Estimating the impacts of water depth and new infrastructures on transport by inland navigation: a multimodal approach for the Rhine corridor

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1. Introduction

It is well known that melted snow, rainfall and evaporations affect the rivers water level and that it may impair transport by inland navigation during a number of days. Indeed, water depth conditions the loading of inland waterway vessels, hence their transport cost and their competitive position versus alternative modes, rail and trucking. The ECCONET research project funded by the European Commission[1] endeavors to measure the potential effects of these phenomena on the Rhine and Danube navigation in the context of the observed weather variability and expected climate change scenarios.

Many interdisciplinary and methodological issues are involved in such an analysis. These are tackled in details in numerous technical reports on statistical data, climate evolution prognoses, boats specifications, adjustment strategies, etc. The present paper, using a number of inputs from several of these reports, focuses on a transport analysis of the competitive position of inland waterways transport using the geographic multimodal transport model NODUS. The reference data for the modeling are 2005 matrixes of Continental Europe origins-destinations transport flows per mode and per type of commodities, and transport cost data. As the transport cost of vessels are function of their loading and draught, the model can be used to analyze the effect of changes in the rivers water depth on transport costs and on the resulting modal splits between the three competing modes, rail, road and inland waterway transports. After calibration the model can be applied for simulating the outcomes for a set of observed years with various yearly water depth distributions as well as for some climate projections in 2050.

Through a variety of assignment algorithms, the NODUS software (Jourquin, 1995; Jourquin and Beuthe, 1996) assigns transport traffics between modes and means over the multimodal trans-European network of roads, rails and rivers or canals. Given the spatial scope of the research, traffics on the Rhine and Danube, the network includes all the regions potentially involved in these traffics from France and Benelux countries to Bulgaria and Romania. Transport costs include variable and fixed costs of carrying goods by the three modes, road costs to places of loading/unloading on wagons or vessels, plus the costs of these operations. However, our analysis has to separate the Rhine and Danube markets, because of differences in operating conditions on the two rivers and in the vessels costs, and differences in water depths as measured in specific places.

The outputs are the changes induced by the waterways conditions in the modal split and the costs of transport for the three modes as well as for the different commodities. These outcomes are computed for some observed years as well as for a set of water depth distributions that are selected from two modeled climate scenarios extending to 2050. Further on, we can also show what would have been the impacts in 2005 had the present network been already improved as planned by the European Commission in its TEN-T Priority program, and also the impacts of infrastructure and of climate change on the use of the different types of waterway vessels.

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[1] The ECCONET consortium is led by TML (BE), with partners from BfG (DE), DST (DE), KNMI (NL), NEA (NL), OMSZ (HU), UCL-Mons (BE), VITUKI (HU), VIA DONAU (A), VU-FEWEB (NL). We thank O. Jonckeren who contributed useful insights to our work.

After this introduction, the second section of this paper gives a general description of the NODUS methodology. The third section describes the three modes' trans-European networks, the 2005 transport demands that can possibly make use of waterway transport on the Rhine, and the cost data. The fourth section explains the modeling of the effects of water level variations. The fifth section presents the results of some simulations relative to the reference period 1977-2006, whereas the sixth analyzes the impacts of climate change over the period 1977-2050. Lastly, the seventh section provides some elements on the use of different types of vessel. The concluding remarks underline some limitations inherent to that type of modeling, and sum-up the research main results.

2. The NODUS transport model

Modeling transport demands and traffics classically proceeds in four steps. The first one generates the global demand in the relevant region; the second step distributes the global demand among origins and destinations in sub-regions or localities, and creates by so doing a flows matrix of origins and destinations (OD matrix). Both steps involve various types of macro or spatial economic analyses; they may take into account the demands and traffics for different types of users so that a set of OD matrixes is created for the different demand segments. Then, the third step splits the distributed traffic flows among the available transport modes. This involves analyzing the decision making process – or utility function - of stakeholders, most often through some kind of discrete choice modeling based on revealed or stated preference statistical analysis. The last step examines the best choice of itinerary on the transport networks and selects the shortest or less costly one.

In contrast, the NODUS approach permits the simultaneous handling of the last two steps. Given an OD matrix, it directly assigns the traffics on the networks by selecting the mode, the transport means as well as the itinerary that minimize the generalized transport cost for each origin and destination. Beside the traditional "all-or-nothing" algorithm that select the "optimal" solution, Nodus can also apply a "multi-flows" algorithm that select a set of solutions corresponding to different likely combinations of modes or means and itineraries.

This more comprehensive and detailed three-step approach is made possible by constructing the transport networks as a virtual network. This concept differs from the usual geographic definition as it replaces each single infrastructure, like a specific waterway segment, by a set of virtual waterways corresponding to the different types of boats that can navigate on that river segment. Hence, the geographical graph of the networks is expanded by all the added virtual segments or vectors. Each virtual vector is identified by a set of parameters, which indicates its number, connections in the network, length, speed, mode, boats or vehicles it allows, etc. These parameters provide the link of each virtual segment to the specific transport cost function corresponding to its characteristics. Additional virtual vectors can also be used to model within the networks all technical operations involved in transportation, like loading/unloading, transferring from one mode or means to another, locks or border operations, etc.

Another difference with the usual four-step methodology is that there is no explicit utility or modal split function as commonly used, which is supposed to express the preferences of the stakeholders among modes. This function is here replaced by a generalized cost function that stakeholders are supposed to minimize. As explained in the previous paragraph this cost function can more accurately detail all the direct costs of transport, but it cannot truly be taken as a real expression of preferences if it does not include non-monetary costs like the cost of time, reliability, security, etc. This difficulty also affects the utility functions, which often are estimated without most of these 'qualitative' cost variables. For that reason, the four-step approach needs to correct, or calibrate, its estimated utility functions on some observed traffic data. Likewise, the three-step approach needs to calibrate its cost functions to obtain the relevant generalized cost functions.

