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Strategies to overcome the possibly restricted utilisation of fairways due to climate changes

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ABSTRACT: Due to the apparent climate change, the probability of occurrence of extreme hydrological events, droughts as well as flood events might possibly change. The concerns of inland shipping, due to droughts are more pronounced compared to flood events, as droughts may last several weeks. Lowered water levels during droughts result in a reduction of maximum transportation capacity of inland vessels and the constriction of navigable fairway width. As a consequence, efficiency of inland shipping would decrease as well as safety and reliability of navigation. The investigations described in the present paper are conducted in the framework of the research program KLIWAS. Using the example of the River Rhine from Mainz to St. Goar, river training measures are analysed that focus on the maintenance of minimum flow depths in free flowing waterways under reduced low water conditions. Initially, the present conditions are analysed in order to localise bottlenecks for navigation, applying different low water discharges. A 2D-hydrodynamic–numerical model is used for this purpose. Subsequently, the potential of a width-reduced *"fairway within fairway"*, in terms of gaining flow depth during droughts is shown.

Keywords: Climate change, Inland shipping, Navigation, 2D Hydrodynamical modelling

1 INTRODUCTION

As a consequence of the apparent climate change, the occurrence of extreme hydrological events might possibly change. The trafficability of inland fairways would be affected adversely by the peak and duration of flood events as well as by duration of extreme droughts. The concerns of inland shipping are much more pronounced by droughts than by flood events, as droughts caused by general weather situations usually last for several weeks. Lowered water levels during droughts lead to a reduction of maximum transportation capacity of inland water vessels and a constriction of navigable fairway width. Thus, efficiency of inland shipping as well as safety and reliability of navigation decrease (Maurer et. al, 2009).

Within the framework of the research project "*Adapted waterways engineering towards varied hydrological conditions due to climate changes*", which is part of the research program KLIWAS *("Impacts of climate change on waterways and navigation – options to adapt")* investigations of potential adaption strategies are carried out by analysing a stretch of the River Rhine between Mainz and St. Goar (Rhine-km 493.0 to 557.5). Considering that the River Rhine is the most important navigable inland waterway in Europe, the status quo of fairway depths guaranteed by the German Federal Waterways and Shipping Administration is quite heterogeneous concerning low water conditions. The fairway depth varies from 2.10 m below GlW_{2002} in the upper Rhine stretch to 2.80 m below GlW_{2002} in the lower Rhine stretch between Duisburg and the Dutch border. In this context, the GlW_{2002} is a low water level specified in 2002 occurring at the discharge GlQ_{2002} that just falls below a gauge on 10 or 20 ice-free days per year in a long-time average. In one stretch of the middle Rhine between Budenheim (Rhine-km 508.0) and St. Goar (Rhine-km 557.5) the fairway depth guaranteed by the German Federal Waterways and Shipping Administration is only 1.90 m below GlW_{2002}. For inland cargo vessels from the lower Rhine to the upper Rhine this river stretch determines the maximum transportation capacity during low water conditions. Furthermore, the mean vessel size is expected to increase about 1% – 1.5% per year in combination with an increasing traffic volume, making a systematic analysis of hydraulic bottlenecks at low water conditions even more essential.

Obviously, the development of adaption strategies is necessary to reduce vulnerability of the waterways by reason of changed climatic conditions and to guarantee minimum flow depths for navigation in the future as well.

2 APPROACH

Before thinking about the development of adaption strategies, an exhaustive analysis of the status quo of the waterway system is required.

In addition to existing low water conditions, potential future situations with further reduced low water levels have to be investigated. Because no reliable hydrological projections of climate change scenarios are available yet, the present analysis is carried out with a stepwise reduced low water discharge from GlQ_{2002} down to GlQ_{2002} - 25%. With this approach, the systems sensitivity to changed discharges becomes apparent. As other sub-projects of the KLIWAS research program focus on the hydrological projections of climate change scenarios, the range of discharges considered in the present study can easily be brought into relation at a later date.

For the considered range of discharges, the water-depth-related bottlenecks are identified by analysing the water depths calculated with a 2D-hydrodynamic-numerical model. Uncertainties result e.g. due to the modellers choice of a particular river bed topography representing only one snapshot of a system’s state. In order to reduce these uncertainties, the identified bottlenecks are verified against documented locations of previous dredging activities and against results of ongoing studies.

