relationships between discharges and water levels have been determined based on time-series data and are assumed to remain unchanged over the course of the projection period. Forecasting the over-time development of these relationships would be extremely complicated, considering the relevant changes of the waterbed, sediment transport etc., and beyond the scopes of this study. Furthermore, trends might not be consistent and changes might fluctuate from positive to negative (Pinter et al., 2006)
- The assessment of the impact of droughts on transport activity is based on the relationship of the bearing capacity of vessels with water levels. Key variable is the level of discharges, or better, the distribution of the time periods according to discharge levels. Transport activity data are given in average annual day tonnes and are assumed to correspond to normal water levels. This level of detail for an analysis of future impacts is quite unique and could only be achieved with the help of high spatial and temporal resolution discharge data.
- The transport activity considered is the total activity on the links intersecting the points examined. Activity and its distribution to

different types of vessels are assumed to remain unchanged over the projection period. Activity projections, that could be used to relax this assumption, would be still subject to other assumptions and very difficult to obtain at this level of spatial detail. Hence, they would not be without noise which should be also considered in the interpretation of the results. Furthermore, by not changing activity over time, we can evaluate the impacts that future climate conditions would have on current activity and obtain easy to interpret estimates.

- Transport costs per day were determined by combining cost data (cost per tonne) for specific trips with average travel time estimates for these trips. The difference between the low and high values used is meant to serve as an indication of the variation of prices that may occur for different reasons, including direction of trip (upstream or downstream), seasonality, etc. The potential impact of water levels on cost is not modelled explicitly and costs are assumed to remain constant over time. On one hand, assuming no changes over time might be a strong assumption but, on the other hand, it ensures that the calculated monetary cost reflects only the impact of climate change.

The main steps taken for the estimation of the economic impacts of low water levels are the following:

- Data on river discharges are used to calculate the number of days with discharge values within location-specific thresholds. Daily projections of river discharges offer a great opportunity to specify with precision the level of operation of the IWW system during the year.
- The results are combined with data on IWW freight activity and indicators regarding the impact of water levels on the bearing capacity of different types of vessels to estimate the impact on the amounts of cargo transported. By using activity at link level we focus on freight associated with the specific locations which is a good estimation of the traffic to be affected according to the duration of a drought event.
- The resulting cost or benefit is estimated by combining freight activity with transport cost values and comparing with the reference period. By maintaining the levels of activity and costs over time, the monetary differences can be attributed to climate change and refer to present day values.

These steps will be described in more detail in the following sections.

3. Calculation and data

3.1. River discharges

We model the impacts of droughts on inland waterways using the discharge levels produced by the LISFLOOD hydrological model. LISFLOOD is a GIS-based spatially-distributed hydrological rainfall-runoff model (De Roo et al., 2000; Van der Knijff et al., 2008; Burek et al., 2013). The LISFLOOD model calculates a complete water balance at a daily time step for every grid-cell (5 × 5 km). The produced runoff is routed through the river network. More details on the model setup can be found in Burek et al. (2013).

To understand the current and projected future climate, numerical climate models are used to describe the physical processes of the climate system. General circulation models (GCMs) describe the various climate components at a global scale. Due to the high complexity of GCMs, it requires a large amount of computational resources. Therefore, regional climate models (RCMs) are using the GCM output data to describe the local consequences of the global change in more detail. Every model applies different but plausible methodologies to simplify the representation of earth's physical processes and therefore generates different outcomes to describe current and future climate, also known as climate modelling uncertainty. To account for this uncertainty within the framework of the PESETA III project (Ciscar et al., 2018), 11 climate simulations within the EURO-CORDEX initiative (Jacob et al., 2014) are selected for current and future climate (Table 1).

The simulations of the future climate in EURO-CORDEX use the new Representative Concentration Pathways (RCPs) as defined in the Fifth Assessment Report of the IPCC (Moss et al., 2010). The climate projections considered in this work are all based on RCP8.5 (Riahi et al., 2011). The RCP8.5 scenario represents a situation in which emissions continue to increase rapidly (worst case scenario),

Table 1
EURO-CORDEX climate projections used in this study.