There remains a noteworthy difference because the standard discrete choice function directly estimates modal shares for a given OD flow, whereas the simple minimization of the generalized cost assigns the entire flow to a unique choice of mode, means and itinerary. This may not be realistic, since the OD matrixes pragmatically aggregate transport flows from/to many different places into a limited number of origins and destinations. A solution to that problem is found in a multi-flows assignment procedure (Jourquin and Limbourg, 2007), whereby the OD flow is spread among the best available transport solutions in inverse proportion to their respective generalized costs. These are selected on the virtual network using the well-known algorithm written by Dijkstra (1959).

3. The networks, the OD matrixes and the cost functions.

The European geographic networks in NODUS extend from Scandinavia to Spain and Italy, from Ireland and United Kingdom to Greece, Romania and the Baltic countries. Road and railroad networks were initially built using the 'Digital Chart of the World' before being improved with the most recent investments. The inland waterway network was fully digitized by the GTM team using many different sources as available. These basic data were analysed and structured so that they were made compatible with the virtual network methodology. Altogether, the entire physical network counts more than 40400 segments on the railroad transport network, 67800 on the road network and 1180 segments on the inland waterways. Other networks, such as the ferry lines can also be used, but are not used in this paper.

The OD flow matrixes for the 10 NST-R commodity classes and, separately, for rail, road and waterway transports at the NUTS2 level, were prepared by NEA for the year 2005, chosen as the reference year, and 2050. They correspond to the freight inland transport actual demands over Continental Europe during that year. They are based on previous NEA's work with TRANSTOOLS (NEA et al., 2009 and 2010) for the European Commission project TEN-CONNECT2 (Tetraplan et al., 2011).

A number of transformations were applied to the initial NEA matrixes. First, the matrixes included an extremely large number of small shipments of less than 1,000 tons per year for a very small total tonnage: in the case of the IWW matrix 49% of the yearly shipments for only 1.2% of the total IWW tonnage. These shipments were judged as less significant and deleted in order to reduce the computation time. Secondly, an additional class of goods for container traffic was created from aggregate information provided by NEA. Thirdly, the initial matrixes included traffics that were not relevant for our research focused on the Rhine and Danube corridors and navigation on these rivers. Traffics between France and Spain, for instance, would never go through these rivers. Thus, we were led to prune the matrixes in order to retain only traffics that could possibly make use of these rivers. That was done by a first NODUS traffic assignment of all the OD flows on the waterway network only, which identified which flows could, if at all, use some segments of the Rhine or Danube. In that process, we also excluded traffics on the Rhine that remained within the lower river part up to Arnhem, and traffic on the Danube that remained below the Iron Gates, since those traffics are rarely affected by low water problems. There may still be from time to time problems created by flood, ice and fog, but information is scarce about these events, which are highly irregular and difficult to forecast. These phenomena are not included in this analysis. In the end, the reduced 2005 ECCONET matrix included traffics for a total of 1,484 million tons.

To give an idea of the market that is retained in the scope of the ECCONET project, figures 1 and 2 illustrate the flows on the waterways network and those on the multi-modal network (including road and railroad transport).