Bringing in mind that the relevant time scales in the context of climate changes are decades rather than years, it is reasonable to include potential future developments of the fairway within the present analysis that might be realised independently from climate changes. For instance, the deepening of the fairway between Rhine-km 508.0 and 557.0 from a guaranteed water depth of 1.90 m to 2.10 m or the reduction of the necessary fairway width due to future developments of ship’s steering devices and autopilots are potential developments that have to be considered in the present analysis.

The width-reduced fairway, the so-called *“fairway within fairway”* is generated within the framework of the KLIWAS project 4.04 *“Determination of the necessary fairway width for safe and easy shipping”* by using a route selection method, adapted especially to low water conditions.

In order to identify the discharge depending hydraulic bottlenecks between Rhine-km 493.0 and 557.5 during reduced low water conditions, two basic states are considered:

1. The status quo of the fairway with a depth of 1.90 m below the water level corresponding to GlQ_{2002} from Rhine-km 508.0 to 557.0 and a depth of 2.10 m in the other river sections (in the following denoted as “*status quo*”).
2. A deepened, width-reduced fairway (*“fairway within fairway”)* with a depth of 2.10 m below the water level corresponding to GlQ_{2002} from Rhine-km 493.0 to 557.5 (denoted as “*potential state*”).

Based on the identified hydraulic bottlenecks, adaption strategies can be developed to gain flow depth under tightened low water conditions. One river training measure considered in the present paper is the implementation of the above mentioned width-reduced *“fairway within fairway”*, but relating the fairway depth of 2.10 m now to the lowered water level corresponding to GlQ_{2002} – 25% instead of GlQ_{2002} (denoted as “*adapted fairway*”).

3 AREA UNDER INVESTIGATION

The stretch of the River Rhine from Mainz to St. Goar has a length of about 65 km and may be subdivided into two completely different river sections (Figure 1 & 2).

Figure 1. Rhine flowing through the region "Rheingau".

From Rhine-km 493.0 to 528.8, the River Rhine flows through a region called "Rheingau". Within this region, the river is characterised by a low water level slope ranging from 0.04 up to 0.2 ‰, cross-section widths up to 750 m and small water depths. Various river bifurcations form the landscape of the Rheingau resulting in complex flow situations. Bed load mainly consists of sand and fine gravel. Bed morphology is characterised by riffles and dunes. The latter occasionally have adverse navigational effects.

Numerous river training works have been realised in the last decades for improving navigation conditions. One measure is e.g. a bed load trap realised near Mainz-Weisenau (Rhine-km 494.3 to 494.46). Since 1989, about 1.7 million m³ sand and gravel have been removed from this spot, which has led to a reduction of dunes passing the upper part of Rheingau.

From Rhine-km 528.8 to 557.5, the Rhine is flowing through the Rhenish Slate Mountains. Within this river section, the river bed is fixed by steep side slopes and thus limited in width. The river bed consists either of solid rock or loose material, namely sandy or stony gravel with embedded blocks.

Figure 2. Rhine flowing through the Rhenish Slate Mountains.

The course of the river is dominated by numerous bends. River banks are protected by rip-rap or side walls over the entire length. In contrast to the Rheingau the low water level slope is much higher, approximately 0.65 ‰. This river section is one of the most intensively used stretches in terms of navigation.

4 HYDRAULIC ANALYSIS OF THE STRETCH

4.1 *The model*

All investigations are carried out by means of the 2D-hydrodynamic-numerical model TELEMAC-2D (Hervouet & Bates, 2000). This finite element code solves the depth averaged Navier-Stokes equations on irregular meshes. Main results at each node of the computational mesh are water depth and depth-averaged velocity components.

The area under investigation is represented in a high resolution unstructured grid consisting of about 800,000 finite elements (triangles). The mean length of element edges is 9.5 m with a minimum of 1.4 m and a maximum of 46.3 m (Figure 3). The lateral model boundaries are given by the extent of the inundation area of a 100-year flood (IKSR, 2001).