	Institute	GCM	RCM
1	CLMcom	CNRM-CM5	CCLM4-8-17
2	CLMcom	EC-EARTH	CCLM4-8-17
3	IPSL	IPSL-CM5A-MR	INERIS-WRF331F
4	SMHI	HadGEM2-ES	RCA4
5	SMHI	MPI-ESM-LR	RCA4
6	SMHI	IPSL-CM5A-MR	RCA4
7	SMHI	EC-EARTH	RCA4
8	SMHI	CNRM-CM5	RCA4
9	DMI	EC-EARTH	HIRHAM5
10	KNMI	EC-EARTH	RACMO22E
11	CLMcom	MPI-ESM-LR	CCLM4-8-17

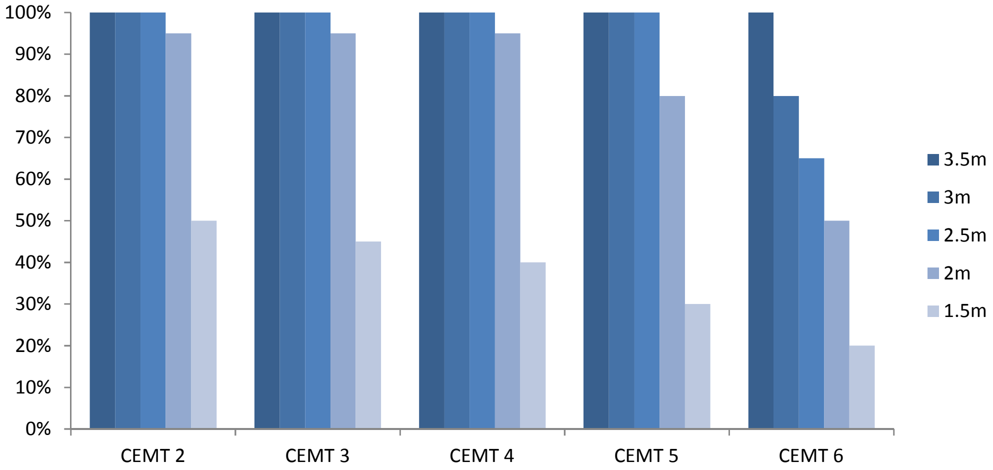

Fig. 2. Bearing capacity of different ship types at different water levels (taken from Scholten and Rothstein (2016) and adjusted).

and typically exceed 3 °C warming before the end of the current century.

After post-processing, the 11 climate projections are used as input for the LISFLOOD model. From LISFLOOD's output, we used the daily discharges (in m^3/s) from 1981 to 2099 to calculate the number of days for which the discharges are within a certain threshold. The results are aggregated to four time periods and the values reported refer to annual average number of days over the three periods of analysis and the historic period:

- Short term future: 2011–2040
- Mid-term future: 2041–2070
- Long-term future: 2071–2099
- Historic period: 1981–2010

Apart from uncertainties in the model structure or parameters, the climate projections used here are accompanied by large uncertainties due to varying, though plausible estimates of future warming. Therefore, we use an ensemble of 11 climate simulations to increase the range of possible input values and ensure that our analysis represents a wide range of plausible future climate projections.

3.2. Bearing capacity

The impacts of low water levels on transport activity and -as a result- on the corresponding costs depend on the draught of the vessel and the gauge of the channel or river. As water levels become lower, vessels operate at reduced capacity in order to reduce their draught, until the point of minimum water at which no transport activity is possible at all.

The thresholds of water levels and discharges depend on the characteristics of the river or channel at a specific point and vary significantly. As a general indication, according to Middelkoop et al. (2001) when the Rhine discharge is below 1000–1200 m^3/s ships on the route from Rotterdam to Basel via Germany have to reduce their loads, while for Vienna the total regulated low water level is 900 m^3/s (values from www.viadonau.org, www.newada.eu).

The technical characteristics, including draught and loading capacity, of the vessels operating on the inland waterway network are specified in UNECE (1996).

Fig. 2 presents the bearing capacity (as proportion) of different types of vessels at given water levels. It has been constructed based on relevant information provided in Scholten and Rothstein (2016) that has been adapted to correspond to the CEMT classification (European Conference of Ministers of Transport) of inland waterways in order to be compatible with the freight activity data. Larger CEMT classes correspond to bigger vessels with bigger drought which are less resilient to the reduction of water levels.

The values in Fig. 2 are combined with transport activity data to estimate the total capacity to be carried through a point at given water levels. The discharges corresponding to the water levels for the specific points on Rhine and Danube are obtained with the help of the relationships presented in Fig. 1.