Figure 1 : Flows on the inland waterways

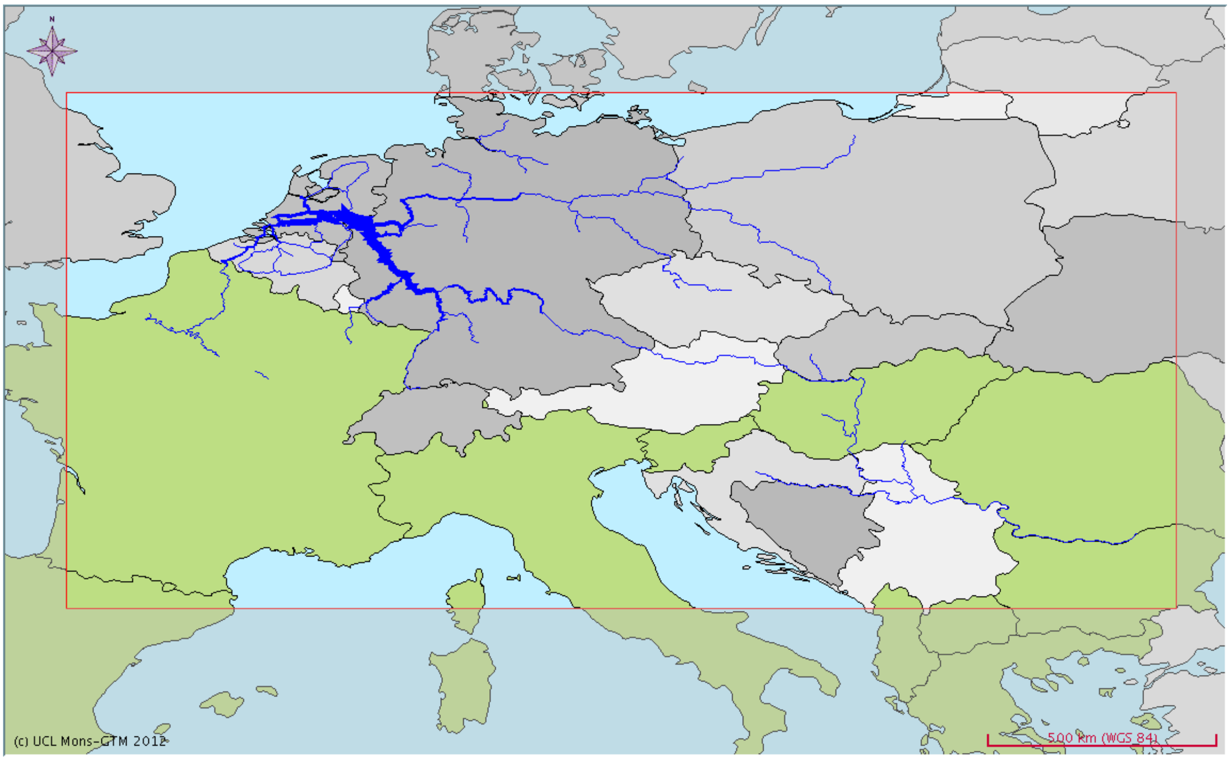
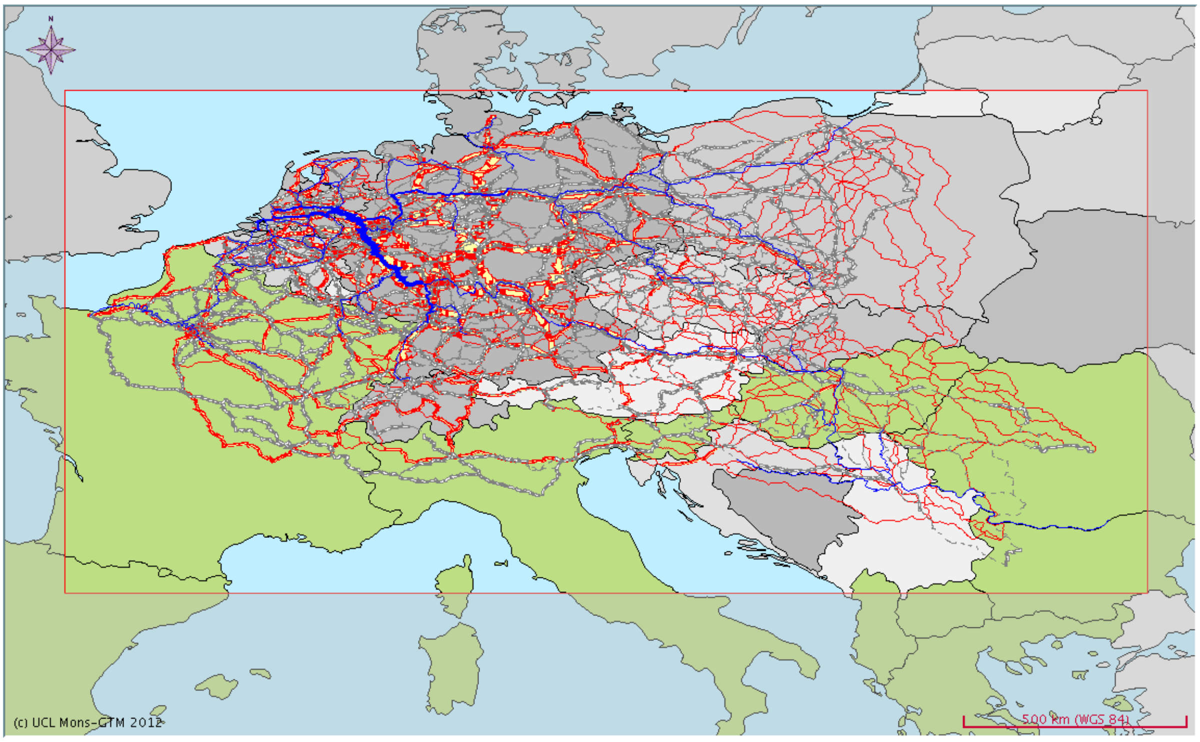


Figure 2 : Flows on the multimodal network



The next step was to separate the Rhine and Danube transport markets. This partition is necessary because vessels with different operational costs are used on the two rivers. Also, different water levels thresholds at different periods of the year will be used for the two rivers in our later analyses. Geographically, the separation between the two markets is taken, somewhat arbitrarily, at the Western end of the Main canal that links the Rhine to the Danube. In the Rhine market, we naturally include all transport flows on the Rhine from/to The Netherlands to/from Basel, but also navigating partly on its tributaries (Mosel, Schelde, Maas and Neckar, etc.). However, some transport flows on both rivers raise an assignment problem between the two markets. As a larger part of these traffics are upstream going East on the Rhine, all these traffics are included within the Rhine river analysis with selected Rhine vessels. Indeed, it is rarely the case that goods in these traffics are transferred at some point from/to Rhine vessels to/from Danube vessels. As to the traffics on the Mosel, the Neckar or the Southern part of the Rhine that also involve navigating on the Danube, there is no significant difference between the volumes going upstream and downstream. As these traffics volume is rather small they were also included in the Rhine market. Furthermore, an examination of the principal OD pairs involving navigation on the Rhine and Danube showed that these traffics mostly operate on the Rhine. This partition allocates 79.2% of the inland waterway volume to the Rhine market, in which 7.3% involves navigation on both rivers. Applying a similar methodology on the road and rail data, 84.4% of the 2005 ECCONET matrix tonnage, all modes together, is included in the Rhine market analysis.