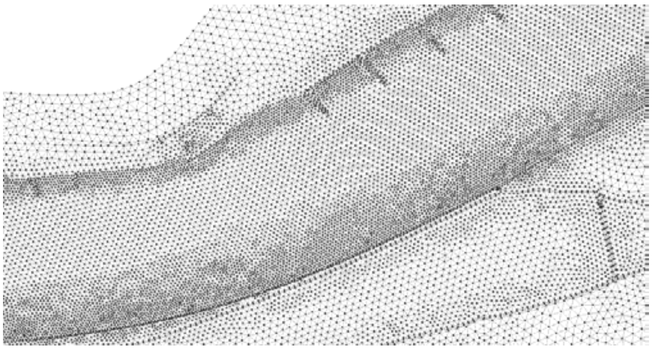

Figure 3. Section of the computational mesh.

The implemented river bed topography is based on interpolated cross section data (Rhine-km 493.0 – 531.0) and areal data (Rhine-km 531.0 – 557.5).

4.2 *Model calibration*

According to the objectives of this study, the model is calibrated against measured water levels in the range of low up to mean water discharges, with grain roughness as calibration parameter. The water level data used for calibration were taken by boat during several measurement campaigns between 2003 and 2005. The data was collected every 100 m on the stream axis and recorded simultaneously at each of the 14 gauge stations within the model stretch. The mean differences of modelled and measured water levels after calibration are -0.03 m (for a discharge at the gauge station "Kaub" of Q_{Kaub} = 599 m³/s), 0.01 m (Q_{Kaub} = 772 m³/s) and 0.02 m (Q_{Kaub} = 1482 m³/s) with standard deviations of 0.04 m, 0.03 m and 0.04 m, respectively (Figure 4).

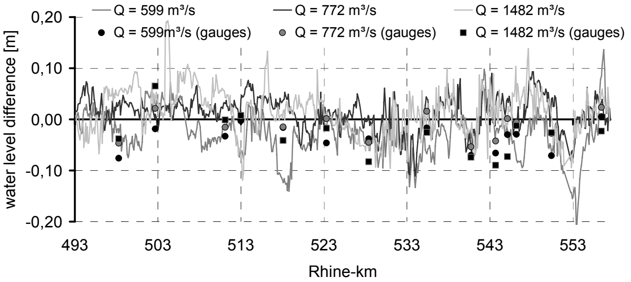

Figure 4. Water level (WL) differences of modelled and measured values ($WL_{model} - WL_{measured}$) after model calibration for discharges from 599 m³/s to 1482 m³/s (Gauge station Kaub, Rhine-km 546.23).

For model validation, a measured water level of the year 2008, corresponding to a discharge of about 1383 m³/s at the gauge station "Kaub" was chosen. Differences between modelled and measured water levels from Rhine-km 506.0 to 528.0

are about -0.10 m, whereas in the remaining stretches measured and computed water levels fit well. Compared to the gauges, the mean value of the differences between calculated and observed water levels is 0.01 m with a standard deviation of 0.04 m. Following this, inaccuracies of water level measurements are supposed to be the reason for the observed differences between Rhine-km 506.0 to 528.0. Over the whole stretch, the mean difference of modelled and measured water levels is - 0.01 m with a standard deviation of 0.08 m.

4.3 *Determination of the "fairway within fairway"*

The minimum widths of the fairway are determined in the separate KLIWAS project 4.04 parallel to the work of project 4.03 presented in this paper mainly. As the lateral dimensions of the "potential state" are needed quite early for input in project 4.03 as well as for field investigations in the framework of both projects, project 4.04 provides an early draft of minimum width from a validated standard tool and upgrades this draft in close correspondence to model development and validation from field data.

The first draft of minimum lateral dimensions of the fairway is determined from the results of the 1D navigational model PeTra1D (**Pe**gelabhängige **Tra**ssierung, english: stage dependent routing) (Figure. 5, black dots). 2D input data on current and water depth from the 2D-hydrodynamic–numerical model (see section 4.1) are averaged for use with the 1D navigational model at each cross section. The flow velocities are averaged across the swept area separately for vessels going upstream and downstream. The swept area and ship position are provided by a preliminary model run with 1D input data from the CASCADE model. CASCADE is a 1D-hydrodynamic-numerical model for the simulation of unsteady flows.