3.3. Freight activity

For the estimation of the economic impacts of low water levels, transport activity figures for 2015 are used (Fig. 3). Only freight transport is considered and the demand is based on the ASTRA-EC (ASSIST, 2014; TRT, 2003) projections. Transport activity is expressed in average year day tonnes carried by each type of vessel. Following the assignment of demand on the IWW network of

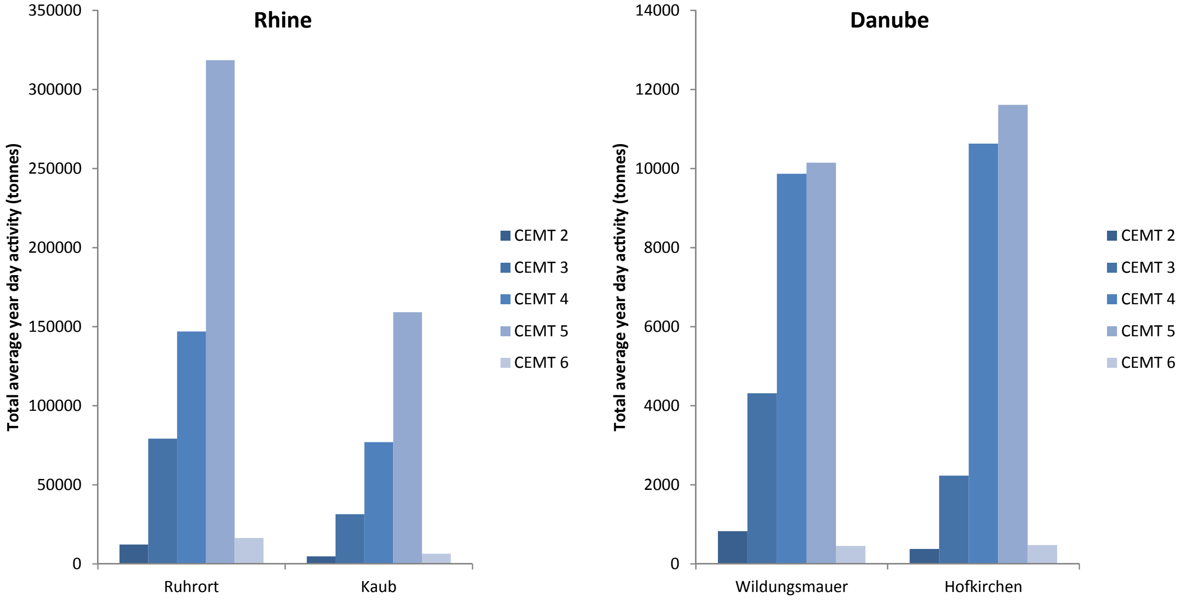

Fig. 3. Transport activity by vessel type at the four points in Rhine and Danube.

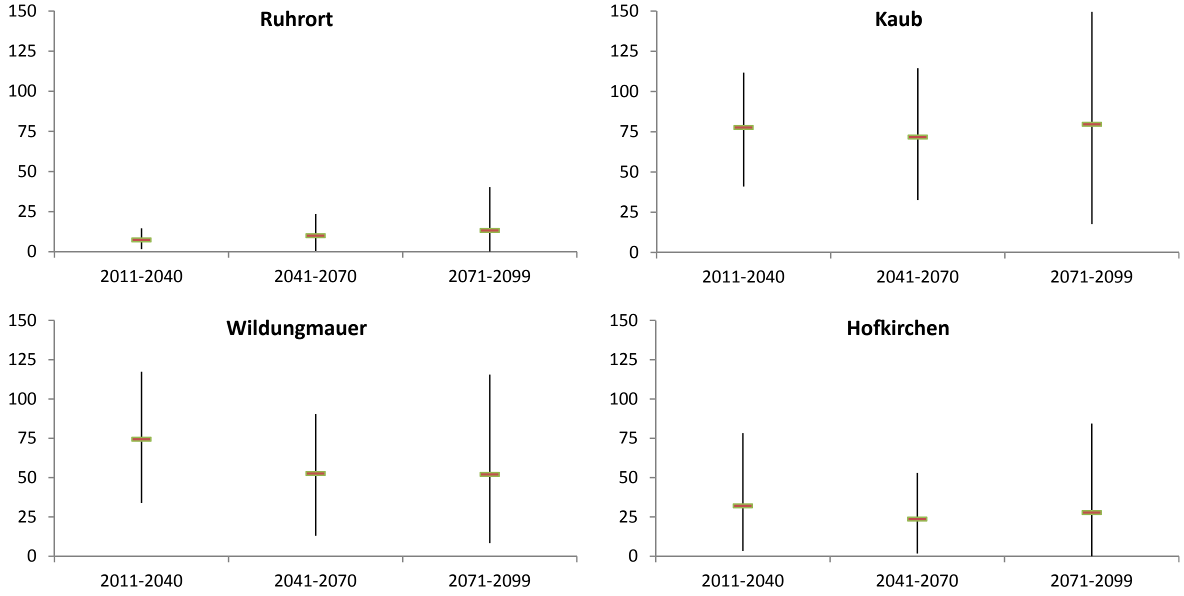

Fig. 4. Average annual number of days with water levels below 1.5 m.