The network model imposes that the total cost function of a trip be an additive linear function with respect to distance, but all cost coefficients can be the result of non-linear function of factors like speed, the number of working hours, or the loading which plays an important role in this study since it is influenced by the rivers water depths. As developed by GTM, four types of cost functions are needed that are associated with the corresponding virtual links. They relate to the costs of travelling, of transit, transhipment and loading/unloading. They include all the costs related to moving a vehicle between an origin and destination, like labour, fuel, insurance, capital and maintenance costs, and, in some cases, equivalent tariffs; transport time (speed) and the cost of inventory of the goods during transportation - an element of the generalized cost; handling and storage costs, including packaging, loading and unloading and services directly linked to a transport; all residual indirect costs like general administrative services which may be assigned to transports on an average basis. For road and railway transport, three different speeds were used for different types of road or locomotive. Rivers or canals are categorized according to six classes of vessels that are considered, CEMT II to IV, Va, Vb, and VIb. The vessels' speeds are adjusted according to whether they navigate upstream or downstream, and their loading is influenced by the categories of transported goods: dry and wet bulk, pieces or containers. It is also taken into account whether the vessel is loaded or empty. NEA and DST adjusted and updated these 2005 IWW cost functions. They were used as the starting costs for the calibration of the 2005 and 2050 models.

Besides these costs, a full account of the generalized transport costs in a multi-modal multi-means context should include some relative costs of transport quality differences, like differential reliability, safety, etc., if it is at all possible. These relative costs may vary from one category of goods to another, since transporting containers or coal requires different types of organisation and care. Also, congestion level on the different networks may also influence the costs and the transport service quality. Unhappily, information about these factors is rather scarce if one considers that the associated equivalent costs are specific to each type of commodity, transport modes and industrial organization (Beuthe and Scannella, 2008), and may vary through the spatial scope of the present research. Hence these additional costs are not introduced in the present study. However, these quality differences are taken into account to some extent by the adjustments made to the cost functions at the stage of the model calibration, which is made separately for each category of commodity.

Real prices for transport services are very difficult to obtain in many cases, so that we mainly use transport production costs as an approximation. From a socio-economic point of view these are certainly the relevant parameters. In some cases, they can also be taken as acceptable approximation of prices or tariffs at least on marginal contestable markets where modes compete for market share. The trucking and inland navigation markets should not be very far from that model. Hopefully, some possible divergences that could affect the markets can be taken into account at the calibration stage of the model.

4. Modelling the effects of water level variations

As explained in the previous sections, the transport cost of every vessel class is a function of the boat loading. For calibrating the model on the 2005 data, we assumed that the vessels were loaded at their observed average loading.

Table 1: Comparison of the actual modal shares with the model assigned modal shares.

	Reference						**Multi-Flow assignement**					
	T			**T.km**			**T**			**T.km**		
NSTR	**IWW**	**Rail**	**Road**	**IWW**	**Rail**	**Road**	**IWW**	**Rail**	**Road**	**IWW**	**Rail**	**Road**
0	5.01%	26.29%	68.70%	5.87%	37.40%	56.73%	5.74%	31.69%	62.56%	5.70%	36.54%	57.75%
1	0.77%	0.27%	98.96%	1.02%	0.29%	98.68%	1.16%	0.26%	98.59%	0.91%	0.30%	98.79%
2	61.29%	22.23%	16.48%	69.43%	20.42%	10.16%	59.69%	24.44%	15.87%	68.91%	19.92%	11.17%
3	54.00%	11.08%	34.92%	64.70%	13.02%	22.29%	54.51%	14.58%	30.92%	63.12%	13.00%	23.88%
4	60.92%	22.94%	16.14%	65.05%	21.92%	13.03%	56.29%	25.06%	18.65%	63.91%	21.83%	14.26%
5	6.77%	40.79%	52.44%	6.00%	50.76%	43.24%	4.88%	43.06%	52.06%	5.66%	49.82%	44.52%
6	4.58%	17.65%	77.77%	3.93%	30.16%	65.91%	5.55%	25.33%	69.12%	3.95%	29.74%	66.32%
7	9.76%	37.27%	52.97%	9.92%	44.17%	45.91%	9.27%	40.88%	49.85%	10.33%	43.49%	46.18%
8	1.68%	1.03%	97.30%	2.25%	1.08%	96.67%	3.17%	1.23%	95.60%	2.27%	1.56%	96.17%
9	1.02%	0.58%	98.40%	1.40%	0.81%	97.80%	2.76%	0.62%	96.62%	1.72%	0.84%	97.45%
10	30.01%	10.88%	59.11%	36.42%	10.70%	52.89%	22.78%	6.85%	70.37%	23.99%	7.98%	68.03%
Total	**9.45%**	**13.24%**	**77.31%**	**12.67%**	**18.97%**	**68.35%**	**9.88%**	**16.94%**	**73.18%**	**12.57%**	**18.57%**	**68.86%**

Source: own computation; commodity 10 corresponds to containers.

As there are separated OD matrixes for the three modes for each commodity, we could first run the Nodus model on each matrix in order to assign each OD on a set of likely itineraries on its mode network and obtain in that way an estimation of the corresponding transport volume in ton-km. With that information it was possible to calibrate the model with respect to the realized transports measured in ton-km as well as to the transported tons. Note that this calibration does not take into account any capacity constraint of the fleet, and also that it proceeds as if the transports volumes are evenly spread over the year since it is based on yearly data. The calibration results with the multi-flows procedure are presented in the above Table 1 that allows the comparison of the modal shares in the 2005 data basis with the shares estimated by the NODUS model. The comparison shows a good fit of the calibration, particularly with respect to the transports in ton-km. Indeed, the global correlation coefficients between the modal shares in the 2005 data basis and the estimated modal shares from the calibration are above 0.99 both in terms of tons and tons-km.