The minimum widths of the fairway are determined for the area-specific reference water level corresponding to a discharge of Q ~ 1490 m^3/s at gauge Kaub, when vessels usually reach their largest possible draught, and currents are considerable. According to typical fleet and traffic conditions at low water stages at the river reach under consideration, the frequently driving one-row one-column push tows (SV) will be considered instead of the largest licensed vessel type as the design ship for economizing the fairway, consisting of a push-boat with two barges, coupled one behind the other or a large motor vessel (GMS), pushing a barge. The ship route is generated automatically, applying the virtual piloting algorithm in PeTra1D. It was forced to primarily exploit existing depths, secondarily choose preferably low (upstream drive) or high (downstream drive) currents. As upstream and downstream drives require for separate model runs, the upstream drive was made first because of its larger need of depth. The vessel sailing downstream was forced to stay as close as possible to the swept area of the vessel sailing upstream. Minimum widths result from addition of both swept paths and common safety distances.

For reasons of safety, the simple parameterisation of navigational dynamics is compensated by artificial worsening of the ships behaviour. To obtain lower boundaries of possible fairway width, the 2D navigational model PeTra2D was applied. Due to its more detailed physics its safety allowances can be significantly reduced. On the other hand, cross currents are considered, which lead to increased minimum width for example at flow diversions (e. g. Figure 5, black rectangles).

Improved drafts of the "*fairway within fairway*" will be obtained by project 4.04 after several steps of upgrading the experimental navigational model PeTra2D. Significant impacts on minimum widths are expected from upgrading the 1D routing to 2D, from implementing the impact of low under keel clearance on ship dynamics, and from consideration of human properties and abilities in the automatic route guiding algorithm. The improved determination of minimum widths is done in project 4.04 interacting with the hydro- and morphodynamical modelling of project 4.03.

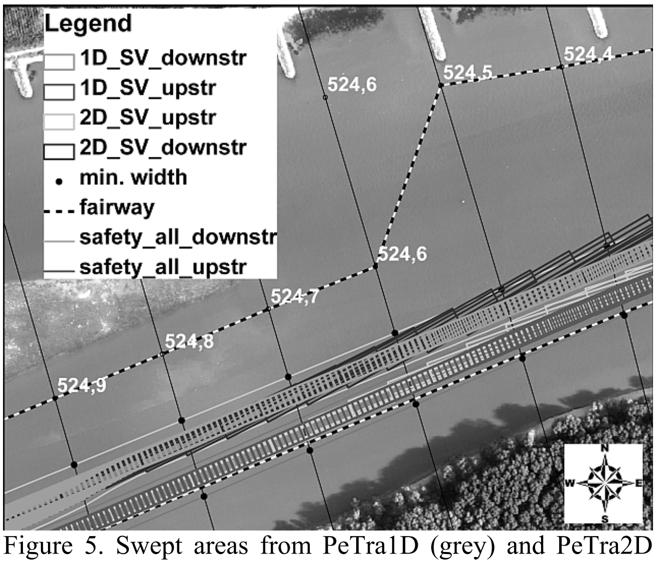

Figure 5. Swept areas from PeTra1D (grey) and PeTra2D (black) calculations of ships driving upstream (lower course) and downstream (upper course) in the area of Rhine-km 524.4 downstream of the island Ilmenaue, influenced by cross-current due to flow diversion. Adding usual safety distances (lines aside rectangles) to PeTra1D results, the first draft of possible fairway width and position was developed (black dots).

