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Applying adaptive design for the replacement of a weir in the Meuse River – a case study

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ABSTRACT: The nature of the Meuse River is more than any other major river in the Netherlands formed by the presence of weirs. These were constructed almost one century ago to enable transport of coal; nowadays, the boundary conditions have changed and will continue to change in the future. The weirs reach the end of their lifetime around 2030; during their replacement, the uncertain future has to be considered. This paper presents an adaptive river design, which is able to adapt to the changing requirements. Special attention is given to the design of an adaptive weir in the Meuse River to replace the present weir at Belfeld. A new design methodology has been developed and applied. The methodology results shown in an adaptation scheme, give an overview of the required regional and weir adaptations. These adaptations are required to serve the scenario-dependent purposes in the future.

1 PRESENT SITUATION

1.1 *Dutch dammed Meuse River*

The Meuse River is the second largest river in The Netherlands after the River Rhine. The river springs in Northern France after which it flows through Belgium and The Netherlands to the North Sea. The catchment area of the Meuse River does not include any snowy high-elevation areas. Hence, the discharge of the Meuse River is solely dependent on the highly variable precipitation in the catchment area. In winter, floods of the river valley are recurrent; in summer, extremely small discharges (< 30 m^3/s) are not exceptional. The latter results in very small water depths in an undammed river, causing a regular non-availability for the navigation sector. In the 18^{th} century a waterway network was initiated to enable navigation throughout the year from Belgium to the River Rhine and the port of Rotterdam and vice versa. This network has been extended by digging canals and improved regarding availability by constructing seven weirs in the Dutch part of the Meuse River. The canals and weirs are indicated in Figure 1. Moreover, Belgium and The Netherlands formed an agreement that governs the water distribution in the binational waterway network in periods of drought.

The weirs that were constructed in the beginning of the 20^{th} century control the water level in the Meuse River during 360 days per year on average. This is achieved by the operation of the two weir parts, which are shown in Figure 1 as well. The lift gates of the Stoney weir are applied for accurate water level control in the weir segment. The Poirée weir is used for water level control over a wide discharge range. The locks adjacent to the weir are flooded and unusable during floods (about 5 days per year). During these floods, the partitions of the Poirée weir are stowed on the riverbank, after which the trestles are laid down on the sill, located in the riverbed. Navigation on the Meuse River does not come to a complete standstill, since vessels can navigate over the sill of the Poirée weir.