Two problems had to be dealt with for introducing the effects of water level into the model. To begin with, the rivers water levels vary over their successive segments. However, modelling the water depth and its variations in a quasi-continuous way along the Danube and the Rhine would create a serious computational problem. An analysis of the more shallow parts of the Rhine and the practices of the inland navigation industry indicated that the water depths at two critical points on the Rhine, Kaub and Ruhrort, were mainly used as references for loading and pricing the transport of boats going through their shallow waters. Furthermore, the comparison of the daily water depth at Kaub and Ruhrort showed that water depth at Ruhrort was practically always higher than at Kaub, with a linear relationship between the two. Hence, it was decided to proceed in three steps: firstly, analyse separately the traffic going through Kaub and, in some cases, also through Ruhrort with reference to the water depth measured at Kaub (49.4% of the tonnage in the Rhine matrix for the year 2005); secondly, analyse the traffic through Ruhrort only with reference to the water levels measured at Ruhrort (18.6% for the year 2005); thirdly, analyse separately the remaining traffic as if it was not encountering any serious shallow water difficulty. Actually, that remaining traffic is analysed using the cost functions calibrated on the average situation in 2005. This led to the partitioning of the Ecconet matrix in three sub-matrixes named “Kaub”, “Ruhrort” and “no critical point”. The same procedure is also applied to the 2050 data.

Secondly, the rivers water level varies from day to day during a given year, and it is necessary to take account of the yearly frequency of water depths if we want to more precisely simulate the impacts of the weather and climate variation for a set of years. DST has shown that the relationship between possible loading and vessels draught is practically linear, and provided the necessary information for computing the (maximum) feasible loading at any given water depth level for representative boats of the six classes included in the research. Thereby, it is possible to run the NODUS model for any given water depth taking into account the corresponding loading of each type of vessel and their operational cost. Again, to avoid running the model up to 365 times for every day of a year, seven intervals of water depth were pragmatically defined which fitted well the frequency distribution of water levels in 2005. Next, counting the numbers of days within each interval it is assumed that the vessels are loaded during a specific interval according to what would be feasible at the mid-water depth of the interval. Lastly, weighted sums over the seven intervals are taken to give estimates of a year total cost of transport and its corresponding modal split for the simulated frequency distributions of water depths. In the end, this additional partitioning of the water level analysis leads to the task of fifteen separate runs of the calibrated model for each commodity, which provide all the information necessary for computing for a given simulated year the necessary global weighted sums. The following Table 2 illustrates part of the methodology as applied to the Kaub sub-sample. For each referenced water depth at Kaub, it indicates the number of days within the corresponding interval, their percentage, the loading of a typical vessel of class Va in case of dry bulk, and its cost per ton-km.

Table 2: The Kaub case in 2005

Water depth	**Days frequency**								**Average cost per ton/km class Va Upstream Dry bulk**	**% Payload Va**
	1993		**1989**		**1985**		**2005**			
	Nbr	**%**	**Nbr**	**%**	**Nbr**	**%**	**Nbr**	**%**		
> 4.3 m	13	3.56%	10	2.74%	18	4.93%	22	6.03%	0.0122	100.00%
at 4 m	80	21.92%	58	15.89%	94	25.75%	83	22.74%	0.0122	100.00%
at 3.4 m	181	49.59%	170	46.58%	119	32.60%	140	38.36%	0.0136	84.00%
at 3 m	90	24.66%	73	20.00%	30	8.22%	51	13.97%	0.0157	68.00%
at 2.70 m	1	0.27%	37	10.14%	65	17.81%	39	10.68%	0.0180	56.00%
at 2.40 m	0	0.00%	17	4.66%	28	7.67%	30	8.22%	0.0221	44.00%
at 2 m	0	0.00%	0	0.00%	11	3.01%	0	0.00%	0.0333	28.00%
Total	**365**	**100.00%**	**365**	**100.00%**	**365**	**100.00%**	**365**	**100.00%**		

Source : BfG and DST information. The average cost is a weighted average across all commodities.

Lastly, it is important to mention that climatologists define a climate with reference to average of a set of weather parameters over a number of years. In this study, a climate is defined over a thirty years period and this definition is adopted for the hydrological parameters whose sensitivities to climate change are evaluated. As an example, the climate of reference in this study is defined over the observed period 1977 -2006. During a thirty period like this one, the water depth distribution obviously varies from year to year. From what is known we can only assume that each year distribution has the same probability of realization. Nevertheless, for a better understanding of what a given climate represents in terms of water depth distributions, it is useful to rank the thirty years in order to assess their relative likelihood (at given percentile values) in terms of their water depths distributions. In line with practices used for analysing extreme phenomena, BfG ranked the years by giving to each of their water depth intervals a score that is inversely proportional to the number of days within each interval. These scores are added up to obtain a unique “dryness” rate that allows the ranking of the thirty years over the rectangular distribution. Then, for illustrating a given climate situation one can select a few significant years like the median one (50% percentile) and some years that are drier with more extreme percentile values.

5. The results

Table 3 gives the results for three observed years within the 1977-2006 years span. They were selected on the basis of their water depth distributions at Kaub, and adjusted for analysing the corresponding Ruhrort distributions which are correlated to the Kaub distributions. The year 1993 is the median year (D2), which means that there is a ½ probability that a drier year would occur. The year 1989 (D5) corresponds to the 80% percentile, which implies that there is a 1/5 probability that a drier year would occur. 1985 is the 90% percentile years (D10), there is only a 1/10 probability that a drier year would occur. Table 3 shows the modal shares of tonnage for their water depth distributions.