TRANSTOOLS[4], transport flows for each link are estimated. The activity on the four points of interest (Ruhrort, Kaub, Wildungsmauer and Hofkirchen) is calculated by considering the flows (in terms of tonnes) on the links intersecting these points.

4. Results and discussion

4.1. Discharges

We used the discharge values of the eleven model runs to estimate the impacts of low water levels at the four selected points. In order to allow the comparison between the different scenarios and points, the number of days with water levels below 1.5 m is calculated for each of the three future periods and the eleven model runs. The results are presented in Fig. 4 and the vertical lines

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[4] More information on the TRANSTOOLS model: http://energy.jrc.ec.europa.eu/transtools/documentation.html.

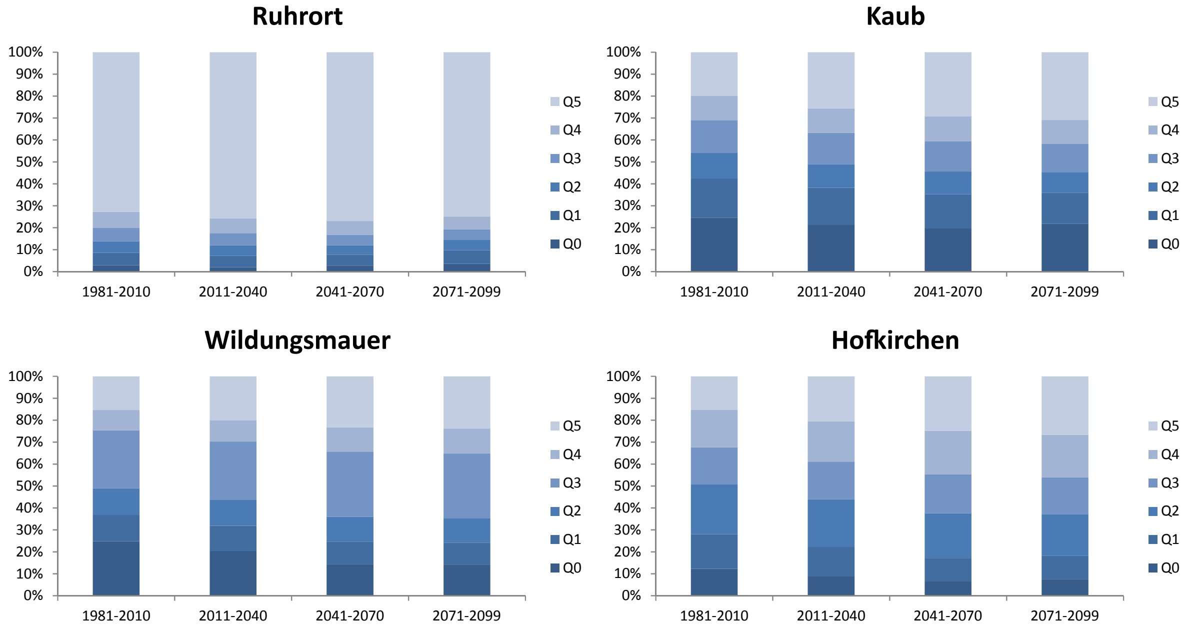

Fig. 5. Distribution of the four time periods for the average of the 11 model runs according to water levels for Ruhrort, Kaub, Wildungsmauer and Hofkirchen.

represent the variability of the different model runs.

For the two sites on the Danube, the number of days with low water levels is projected to decrease compared to the historic period for both points (Wildungsmauer and Hofkirchen). For Ruhrort on Rhine, the average number of low water days is projected to increase while for Kaub on Rhine to marginally increase in the last period (2071–2099) following an initial decline. For comparability, in the ECCONET project (Nilson et al., 2012) a general trend of declining of the number of days with discharges undershooting the 95th percentile of the flow-duration curve was observed during the observed period (1950–2005) for both Rhine and Danube.