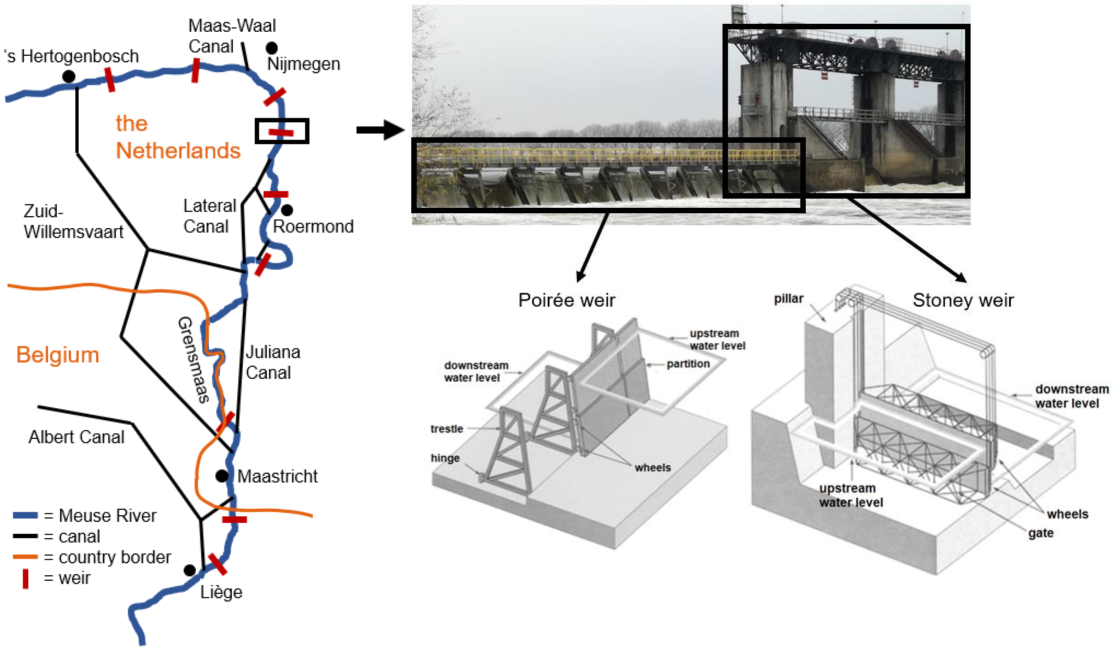

Figure 1. The waterway network of the Meuse River, in which the weirs are located (Schot, Lintsen, Rip, & De la Bruhèze, 1998).

1.2 *Deficiencies of the present weirs*

As the weir structures were constructed almost 100 years ago, they approach the end of their lifetime. Within the Dutch national program 'Risk Assessment of Hydraulic Structures' (in Dutch: Risico Inventarisatie Natte Kunstwerken (RINK)) each weir structure has been inspected. The pillars of the Stoney part show some concrete degradation, although there is some debate on this, since inspections give contradictory results. On top of this uncertainty, the current manual operation of the Poirée weir is outdated. The crane stowing the partitions on the riverbank during a flood wave is assisted by workmen. The required specialist workmanship does not meet the national Working Conditions Act (in Dutch: Arbowet). This paper focusses therefore on the total replacement of the weirs in 2030, when the weirs have reached the end of their technical and functional lifetime. Rijkswaterstaat, part of the Dutch Ministry of Infrastructure and Water Management, initiated a process in 2015 in which the civil engineering sector was invited to collectively develop weir replacement strategies (De Bouwcampus, 