Table 3: Tonnage modal share of selected years (million tons)

		Kaub	**Ruhrort**	**No critical point**	**Total**	**%**
1993 (D2)	**IWW**	57.08	40.55	63.44	161.07	10.85%
	Rail	135.81	47.59	63.8	247.19	16.65%
	Road	540.47	187.67	347.87	1,076.02	72.49%
1989 (D5)	**IWW**	56.19	40.40	63.44	160.03	10.78%
	Rail	136.12	47.58	63.80	247.49	16.67%
	Road	541.05	187.83	347.87	1,076.76	72.54%
1985 (D10)	**IWW**	55.20	40.31	63.44	158.94	10.71%
	Rail	136.55	47.58	63.8	247.92	16.70%
	Road	541.62	187.92	347.87	1,077.42	72.59%
2005 (reference)	**IWW**	55.94	40.39	63.44	159.77	10.76%
	Rail	136.25	47.58	63.80	247.62	16.68%
	Road	541.17	187.84	347.87	1,076.89	72.55%
Average daily	**IWW**	56.76	40.47	63.44	160.66	10.82%

distribution over 1977-2006	**Rail**	135.98	47.58	63.80	247.36	16.67%
	Road	540.62	187.76	347.87	1,076.26	72.51%

Source : own computation

It shows that between the 1993 median year and the much drier 1985 the IWW's share approximately decreases by 0.14% to the benefit of road (+0.10%) and railway (+0.05%) transport[2]. In 1985, IWW loses two million tons. The next Table 4 gives the three modes variations (%) of total transport costs with respect to the 2005 reference year. Comparing the years 1993 and 1985, it can be seen that the total transportation cost for the three modes over the studied area increases by about 0.32%. Also, the total cost of each mode increases, even in the case of IWW despite the fact that it loses the transport of two million tons to the other two modes. This is due to the fact that the average loading factors of the vessels is lower, resulting in higher costs per transported ton.

Table 4: Total cost variations in %, per year, sub-matrixes and modes (base year 2005)

		Kaub	**Ruhrort**	**No critical point**	**Total**
1993 (D2)	**IWW**	99.518%	100.095%	100.000%	99.776%
	Rail	99.636%	100.071%	100.000%	99.771%
	Road	99.645%	99.836%	100.000%	99.836%
	Total	99.630%	99.950%	100.000%	99.813%
1989 (D5)	**IWW**	99.926%	99.978%	100.000%	99.959%
	Rail	99.900%	99.994%	100.000%	99.932%
	Road	99.919%	100.009%	100.000%	99.967%
	Total	99.912%	100.000%	100.000%	99.957%
1985 (D10)	**IWW**	100.370%	100.003%	100.000%	100.186%
	Rail	100.269%	99.989%	100.000%	100.177%
	Road	100.256%	100.031%	100.000%	100.109%
	Total	100.271%	100.013%	100.000%	100.134%
Average (1977-2006)	**IWW**	99.577%	100.026%	100.000%	99.792%
	Rail	99.766%	100.033%	100.000%	99.850%
	Road	99.748%	99.919%	100.000%	99.888%
	Total	99.739%	99.972%	100.000%	99.869%
2005 (reference)	**IWW**	100.000%	100.000%	100.000%	100.000%
	Rail	100.000%	100.000%	100.000%	100.000%
	Road	100.000%	100.000%	100.000%	100.000%
	Total	100.000%	100.000%	100.000%	100.000%

Source : own computation

6. Climate change over the 1977-2050 period

The next step is to analyze the possible outcomes in 2050 on the basis of 2050 OD demand matrixes forecast by NEA and the foreseeable infrastructure at that time. First, the demand matrixes were handled in a procedure similar to the one used on the 2005 matrixes. Then, the 2050 model was

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[2] Slight discrepancies in the Tables result from rounding errors.

calibrated by adjustment of the initial cost functions taking into account the assumed 2050 infrastructures. As before, we obtained a good fit of the model to the reference data.

A number of infrastructure projects for improving the transport network are programmed in many European countries. The most important ones are included in the list of TEN-T European priority projects, and several of these projects may concern the Rhine-Danube corridor. Those were assumed to be completed by 2050. Priority project 18 concerns waterways and includes the upgrade from class Va to class Vb of the Juliana canal from Nijmegen to Lanaye, the construction of a larger lock at Lanaye that will allow the navigability of class VIb vessels on the canal Albert up to Liège, and two new locks at Ampsin-Neuville and Ivoz-Ramet for upgrading the Mass river to class VIb between Liège and Namur. Priority project 30 aims at improving the waterway connection between Paris and the Belgian and Dutch networks with a new Vb canal between Compiègne and Creil, and several other projects on the Oise, Leie (Vb), Schelde (Va), and the upgrading at Va of the canals between Condé and the Sambre at Charleroi. Priority 5 project corresponds to the recently completed Betuwe freight rail line between Rotterdam and Emmerich. Priority project 22 aims at improving the railway link between Athina-Sofia-Budapest-Wien-Praha- Nürnberg/Dresden[3]. Priority project 7 concerns an improved motorway between Budapest and Costanza.

Table 5 compares the ECCONET estimated 2005 matrix and the projected 2050 matrix. It shows a relatively strong increase of 48.07% of all traffics over the period, with a 2.27% increase in road transport share, whereas IWW and Rail shares decrease respectively by 0.84 and 1.43 %. When looking at the geographical spread of origins and destinations over Europe, it is interesting to note a higher concentration around harbors, particularly in Germany, and a measured shift towards Eastern Europe countries.