Further elaborating on the critical water levels per ship type (Fig. 2), the distribution of the number of days of each of the four time periods to the six following groups is calculated:

- Q0: number of days with discharges corresponding to gauge below 1.5 m
- Q1: number of days with discharges corresponding to gauge between 1.5 m and 2 m
- Q2: number of days with discharges corresponding to gauge between 2 m and 2.5 m
- Q3: number of days with discharges corresponding to gauge between 2.5 m and 3 m
- Q4: number of days with discharges corresponding to gauge between 3 m and 3.5 m
- Q5: number of days with discharges corresponding to gauge higher than 3.5 m

In Fig. 5 the distribution for each one of the four locations is presented. It refers to the average number of days as estimated by the eleven model runs. It is observed that there is a general trend to decrease the number of days with lower water levels and increase the number of days with higher water levels. As a result, the IWW network is projected to operate with fewer disruptions due to low water levels in the specific locations. An exception is Ruhrort, where the frequency of Q3-Q5 events after 2070 is expected to be at marginally higher levels than today. This projection is driven mainly by scenario 10 (Institute: KNMI, GCM = EC-EARTH and RCM = RACMO22E), which assumes a lower discharge volume for the Rhine in the period 2070–2100, a decrease which would be particularly pronounced in Ruhrort (Fig. 6).

4.2. Economic valuation

We calculate the monetary costs or benefits by combining current activity data with bearing capacity restrictions and transportation cost. To determine the range of unit transport costs, data from various sources were considered, including Scholten and Rothstein (2016) and Bruinsma et al. (2012). The range aims to capture price variation that may be attributed to various reasons including season, direction of trip (upstream-downstream), data etc.

For the Rhine market, according to the ECCONET project (Bruinsma et al., 2012), transport cost varies from 3.5€/t to 7.5€/t for the Rotterdam-Duisburg trip and from 9€/t to 20€/t for the Rotterdam-Basel trip. According to Scholten and Rothstein (2016) the price range for trips from and to the ports of Amsterdam, Rotterdam and Antwerp is from 15€/t to 25€/t for Danube, and from 5€/t to

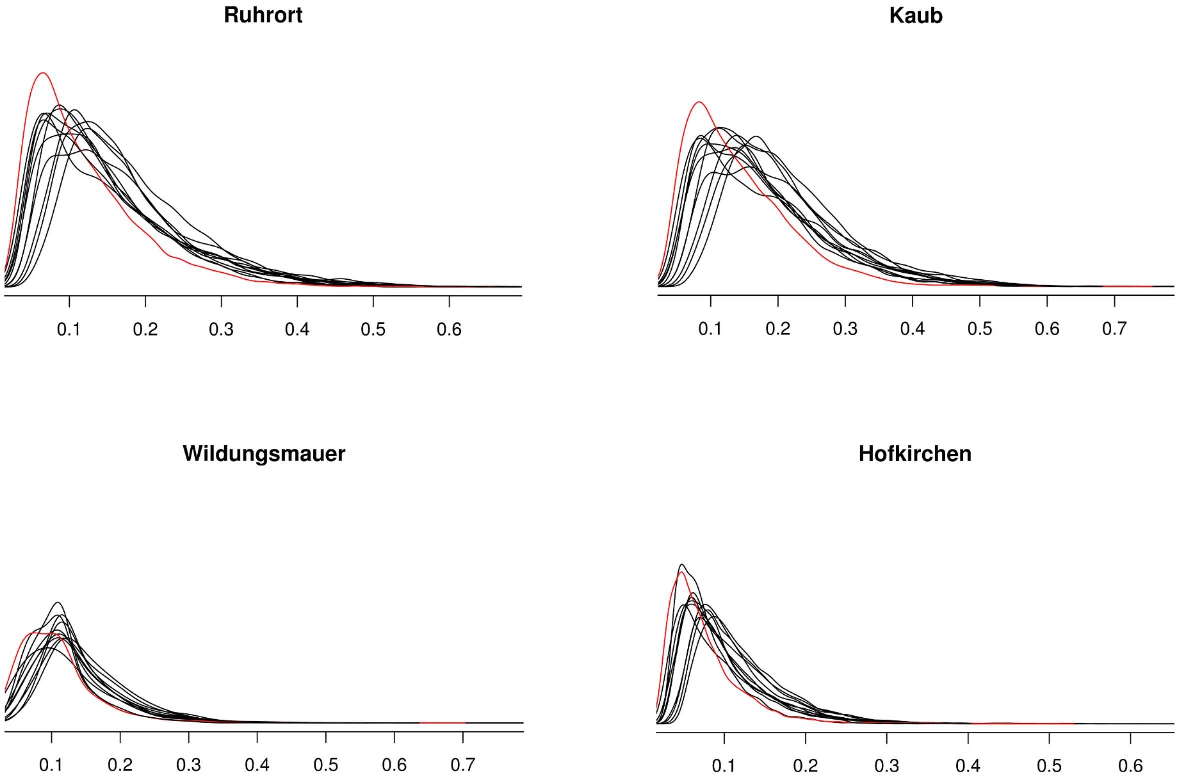

Fig. 6. Probability distribution of water levels, daily average for 2070–2100 period, normalised by maximum value across all scenarios for each point (scenario 10 highlighted in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

12€/t for Rhine. Transport cost values for specific trips on Danube and Rhine were combined with the corresponding average travel time obtained from the results of TRANSTOOLS to calculate transport cost per tonne per day. The daily transport cost values applied to estimate the economic impacts are 4€/tonne/day (low) and 8€/tonne/day (high).