2015). The co-creation meetings resulted in multiple ideas for future use of the Meuse River and the weirs, called perspectives. One of them, named 'the Adaptive Meuse', combines the weir replacement with the concept of adaptive delta management and forms the basis of the research conducted by Frijns (2019). This paper presents a summary of this research.

1.3 *Adaptive designing*

Adaptive delta management states that designs have to be flexible and able to switch between multiple strategies for future challenges concerning flood safety and freshwater storage. The exact purposes that have to be served in the future in the river area depend on the future developments. The basis design of 2030 therefore has to be adapted in different ways to deal with these.

The uncertainty of the future developments is described in the approach of adaptive delta management by the Dutch delta scenarios, named BUSY, STEAM, REST AND WARM (in Dutch: DRUK, STOOM, RUST and WARM) (Bruggeman, et al., 2016). These scenarios, indicated in Figure 2, represent unique combinations of two general (inter)national developments: the rate of

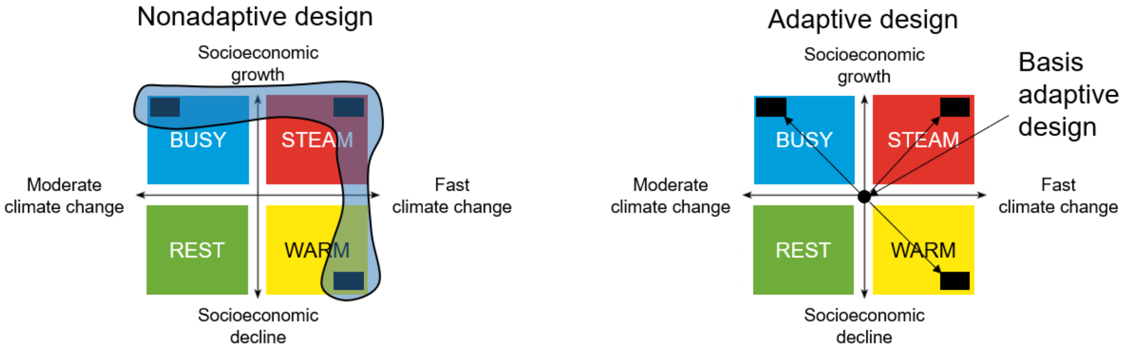

Figure 2. Schematic overview of a nonadaptive and adaptive design in relation with the Dutch delta scenarios (Bruggeman, et al., 2016).