Regarding that larger vessels than SVs of a length of L = 185 m are unlikely to sail at low water stages, the adaption method "*fairway within the fairway*" is not expected to have any significant impact on safety, and only slight impact on ease of shipping due to the following reasons:

- The "*fairway within fairway*" will only be provided at low water stage. Larger vessels than SV of length L = 185 m) are very unlikely to sail at such conditions due to general restrictions to fairway conditions in length and width by the water depth.
- The width of today's fairway within River Rhine was dimensioned mainly to allow a 110 m vessel to transverse without loosing maneuverability. This postulation is not fulfilled for other rivers and channels as well, and is not practicable for large units permitted at River Rhine at existing dimensions of the fairway anyway.
- Widths of existing fairways, e. g. at Rivers Mosel, Neckar, Danube or Upper Rhine as well as measured swept areas from observations at Middle Rhine (Maedel et al., 2008) are 80 m or less, showing that at least for smaller vessels, minimum width of 80-90 m as calculated in this study should be practicable. Long vessels at maximum draught and swept area usually don't traffic at low water stages. However, the common fairway is provided to them.
- As the „*fairway within fairway*" is expected to be implemented earliest in 2050 in the context of KLIWAS, significantly improved steering devices, maneuvering properties, information systems and maybe autopilots should be available on most ships, increasing ease of shipping in a fairway dimensioned for common ships of today.
- A significant impact on fluidity of traffic of the "*fairway within fairway*" on fluidity of traffic is very unlikely, because meeting traffic of the largest vessel type to assume (SV) with itself is still possible from calculations. Due to slightly higher under keel clearance, ship velocities within the "*fairway within fairway*" could eventually even increase.

If huge vessels should traffic despite unfavourable conditions at low water stages, there is still no safety risk to expect, because to those vessels today's fairway width as well as depth are still available. Furthermore, meeting large draught vessels within the deepened "*fairway within fairway*" could be avoided by waiting, due to the very local character of the adaption approach.

4.4 *Identification of hydraulic bottlenecks*

In order to identify the hydraulic bottlenecks within the model stretch, numerical simulations are conducted using the low water discharge GlQ_{2002} as well as reduced low water discharges given in Table 1 as inflow boundary conditions. For the investigation of the "*potential state*", the "*fairway within fairway*" has to be implemented into the model. This is done by deepening all spots of the river bed inside the area of the width reduced fairway with a water depth less than 2.10 m related to $WL_{GlQ2002}$.

Table 1. Inflow boundary conditions of the Rhine and the tributaries Main and Nahe for the hydraulic analysis of the model stretch.

	GlQ_{2002}					
	-0%	– 5%	–10%	–15%	–20%	- 25%
Q_{Rhine} [m³/s]	670	636.5	603	569.5	536	502.5
Q_{Main} [m³/s]	60	57	54	51	48	45
Q_{Nahe} [m³/s]	20	19	18	17	16	15

Identified bottlenecks or shoals are assessed in a different way depending on their position in the fairway. Shoals occurring close-by the fairway's boundary are not as critical as spots in the middle of the fairway (Figure 6), as the former ones can be marked by buoys and circumnavigated by the vessels. In order to distinguish whether the shoals are within the middle of the fairway or at its boundary, different zones in the fairway are defined. This is done by reducing the fairway width as well as the "*fairway within fairway"* width on both sides by 10 m and 20 m, respectively (compare Figure 6). Insufficient water depths in the outermost zones of the fairway are neglected.

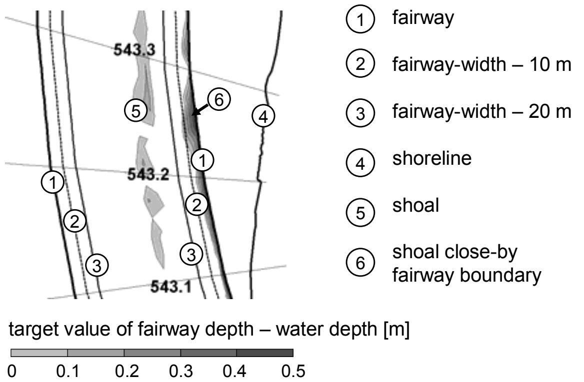

Figure 6. Schematic diagram of shoals and width reduced fairway polygons for evaluation of water shoals.

For the evaluation of hydraulic bottlenecks, the minimum water depth of each shoal is plotted along the considered river stretch. Figure 7 shows examples of the reduced low water discharge GlQ_{2002} - 25%. In addition, it is differentiated whether the shoals occur in the "fairway – 10 m"-section or in the "fairway – 20 m"-section. In case of the "*status quo*"-calculations, minimum water depths down to 1.51 m occur within the fairway. The depth of 1.37 m at Rhine-km 496.4 is located 40 m downstream of a bridge pier and thus not a direct obstruction for navigation. It is obvious, that the trafficability of the entire stretch can only be improved significantly, if several of the critical spots are removed simultaneously.