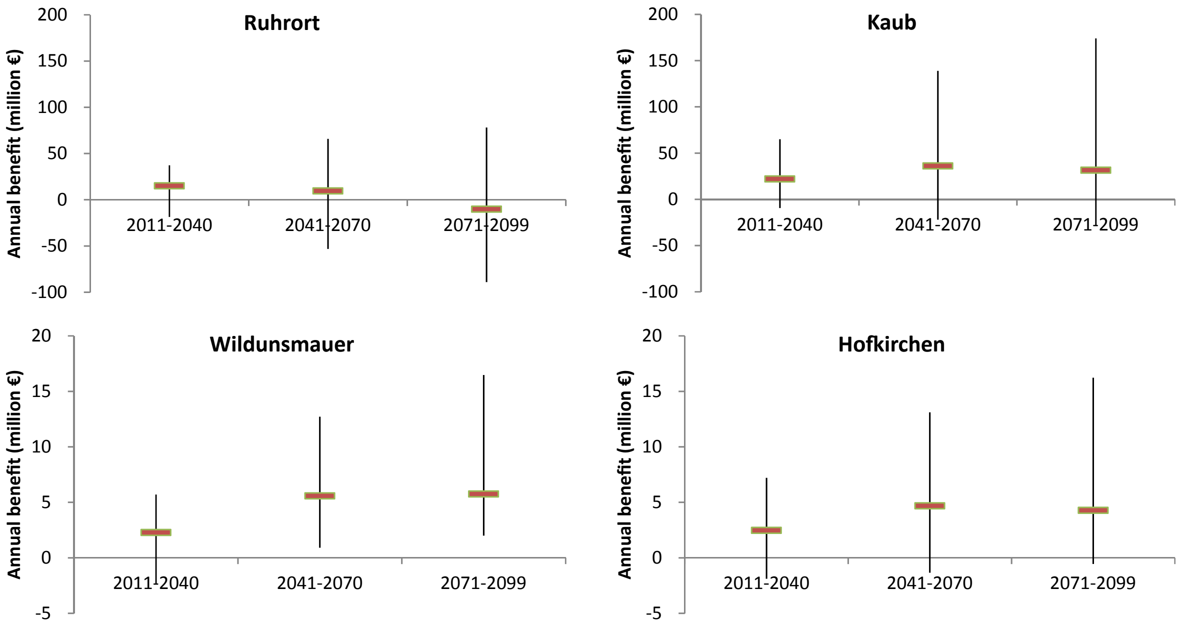

Fig. 7. Average annual benefit or cost of low water levels (in comparison to the reference period).

In Fig. 7 the annual average costs or benefits for each projected future period (2011–2040, 2041–2070, 2071–2099) in comparison to the historic period (1981–2010) are presented and the vertical lines represent the variability of the different model runs.

For the majority of the cases (model runs and points), we expect a benefit from the decrease in the number of low water level days. The expected monetary impact ranges from −€89 million (extreme negative scenario for Ruhrort) to €174 million (most optimistic scenario for Kaub). On the Rhine -where freight activity by inland waterways is significantly higher than on the Danube- the impacts are proportionally higher in Kaub, which is considered to be a key bottleneck on Rhine and seems to be benefiting on average according to the projected discharges.

5. Conclusions

In this study we evaluate the economic implications of climate change for inland waterways transport focusing on the impacts of low water levels and considering uncertainty associated with climate projections.

Due to the nature of this mode's network, the location specific characteristics that define the gauge or discharge levels have to be taken into account in order to evaluate the impact of projected discharges. We focus on four points on the Rhine and the Danube that are critical for the operation of the inland navigation system across Europe as a whole. We identify location specific discharge limits and compare the expected daily simulation results against them. This allows us to capture any value below the limits, regardless of the season, and address the issue identified by Jonkeren et al. (2014) as regards the need to explore (increasing) winter and (decreasing) summer discharges separately.

Uncertainty is taken into account by considering various climate change scenarios. Furthermore, the projection potential of the navigability of the rivers is significantly improved by using discharges from a dynamic hydrological model.