climate change and socioeconomic developments. The scenarios have been set by the Royal Netherlands Meteorological Institute (KNMI) and a combination of The Netherlands Bureau for Economic Policy Analysis (CPB) and The Netherlands Environmental Assessment Agency (PBL), respectively (Bruggeman, et al., 2016).

Figure 2 shows the difference between a nonadaptive and an adaptive design. The first leads to a robust design which meets the most extreme, plausible set of requirements (indicated with the black boxes in Figure 2) of all scenarios. However, only one of the scenarios develops, so some investments turn out to be inefficient. Therefore, an adaptive design starts with a basis adaptive design (indicated with the dot in the middle in Figure 2). This design meets the requirements during the first period of the weir's lifetime; changed requirements thereafter are met by adaptations to the basis adaptive design (indicated with the arrows towards the black boxes in Figure 2). Adaptation measures are only taken if and when the demands to the design change. In this paper, a basis adaptive design is presented in combination with an adaptation scheme. The adaptation scheme, shown in Figure 3, presents in the first two columns an overview of the purposes that apply in each scenario. The last three columns show the (combination of) adaptation measures that have to be taken to meet these purposes. These columns have been realized after a regional and local analysis, which are elaborated in more detail in this paper.

1.4 *Reading guide*

Chapter 2 of this paper addresses the methodology that is used to obtain an adaptive weir design. Besides, it elaborates on the water level control by operation of the weir gates. In Chapter 3, the design is elaborated in a geographical downscaling order, including the basis adaptive design of the river area. Furthermore, the adaptation measures are set up to end up with the adaptation scheme of Figure 3. The interpretation of the adaptation scheme is given in Chapter 4. Chapter 5 presents the discussion and conclusion of this paper.

Legend (A = regional adaptation measures; B = weir adaptation measures)
A ∩ B = intersection (A and B)
A ∪ B = union (A or B)
A ⊃ B = superset [(only A) or (minimized A + B)]

<table>
<tr><th>Purpose</th><th>Scenario (year) in which the purpose applies</th><th>Regional adaptation measures</th><th>Binary operator</th><th colspan="2">Weir Belfeld adaptation measures</th></tr>
<tr><td rowspan="2">Increasing the discharge capacity of the river valley</td><td>BUSY (2050)</td><td rowspan="2">‘Room for the River’ measures</td><td rowspan="2">⊃</td><td rowspan="2">Enlarging the flow opening</td><td>By 10%</td></tr>
<tr><td>STEAM (2050, 2100)
WARM (2100)</td><td>By 15%</td></tr>
<tr><td rowspan="3">Preventing more frequent flooding of the river valley</td><td>BUSY (2050)</td><td rowspan="3">Raising the main channel embankments
∪
dredging the main channel</td><td rowspan="3">∪</td><td rowspan="2">Enlarging the flow opening</td><td>By 10%</td></tr>
<tr><td>STEAM (2050)</td><td>By 15%</td></tr>
<tr><td></td><td colspan="2">∪
shifting the set point location</td></tr>
<tr><td>Accommodating higher container vessels</td><td>BUSY (2050)
STEAM (2050)</td><td>Raising bridges on the Maasroute</td><td>⊃</td><td colspan="2">Shifting the set point location</td></tr>
<tr><td rowspan="2">Providing more freshwater storage</td><td>BUSY (2050, 2075)
STEAM (2075, 2100)
WARM (2075, 2100)</td><td rowspan="2">Dredging a new lake
∪
enlarging an existing lake</td><td rowspan="2">∪</td><td rowspan="2">Heightening to maximum</td><td>NAP +15.10 m</td></tr>
<tr><td>BUSY (2100)</td><td>NAP +15.30 m</td></tr>
<tr><td>Increasing the dynamics in dedicated natural areas</td><td>BUSY (2050)</td><td>-</td><td>-</td><td colspan="2">Shifting the set point location</td></tr>
<tr><td>Accommodating larger vessels to the Prins Willem-Alexanderport</td><td>BUSY (2075)</td><td>Deepening the Prins Willem-Alexanderport</td><td>-</td><td colspan="2">-</td></tr>
<tr><td rowspan="2">Improving the accessibility of the Prins Willem-Alexanderport</td><td rowspan="2">BUSY (2100)</td><td rowspan="2">Deepening the Prins Willem-Alexanderport</td><td>∩</td><td colspan="2">Removal of weir Roermond
∪
replacing weir Roermond upstream</td></tr>
<tr><td>⊃</td><td colspan="2">Heightening to maximum NAP +15.30 m</td></tr>
<tr><td>Providing more frequent flooding of the river valley</td><td>WARM (2075, 2100)</td><td>Lowering the river valley</td><td>∪</td><td colspan="2">Heightening to maximum NAP +15.10 m</td></tr>
</table>