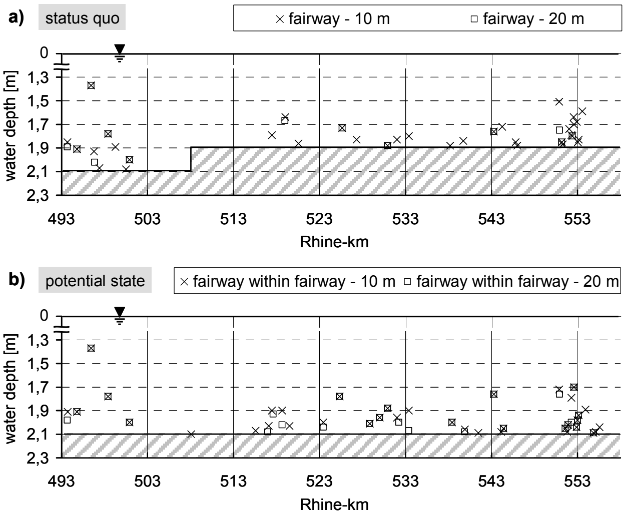

Figure 7. Minimum water depths of each shoal smaller than the fairway depth within the width reduced fairway polygons (compare Figure 6) during reduced low water discharge GlQ_{2002} -25% in case of “*status quo*” (a) and “*potential state*” (b).

Considering the Figures 7 a and b, the improvement of the hydraulic situation in terms of increasing minimum water depths due to the implementation of the *“fairway within fairway”* ("*potential state*") is clearly visible. This is mainly caused by the chosen position of the width-reduced fairway, as naturally existing, deeper sections are used wherever possible. The increased fairway depth of 2.10 m between Rhine-km 508.0 and 557.0 however leads to the formation of new shoals in some parts of the fairway, which did not occur in case of the “*status quo*”-analysis. Shoals appear either locally, caused by bed forms or rock projections, or widely stretched. As the analysis of minimum water depths does not give information about the spatial dimensions of the identified bottlenecks, Figures 8 and 9 show the volume deficits within the fairway per kilometre for low flow conditions.

Compared to previous dredging activities, there is a good agreement of dredging locations and calculated volume deficits.

According to the “*status quo*”-calculations many shoals occur between Rhine-km 542.0 and 552.0. By implementing the *“fairway within fairway”* (“*potential state*”-analysis), the volume deficits can be reduced significantly. In contrast, the volume deficits between Rhine-km 514.0 and 529.0 partly increase. This is caused by the increased target value of the fairway depth of the “potential state” with 2.10 m.The “*potential state*” comes along with insignificant volume deficits in case of GlQ_{2002} and GlQ_{2002} – 5%, whereas the volume deficits are approximating to the one of “*status quo*” with greater reductions of GlQ_{2002} (Table 2). Hence, providing sufficient flow depth in case of reductions of low water discharges of more than 5 % requires the investigation of additional river training or maintenance measures.

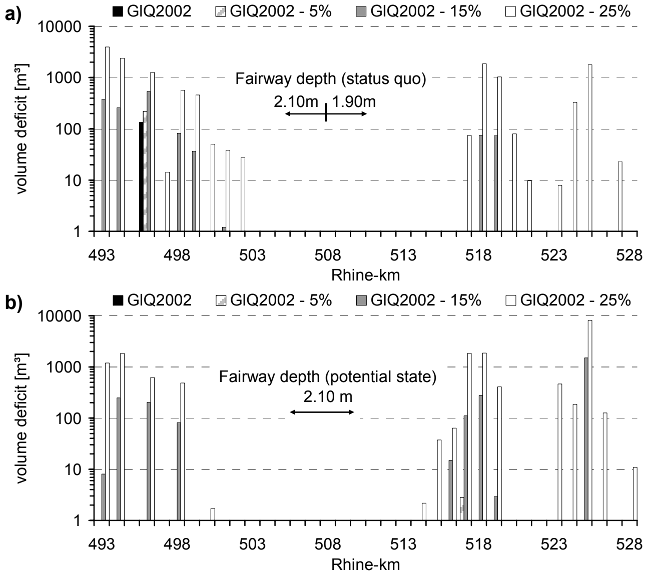

Figure 8. Volume deficits per kilometre within the fairway (“*status quo*”, Figure 8 a) and within the “*fairway within fairway”* (“*potential state*”, Figure 8 b) during low water discharge GlQ_{2002} and reduced low water discharges, Rhine-km 493.0 to 529.0.