European inland waterways appear to be one of the few sectors where climate change can have negligible or even positive impact even in the "worst case" RCP8.5 emission scenario. Most climate models simulate an increase of the discharge levels of the main inland waterways routes, the Rhine and the Danube, probably due to the earlier start of the melt season. The projected discharge levels would result in higher average water levels and –most importantly- would reduce the number of days with a water level below the minimum required for navigation.

The results for the selected points show that for the two points on the Danube the number of low water days is projected to decrease while a similar trend is projected for Kaub on the Rhine, leading to an overall positive average economic impact. More specifically, the average annual economic benefits of the decrease of low water levels by the end of the century for Kaub, Wildunsmauer and Hofkirchen were projected to be €31million, €6million and €4million, respectively. On the other hand, an average annual economic loss of €10million has been estimated for Ruhrort as a result of the projected increase of the average number of low water days by the end of century.

However, given the relatively moderate impact estimates and large uncertainty associated within the different model runs, we consider that the results do not indicate a significant impact of climate change on the operation of IWW. This is in line with the findings of Beuthe et al. (2014) who conclude that limited change would have a minimal impact on waterway's navigation while modest effect of climate changes on modal shift were estimated by Jonkeren et al. (2014) and Beuthe et al. (2014).

The location specific nature of the relationship between discharges and water levels does not allow generalising this outcome but the variation of the projections of the model runs indicates that the risks of droughts should not be ignored.

It is important to note that for the inland waterways to work as a system, all parts of the system should operate without disruptions. The sample of four points used here is only a preliminary indication of the direction of the impacts for IWW. As we have seen in the case of projections for Ruhrort, in some scenarios and under specific conditions, one or more points of the IWW may face low water levels, even if the other points do not. This is probably the case in the Danube with increasing discharges in the upper Danube, while the lower Danube showing a decrease in water availability in the future (Bisselink et al., 2018). In such cases, depending on the network connections and vessels traffic, the disruption in one point can indirectly affect the rest of the system.

To account for uncertainty in this study, we used an ensemble of future climate projections to force a single hydrological model. For future work, a multi-model ensemble simulation method could be applied for more accurate future predictions as each hydrological model has its own structure and characteristics with their own strengths and weaknesses.

6. Disclaimer

The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2019.10.012.

References

ASSIST, 2014. The ASTRA-EC model user guide. Project co-funded by European Commission 7th RTD Programme. Fraunhofer-ISI, Karlsruhe, Germany.

Beuthe, M., Jourquin, B., Urbain, N., Lingemann, I., Ubbels, B., 2014. Climate change impacts on transport on the Rhine and Danube: a multimodal approach. Transport. Res. Part D 27, 6–11.

Bisselink et al., 2018. Impact of a changing climate, land use, and water usage on Europe's water resources, EUR 29130 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-80288-1, 10.2760/09027, JRC110927.

BMLFUW, 2012. Hydrographisches Jahrbuch von Österreich 2010, ed. Hydrographischer Dienst, Bundesministerium fuer Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Wien.

Bolle, A., Schwab, R., 1980. Jahrbuch der Hafenbautechnischen Gesellschaft, Siebenunddreissigster Band 1979/80. Springer-Verlag, Berlin Heidelberg New York.

Bruinsma, F., Koster, P., Holtmann, B., van Heumen, E., Beuthe, M., Urbain, N., Jourquin, B., Ubbels, B., Quispel, M., 2012. Consequences of Climate Change for Inland Waterway Transport, Deliverable 3.3 of ECCONET project. Report prepared for the European Commission, Directorate-General for Energy and Transport. Available: <https://www.ecconet.eu/deliverables/index.htm> (last accessed: 30/3/2017).

Burek, P., De Roo, A., van der Knijff, J., 2013. LISFLOOD - Distributed Water Balance and Flood Simulation Model - Revised User Manual. EUR 26162 10/2013; Publications Office of the European Union. Directorate-General Joint Research Centre, Institute for Environment and Sustainability, ISBN: 978-92-79-33190-9.

Christodoulou, A., Christidis, P., Demirel, H., 2018. Sea-level rise in ports: a wider focus on impacts. Maritime Econ. Logist. https://doi.org/10.1057/s41278-018-0114-z.