Table 5: Modal split comparison-2005 and 2050 ECCONET Rhine matrixes

		T (Millions T)	%	T.km (Millions)	%
2005	**IWW**	140.26	9.45%	82,779.66	12.53%
	Rail	196.50	13.24%	123,267.29	18.66%
	Road	1,147.52	77.31%	454,633.72	68.81%
		1,484.28	**100.00%**	**660,680.67**	**100.00%**
2050	**IWW**	189.12	8.61%	123,534.49	10.74%
	Rail	259.72	11.82%	182,425.50	15.86%
	Road	1,748.93	79.58%	844,207.21	73.40%
		2,197.78	**100.00%**	**1, 150,167.20**	**100.00%**

Source : own computation.

Table 6, evaluates the impact that the new 2050 infrastructures would have on the modal split in 2005. It shows a slight increase of both IWW and Road to the detriment of Rail (-3 million tons), and suggests that the new infrastructures planned for the three modes would not induce any substantial modal shift within the given demand matrix; their individual effects would roughly cancel each other in the aggregate, and there would be a substantial amount of routing substitution inside each mode. Obviously, this does not detract anything from their usefulness. Moreover, it is worth reminding that some of these new infrastructures, like the Seine-Nord-Europe, could not play an important role in the present context since only traffics that could possibly use the Rhine were kept into the basic ECCONET matrix. In contrast, the new Betuwe line is certainly a strong competitor to waterway navigation and road transport, whereas the Juliana canal is directly connected to the Rhine. Indeed,

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[3] The project of deepening the Danube between Straubing and Vilshofen in Southern Germany is not included. It will be in the part dealing with the Danube where its deepening on this stretch can be linked to the water depth measured at Hofkirchen.

the difference between the tonnages assigned to rail on the Betuwe corridor shows a clear increase of rail shipments. Likewise, a substantial increase of traffic is shown on the upgraded Juliana canal, where larger class Vb boats will be able to navigate after is completion.

Table 6: Effects of 2050 infrastructures (Matrixes 2005, calibrated cost functions 2005)

		T (Millions T)	%	T.km (Millions)	%
2005	IWW	146.70	9.88%	82,652.52	12.57%
	Rail	251.43	16.94%	122,097.75	18.57%
	Road	1,086.15	73.18%	452,780.97	68.86%
		1,484.28	**100.00%**	**657,531.28**	**100.00%**
2050	IWW	147.25	9.92%	83,053.87	12.61%
	Rail	248.38	16.73%	121,406.45	18.44%
	Road	1,088.65	73.35%	454,000.60	68.95%
		1,484.28	**100.00%**	**658,858.57**	**100.00%**

Source: own computation.

After these preliminary considerations, the simulations of the climate change impacts on transports can be dealt with. These must be computed on a coherent basis that allows a comparison between the 2005 and 2050 results. To that effect, BFG developed over the period 1977 to 2050 two long term climate scenarios that are associated to the hydrologic situation on the Rhine: a “dry” and a “wet” scenario. These are based on a number of recent international studies which are well reviewed in a report of the ‘International Commission for the Protection of the Rhine’(ICPR, Report 188, 2011). They translate into distributions of daily water depths for every year, like the thirty years within the two reference periods 1977-2006 and 2020-2050 respectively. However, each set of thirty years exhibits a large variety of yearly water distributions which, and, actually, corresponds to only a small ‘sample’ from the assumed rectangular distribution. Hence, it would not be really appropriate to compare the results of the given percentile years from one period to another. The results computed for the average daily distributions of water depths provide a more reliable comparison. These distributions at Kaub are given in Table 7. It appears that the two “dry” distributions are hardly different, whereas the “wet” distribution in 2050 indicates a somewhat more humid climate. This similarity between the two periods explains to a large extent the stability of some of the results in Table 8, where the inputs of Table 7 are used.

Table 7: Average distributions of water depth days at Kaub

Water depth	Days frequency									
	Average observations		Model 1977-2006				Model 2020-2050			
			Dry		Wet		Dry		Wet	
	Nbr	%	Nbr	%	Nbr	%	Nbr	%	Nbr	%
> 4.3 m	55	15,07%	58	15,89%	49	13,42%	57	15,62%	67	18,36%
at 4 m	97	26,58%	97	26,58%	87	23,84%	96	26,30%	112	30,68%
at 3.4 m	129	35,34%	105	28,77%	127	34,79%	106	29,04%	114	31,23%

at 3 m	55	15,07%	59	16,16%	69	18,90%	56	15,34%	50	13,70%
at 2.70 m	20	5,48%	30	8,22%	26	7,12%	29	7,95%	18	4,93%
at 2.40 m	7	1,92%	10	2,74%	5	1,37%	13	3,56%	4	1,10%
at 2 m	2	0,55%	6	1,64%	2	0,55%	8	2,19%	0	0,00%
Total	**365**	**100,00%**	**365**	**100,00%**	**365**	**100,00%**	**365**	**100,00%**	**365**	**100,00%**

Source: BfG information

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Table 8: Simulations of the climate impacts over the period 2005-2050

Model relevancy evaluation

Climate impacts with 2050 demand & network

Scenario	**Mode**	**Observations**	**Climate scenario 1977-2006**		**Climate scenario 2020-2050**		**Climate scenario 2020-2050**	
		2005 Data	2005 Data		2005 Data		2050 Data	
			Dry	Wet	Dry	Wet	Dry	Wet
Average	**IWW**	10,82%	10,79%	10,82%	10,78%	10,84%	9,38%	9,45%
	Rail	16,67%	16,68%	16,67%	16,68%	16,66%	11,52%	11,50%
	Road	72,51%	72,53%	72,52%	72,54%	72,50%	79,10%	79,05%

Climate impacts if demand & network remain identical

As indicated in Table 8, the two first sections show the relevancy of the climate modeling by the comparison between the results obtained for the observed 2005 data and the results of the climate model in average over the period 1977-2006 for the "dry" and "wet" scenarios. We see that the modal split of the simulated average of the "wet" scenario corresponds closely to the observed 2005 situation. The "dry" scenario results are hardly different, even though it indicates a slight decrease of the IWW share to the benefit of both Rail and Road.