Figure 3. Adaptation scheme of weir segment Belfeld (Frijns, 2019).

2 METHODOLOGY

2.1 *Design methodology*

A new adaptive design for the weirs in the Meuse River is created with help of the Systems Engineering methodology (Department of Defense, 2001). This methodology consists of an iterative process of a functional analysis, requirements analysis, design synthesis and design verification & validation. It is applied at different design levels to address the adaptation measures at these levels. In this paper the system of the Meuse River is analyzed on three design levels, indicated in the enumeration below and in Figure 4:

- The global design level covers the entire Dutch dammed Meuse and two weir segments in Belgium up to weir Monsin. The latter two are included, because they impose boundary conditions on the Dutch water management.

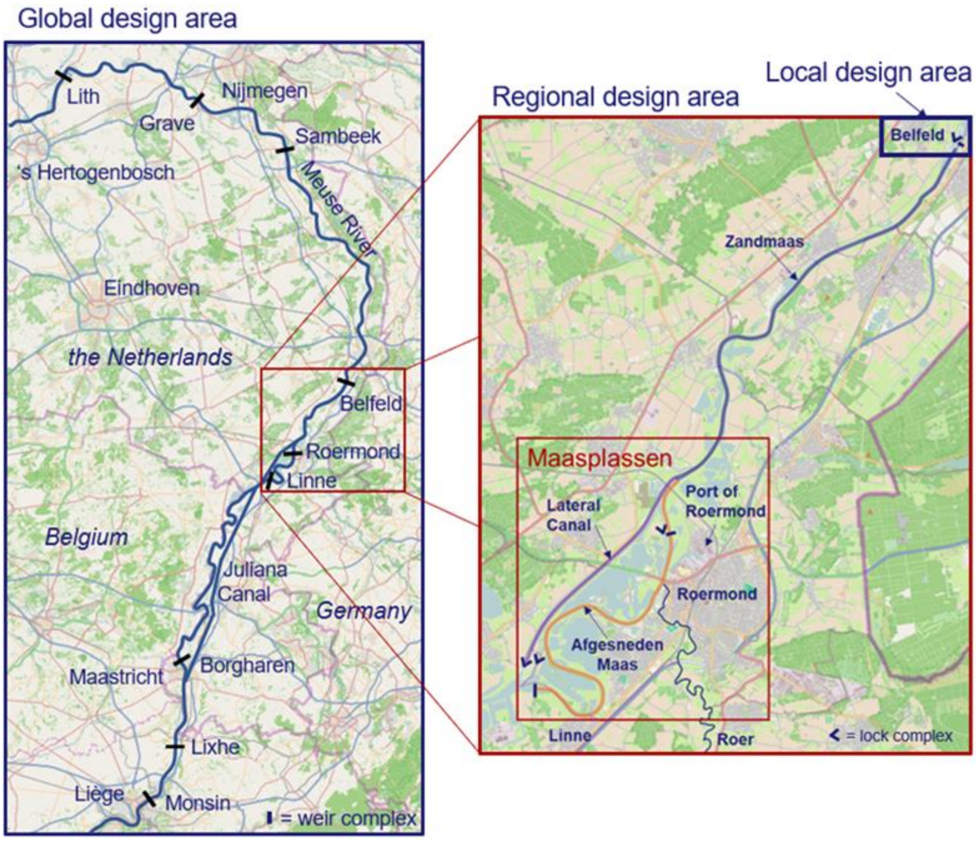

Figure 4. Differentiation of the global, regional and local design level.

- The regional design level includes the most adaptive segment, selected on basis of the proposed weir replacement strategies in the global design level. To serve future purposes, regional adaptation measures are proposed, which are eventually added to the adaptation scheme of Figure 3.
- The local design level addresses the design and feasibility of the adaptive weir itself. Adaptations to the weir can be made in the future to cope with the changed requirements. These are filled in the adaptation scheme of Figure 3.

2.2 *Water level control*

A simple and robust 1D hydraulic model is applied to compute the water levels within a weir segment. A prismatic, rectangular channel with a constant bed slope per weir segment is assumed. The water levels are obtained by solving an equation, derived from the energy balance, numerically with help of the boundary conditions (Tuin, Voortman, & Kabout, 2016).

The boundary conditions are set by the weirs, which are the controlling structures of the water level. The position of the weir gates for a specific discharge determines the water level throughout the weir segment. If the weirs are operational, it is aimed to maintain the water level at its target water level at a certain location in the weir segment. The target water level at a specific location is called the set point of the weir (Frijns, 2019). By changing the position of the weir gates, the location of the set point can be shifted throughout the weir segment. For the present weirs, the set point is located just upstream of the weir itself, shown in the left plot of Figure 5. The water levels in the weir segments increase if the discharge increases, except at the location of the set point. In the right plot, the set point is located at the most upstream navigable location in the weir segment. In this situation, the water level in the downstream part of the weir segment decreases if the discharge increases. The location of the set point as in the right plot is favorable for container transport as it provides more air clearance. Moreover, the weir is opened more frequently, but on the other hand the water level variability in the upstream part of the weir segment decreases. This disadvantages currently ecologically high-valued areas which are located here.