Ciscar, J.C., Ibarreta, D., Soria, A., Dosio, A., Toreti, A., Ceglar, A., Fumagalli, D., Dentener, F., Lecerf, R., Zucchini, A., Panarello, L., Niemeyer, S., Pérez-Domínguez, I., Fellmann, T., Kitous, A., Després, J., Christodoulou, A., Demirel, H., Alfieri, L., Dottori, F., Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Cammalleri, C., Barbosa, P., Micale, F., Vogt, J.V., Barredo, J.I., Caudullo, G., Mauri, A., de Rigo, D., Libertà, G., Houston Durrant, T., Artés Vivancos, T., San-Miguel-Ayanz, J., Gosling, S.N., Zaherpour, J., De Roo, A., Bisselink, B., Bernhard, J., Bianchi, A., Rozsai, M., Szewczyk, W., Mongelli, I., Feyen, L., 2018. Climate impacts in Europe: Final report of the JRC PESETA III project, EUR 29427 EN. Publications Office of the European Union, Luxembourg ISBN 978-92-79-97218-8.

De Roo, A.P.J., Wesseling, C.G., Van Deursen, W.P.A., 2000. Physically-based river basin modelling within a GIS: The LISFLOOD model. Hydrol. Process. 14, 1981–1992.

ELWIS, 2016. Elektronischer Wasserstraßen – Informationsservice, Available: <https://www.elwis.de/Aktuelles/index.html>.

Hendrickx, C., Breemersch, T., 2012. The effect of climate change on inland waterway transport. Transport Research Arena-Europe 2012, Proc. – Soc. Behav. Sci., vol. 48, pp. 1837–1847.

Holtmann, B., van Heumen, E., Beuthe, M., Urbain, N., Jourquin, B., Ubbels, B., Quispel, M., Bruinsma, F., Koster, P., 2012. Evaluation Of Adaptation Measures: Nodus Model Results And Detailed Cost Analyses, Deliverable 3.4 of ECCONET project. Report prepared for the European Commission, Directorate-General for Energy and Transport. Available here: <https://www.ecconet.eu/deliverables/index.htm> (last accessed: 30/3/2017).

Jacob, D., et al., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. Regional Environ. Change 14, 563–578. https://doi.org/10.1007/s10113-013-0499-2.

Jonkeren, O., Rietveld, P., van Ommeren, J., 2007. Climate change and inland waterway transport - welfare effects of low water levels on the river Rhine. J. Transp. Econ. Policy 41 (3), 387–411.

Jonkeren, O., Jourquin, B., Rietveld, P., 2011. Modal-split effects of climate change: the effect of low water levels on the competitive position of inland waterway transport in the river Rhine area. Transport. Res. Part A 45, 1007–1019.

Jonkeren, O., Rietveld, P., van Ommeren, J., 2014. Climate change and economic consequences for inland waterway transport in Europe. Regional Environ. Change 14, 953–965. https://doi.org/10.1007/s10113-013-0441-7.

Middelkoop, H., Daamen, K., Gellens, D., Grabs, W., Kwadijk, J.C.J., Lang, H., Parmet, B.W.A.H., Schädler, B., Schulla, J., Wilke, K., 2001. Impact of climate change on hydrological regimes and water resources management in the Rhine basin. Clim. Change 49 (1–2), 105–128.

Moss, R., et al., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756.

Nilson, E., Lingemann, I., Klein, B., Krahe, P., 2012. Impact of Hydrological Change On Navigation Conditions, Deliverable 1.4 of ECCONET project. Report prepared for the European Commission, Directorate-General for Energy and Transport. Available here: <https://www.ecconet.eu/deliverables/index.htm> (last accessed: 30/3/2017).

Pinter, N., Ickes, B.S., Wlosinski, J.H., van der Ploeg, R.R., 2006. Trends in flood stages: contrasting results from the Mississippi and Rhine River systems. J. Hydrol. 331, 554–566.

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., Rafai, P., 2011. RCP 8.5—scenario of comparatively high greenhouse gas emissions. Clim. Change 109, 33–57. https://doi.org/10.1007/s10584-011-0149-y.

Scholten, A. and Rothstein, B., 2016. Navigation on the Danube - Limitations by low water levels and their impacts, JRC Technical Reports, ISBN 978-92-79-64798-7, doi:10.2788/236234, European Commission.

TRT, 2003, Il modello ASTRA-Italia per la valutazione strategica di politiche di trasporto, Milano.

UNECE (United Nations Economic Commission for Europe), 1996. European Agreement on Main Inland Waterways of International Importance' (AGN), ECE/TRANS/120/Rev.4. Economic Commission for Europe, Inland Transport Committee, United Nations, Geneva.

Van der Knijff, J.M., Younis, J., De Roo, A.P.J., 2008. LISFLOOD: a GIS-based distributed model for river basin scale water balance and flood simulation. Int. J. Geogr. Inform. Sci. 24 (2), 189–212. https://doi.org/10.1080/13658810802549154.