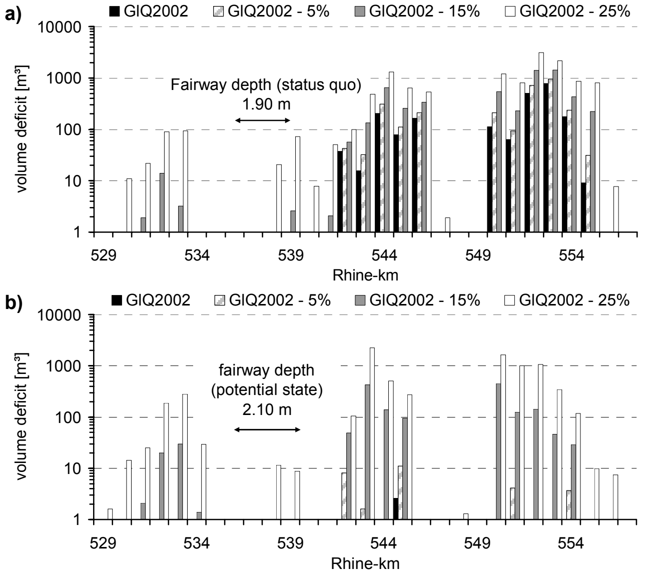

Figure 9. Volume deficits per kilometre within the fairway (“*status quo*”, Figure 9 a) and within the “*fairway within fairway”* (“*potential state*”, Figure 9 b) during low water discharge GlQ_{2002} and reduced low water discharges, Rhine-km 529.0 to 557.5.

Table 2. Total volume deficits [m³] within the fairway in case of “*status quo* and “*potential state*“ occurring during different low water discharges.

	GlQ_{2002}					
	-0%	– 5%	–10%	–15%	–20%	- 25%
„status quo“	2285	3161	4533	7186	13050	26590
„potential state“	4	35	787	4003	11245	25203

5 ADAPTION STRATEGY

With the objective to gain flow depth during reduced low water levels, the *“fairway within fairway”* is implemented into the model (“*adapted fairway*”). The way of implementation is equal to the “*potential state*”, except relating the fairway depth of 2.10 m to the water level corresponding to GlQ_{2002} – 25% instead of $WL_{GlQ2002}$. The deepening of the fairway corresponds to a total volume of about 58,180 m³.

As shown in Figure 10, nearly all minimum water depths within the fairway increase to the target value of 2.10 m corresponding to GlQ_{2002} - 25%. Values of the minimum water depth below 2.10 m occurring after the implementation of the *“fairway within fairway”* are caused by two facts: On the one hand, marginal reduced water levels due to the measure which result in the occurrence of new shoals and, on the other hand, the small-sized shoals with an horizontal extent less than 2 m where the bed level was not modified. A modification of these small areas with very small depth lacks of up to 0.02 m would have led to the unfavourable situation of very small element sizes in the numerical model.

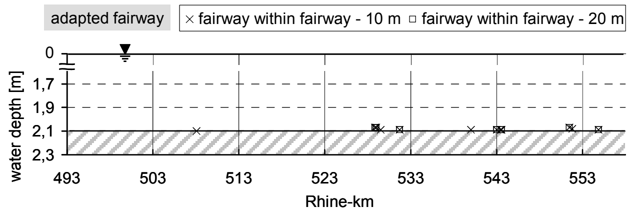

Figure 10. Minimum water depths of shoals smaller than the fairway depth of 2.10 m within the width reduced fairway polygons during reduced low water discharge GlQ_{2002} - 25% (*“adapted fairway*”, Rhine-km 493.0 to 557.5).