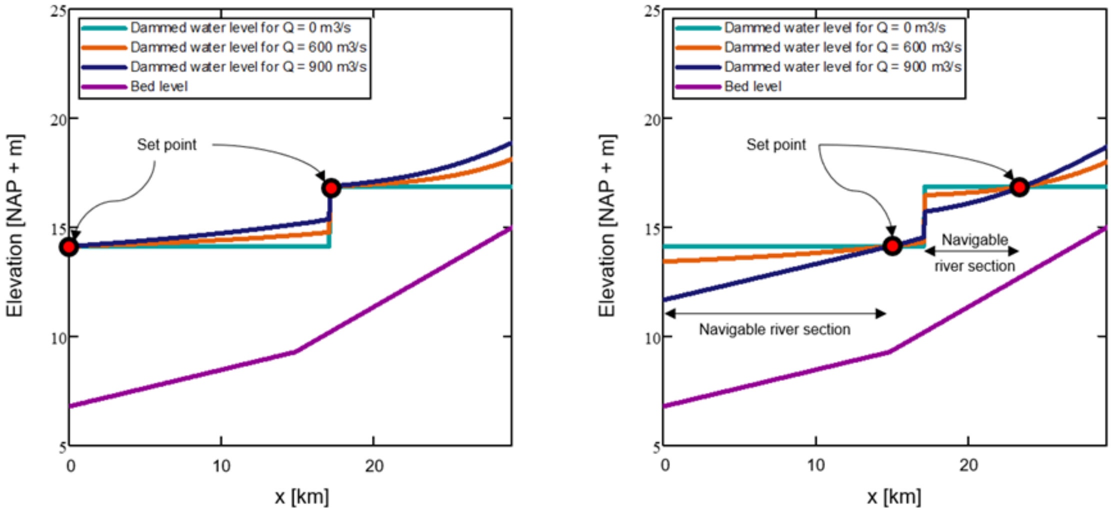

Figure 5. Dammed water levels for various discharges with the current location (left) and theoretical location (right) of the set point.

3 ADAPTIVE WEIR DESIGN

3.1 *Global design*

As stated earlier, the global design level is applied to select the regional design area, which includes the most adaptive river segment. By adaptations in this segment, future purposes can be served. The adaptivity of each weir segment (see Figure 4 for their locations) is addressed by proposing multiple weir replacement strategies. Frijns (2019) concludes that the weir segments of Roermond and Belfeld are most adaptive. The weir segment of Roermond is not part of the main navigation route, since commercial navigation uses the parallel Lateral Canal (see the overview on the right of Figure 4). The weir segment of Roermond can therefore be restricted to only recreational vessels in the future. Moreover, by the presence of many lakes, called the Maasplassen (see the overview on the right of Figure 4), adaptations in this area, in combination with adaptations to the weir at Belfeld, can contribute to freshwater storage and stimulate recreation and ecology in the future. Therefore, section 3.2 and 3.3 focus on the weir segment of Belfeld and the corresponding weir, where the adaptations have to be incorporated with the navigation function.

3.2 *Regional design; development of regional adaptations measures*

As it is infeasible and undesired to displace a weir structure, to change the number of weirs and to change the location of weirs in the area during their lifetime, the location and number of weirs in the area for the upcoming century is set by the design choices made in 2030. Since the current locations and heights of the weirs at Belfeld and Roermond do meet the present requirements and to prevent groundwater related problems, one-to-one replacement of the weirs is preferred. Also, by selecting this weir replacement strategy, additional measures in the river area, such as heightening embankments and constructing new locks next to the weirs, are saved.

However, this basis design does not meet the requirements up to 2130: adaptations are required in the upcoming century to cope with the developments. The considered regional adaptation measures, taken along the weir segment of Belfeld, are intended:

- to increase the discharge capacity and prevent more frequent flooding of the river valley by ‘Room for the River’ measures;
- to accommodate navigation in the regional design area by dredging the main channel, deepening a lock, deepening a port, raising a bridge and/or dredging the navigation channel in a lake;
- to increase the freshwater storage in the regional design area by dredging a new lake or enlarging an existing lake.