The third section gives the results obtained when the average climate situation over the period 2020-2050 is applied while keeping unchanged the 2005 network and demand matrixes. Its comparison with the results given in the second section for the average over the period 1977-2006 shows that there is no serious climatic impact on the model shares computed for the "dry" and "wet" scenarios.

The fourth section gives the results of the average climate situation over the period 2020-2050 when applied to the 2050 demand matrixes and networks. Comparing these results to the previous ones in third section, we observe some substantial changes. The shares of IWW and Rail strongly decrease to the benefit of Road transport. However, on the basis of the above comments and the comparison of the 2005 and 2050 reference data (Table 5), these evolutions cannot be attributed to a climate change but rather to the general economic evolution, the changes in relative costs as well as the change in the geographic spread of origins and destinations that were mentioned above.

7. Analysis of the vessels relative use

Lastly, it is also interesting to have a look at the relative use of the different types of vessels. As indicated earlier, six classes of vessels are included in this ECCONET analysis, with specific cost functions and capacities. The representative vessels in each class are presented in the following Table 9.

Table 9: Types of ships on the Rhine and their characteristics

#	CEMT class	Name (type of ship, train)	Length (m)	Beam (m)	Draught min. (m)	Draught max. (m)	Payload at max. draught (t)
1	**II**	**Kampine**	55	6.6	1.40	2.50	600
2	**III**	**Gustav Koenigs**	80	8.2	1.10	2.50	1,080
3	**IV**	**Johann Welker ("Europe"-ship)**	85	9.5	1.20	2.80	1,560
5	**Va**	**GMS 110**	110	11.4	1.35	3.50	2,873
6	**Vb**	**GMS 110 + 1 x E-II Rhine**	185	11.4	1.35	3.50	5,292
7	**VIb**	**PB + 2 x 2 Rhine E-II barges**	193	22.8	1.70	4.00	11,356

For this more detailed analysis, a second model was developed for analyzing the 2005 OD matrix relative to IWW only. The calibration of the model was made with respect to the fleet operating on the Rhine, as given by the Economic and Social Council of the United Nations (2010). Assuming then that the least cost vessel must be mostly used on a given OD relation, the simpler "all-or-nothing" assignment technique available in NODUS is applied. Hence, this analysis is closer to an optimization procedure than to a simulation as the one developed with the multi-flows assignment. Table 10 shows how well the calibrated model fits the fleet data.

Table 10: Performance of the "IWW only" model on 2005 data

Class of ship	**Fleet**	**Model**	
II	18%	*7.50%*	19.19%
III		*11.69%*	
IV	20%		22.63%
Va	42%	*30.72%*	40.88%
Vb		*10.16%*	
VI	17%		17.31%

This second model can be used for estimating the impact of the new infrastructures planned for 2050. The results of this simulation appear in Table 11. As expected, the improvement of the IWW network offers the opportunity to use larger vessels, especially those from classes III, IV and Vb. Actually, these shifts between types of vessels result in a total transportation cost reduction of 1.61%, as larger vessels with lower cost per ton transported can be used on some itineraries.

Table 11: impact of the new infrastructures on the use of the different types of ships

2005 Demands and Costs with			
Class of ship	**2005 infrastructure (Millions T)**	**2050 infrastructure (Millions T)**	**Difference**
II	10.51	9.19	-12.58%
III	16.39	16.94	3.39%
IV	31.74	32.51	2.42%
Va	43.08	41.58	-3.54%
Vb	14.25	15.78	10.72%
VI	24.28	24.28	0.00%

Table 12 also shows the impacts of the two climate scenarios on the use of the different vessels. Without any change of infrastructure the use of class II vessels remains unchanged, but the “wet” scenario allows the substitution of larger boats to the smaller class III and IV vessels.

Table 12: climate impact on the use of the different types of ships

2005 Demands, Infrastructures and Costs			
Class of ship	**Average Dry scenario**	**Average Wet scenario**	**Difference**
II	10.51	10.51	0%
III	19.03	16.69	-12.28%
IV	40.11	39.49	-1.54%
Va	34.37	36.51	6.23%
Vb	12.47	12.94	3.70%
VI	23.76	24.11	1.48%

8. Final comments

To conclude this analysis of the Rhine market, it is important to underline some of the methodology limitations. First, the basic data about freight transport activities in 2005 are themselves derived from a modeling of European freight transports. These are not really observed data, which, actually, do not exist at this level of detail. Furthermore, these are yearly data, which means that the analysis proceeded as if the corresponding traffics were equally spread over the year. Secondly, the model does not fully integrate the capacity constraint of the fleet, even though the "IWW only" model is calibrated on the existing fleet operating on the Rhine. The NODUS modeling and simulations assume that transport costs are minimized. This hypothesis is quite reasonable in the framework of a freight transport analysis, but does not take into account the full complexity of shipping decision making. However, we can trust that the calibration of the cost functions integrates to some extent the missing factors into the model.

The main conclusion that can be drawn from this analysis is that the possible climate changes from 2005 to 2050 and their impact on the Rhine hydrology, as modeled by the two long term dry and wet scenarios, are not likely to be strong enough to induce any significant shift in modal shares. However, we should note that a drier scenario would justify maintaining more small vessels in operation despite the planned improvements in waterway infrastructure.

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