The differences in water levels between the “*status quo*”-calculations and the “*adapted fairway*”-analysis are small with a maximum value of about 0.02 m during the reduced low water discharge GlQ_{2002} – 25% (Figure 11). However, values smaller than 0.01 m are predominant in the river stretch.

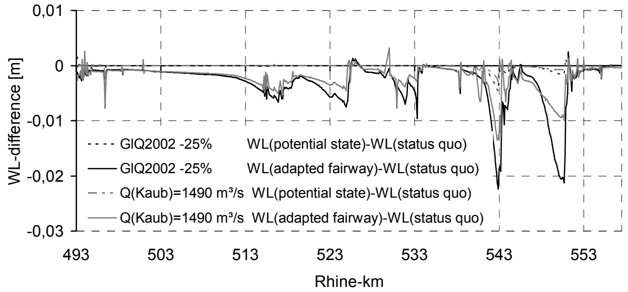

Figure 11. Water level (WL) differences between “*potential state”* and “*status quo*“ as well as between “*adapted fairway*” and “*status quo*” for GlQ_{2002} -25% and Q_{Kaub} = 1490 m³/s.

The water level difference due to the “*adapted fairway*” in case of a discharge of 1490 m³/s at the gauge station "Kaub", which is correlated to the maximum water level, where the transportation capacity is water depth-dependent is about 0.01 m in maximum (Figure 11).

As a consequence of the river bed modification, changes of the morphodynamics have to be expected. A first hint is given by changed flow velocities due to the modified bed levels and the small differences of water levels between the “*status quo*”- and the “*adapted fairway*”-case. Figure 12 shows an example of the differences between the flow velocities in case of GlQ_{2002} – 25% (Q_{Kaub} = 562.5 m³/s) and the discharge of 1490 m³/s, which has more relevance in the context of bed load transport than the low water discharge.

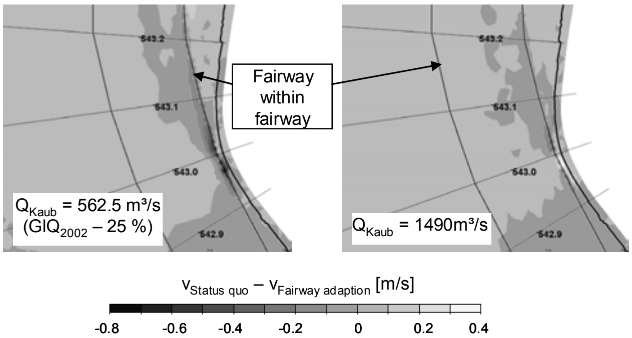

Figure 12. Differences of scalar velocities (“status quo” – “adapted fairway”) during GlQ_{2002} -25% (Q_{Kaub} = 562,5 m³/s) and Q_{Kaub} = 1490 m³/s.

For Q_{Kaub} = 1490 m³/s, the differences reach values of - 0.45 m/s, so that bed level changes can be expected. In a next step these long term adaptions of the river bed will be investigated. Herefrom, maintenance strategies shall be developed to keep up the dynamic equilibrium of the river bed as well as the implemented *“adapted fairway”*.

6 CONCLUSIONS

Reliable values for the range of discharge reduction that can be expected for the end of this century do not exist up to now. Therefore, a sensitivity analysis has been conducted for reduced low water conditions with regard to the occurrence of shoals within the fairway. The Rhine stretch from Mainz to St. Goar (Rhine-km 493.0 to 557.5) was chosen for these investigations. It could be shown, that, depending on the level of discharge reduction, the present river training and maintenance strategies have to be adapted to guarantee minimum flow depths within the fairway.

The analysis shows that, from a technical point of view, a width reduced, deepened *“fairway* *within fairway"* seems to be a suitable measure for the purpose of gaining flow depth. Considering the reduced low water discharge GlQ_{2002} -25%, sufficient fairway depths could be obtained by this measure. Changes of flow velocities due to the implemented *"fairway within fairway"* necessitate further morphological investigations in order to develop maintenance strategies to keep up the dynamic equilibrium of the river bed as well as the implemented *"fairway within fairway"*.

Besides the *"fairway within fairway"* further strategies for gaining flow depth in periods of reduced low water conditions are going to be considered.

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