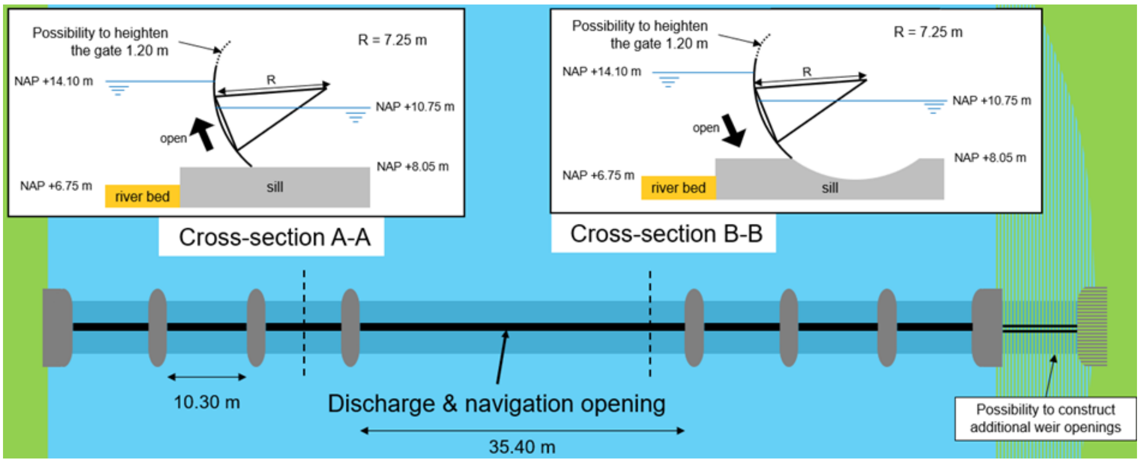

Figure 6. Overview of the proposed adaptive weir at Belfeld, including the feasible adaptations (Frijns, 2019).

3.3 *Local design; development of weir adaptation measures*

Besides the regional adaptation measures, locally (at the weir) adaptations can serve future purposes, provided that an adaptive weir has been designed. After considering and evaluating many alternatives (Frijns, 2019), an adaptive weir at Belfeld has been designed that consists of seven radial gates next to each other, as shown in Figure 6. A 35.4 m wide submersible radial gate is applied for accurate water level control and the passage of vessels during a flood wave, six 10.3 m wide radial gates close off the other weir openings. This design can be adapted in the future to serve the purposes that apply. Feasible adaptations are:

- constructing additional weir openings at the eastern embankment to increase the discharge capacity of the weir, enabled by the location of the new weir;
- adjusting the management of the weir gates, enabled by the choice of the radial gates. The location of the set point (see Figure 5) can be shifted throughout the weir segment, which allows management of the air clearance and water level dynamics for container transport and ecological development, respectively;
- heightening the dammed water level during zero discharge from NAP +14.10 m to a maximum of NAP +15.30 m. Unto this level, an economical design of the radial gate is feasible.

Since adapting the concrete substructure is very complicated and costly, additional investments are needed in 2030 to enable the potential future heightening of the dammed water level. This requires an additional initial investment of approximately €35 mln, leading to a total of €150 mln. If the water level has to be heightened in the future, only the gates and height of the superstructure have to be adapted.

4 RESULTING ADAPTATION SCHEME

The resulting adaptation scheme of the weir segment of Belfeld after construction of the proposed adaptive weir is presented in Figure 3. The scenario-dependent purposes are mentioned in the first two columns; regional and weir adaptation measures that serve these in the last columns. The binary operator between the adaptation measures indicates if the measures have to be taken in combination with or instead of each other. The asset-owner Rijkswaterstaat can apply this adaptation scheme to overview the options to serve future purposes. By the large adaptivity of proposed weir design, regional adaptation measures along the river with undesired implications, such as disturbance of the ecosystem or usage of scarce land area, can be discarded or minimized. On top of that, insight is gained on the measures and design choices of today that limit or enable a number of adaptations in the future. For example, the establishment of residential areas can limit the applicability of regional adaptation measures, like dredging a new lake as freshwater buffer. Via the adaptation scheme, one can see that heightening the weir is then the only option to provide more freshwater storage. Thanks to the construction of an adaptive weir, this heightening is achieved relatively simple and cheap.

5 CONCLUSION AND DISCUSSION

In conclusion, on a global level, a change of the locations and numbers of weirs in the Meuse River is presently not desired and required, since the functions are met with the current weir layout. To cope with future uncertainties in a cost-efficient way, replacing weir Belfeld by an adaptive weir is a good alternative to a robust nonadaptive design. To serve future purposes, adaptation measures have to be taken, of which an overview is given in an adaptation scheme. In this adaptation scheme, regional adaptation measures (in the river area) and local adaptation measures (at the weir itself) are proposed to give the asset-owner, Rijkswaterstaat, a full overview of required measures in the future lifetime of the asset. The developed methodology still has to be applied at the other weirs within the global design area. Involvement of Rijkswaterstaat and other stakeholders will lead to an improved adaptive river design and adaptive weir design.

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