AMBER

www.amber.international

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 689682.

D3.4 River Infrastructure Planning Decision Support Tool

This is version 2.0 of the D3.4 River Infrastructure Planning Decision Support Tool. This document is a deliverable of the AMBER project that has received funding from the European Union's Horizon 2020 Programme under Grant Agreement (GA) # 689682.

History of changes

Version	Date	Changes	Pages
1.0	23 May 2019		
2.0	25 Oct 2019	Extensive revisions to text to improve clarity and understanding of the infrastructure planning tool plus additional figures added.	5 to 26

DISCLAIMER

Executive summary

This is version 2.0 of deliverable D3.4 River Infrastructure Planning Decision Support Tool. This document is a deliverable of the AMBER project. This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 689682.

A decision support tool has been developed to optimise environmental and socioeconomic trade-offs associated with river infrastructure (i.e. barriers), including river connectivity, hydropower generation, and shipping and other costs. The model extends previous work by considering (i) *multithreaded river sections*, essential for estimating river connectivity in the presence of diverted channels for hydropower and shipping, (ii) *backwater effects* caused by the lowering or raising of artificial in-stream structures, which , in turn, affect hydropower generation potential and transport capacity of shipping vessels, and (iii) the integration of *realistic cost functions* for estimating the cost of hydropower installation/retrofitting and cross-port shipping of goods by a heterogeneous fleet of vessels. To demonstrate the applicability of the planning tool, a database for the Neckar River in Germany was created. The database contains more than 1000 existing river barriers and more than 4,000km of river and includes detailed information on river flow, hydropower, and waterborne traffic.

The planning tool is designed to find the best combination of river infrastructure modification, mitigation, and removal actions in order to optimise three key performance indicators (KPIs): 1) river connectivity based on a generalisation of the well-known Dendritic Connectivity Index, 2) hydropower potential/revenue and 3) total cost, broken down by the cost of structural engineering works, installation and retrofitting of hydropower, and annual shipping. The model focuses specifically on the socioeconomic benefits of hydropower and shipping, as these are the two main human uses of rivers within the Neckar catchment. The model could be readily modified to consider other environmental and socioeconomic factors, which may be important in other planning areas, such as irrigation, water supply, fishing, recreation, and water purification.

The planning model has been specially configured to examine ten scenarios for adaptive barrier management. The results show which river infrastructure modification, mitigation, and removal actions could be undertaken to maximise connectivity, maximise hydropower, or minimise total cost subject to defined river connectivity and energy production targets.

Authors

Tim Feierfeil (IBK), Jesse O'Hanley (IBK), Klemens Kauppert (IBK).

Contents

1 FOREWORD

The aim of this report is to illustrate potential uses of the planning tool in identifying cost-effective proposals for river infrastructure modification, mitigation, and removal. The planning tool incorporates the best available data for the Neckar River catchment study site in relation to:

1. The number and spatial position of artificial structures
2. Physical and design characteristics of structures (for example, height, elevation, and installed hydropower capacity)
3. Hydraulic data (for example, low/medium flow and natural water depth)
4. Barrier passability
5. Structure modification, mitigation, and removal costs
6. Shipping costs, transport volumes, and fleet make-up
7. Hydropower installation and retrofitting costs

However, as with any application of a decision support tool, any errors or gaps in the data may influence the precision of results generated with the tool. Further, it is impractical for a planning tool to account for every environmental and socioeconomic attribute of more minor concern. Among the factors not considered within the planning tool are:

1. Groundwater level changes (potentially important for agriculture)
2. Protection of cultural heritage
3. Changing demand for hydroelectric energy
4. Water legislation
5. River shipping policies and regulations

Any real-world application of the planning tool would need to take the above caveats into consideration and would need to involve the direct participation of both technical experts and key stakeholders in developing an agreed action plan. Accordingly, the report makes no specific recommendations about possible barrier modification, mitigation, or removal actions for the chosen study site, nor does it endorse any specific planning scenario discussed.

2 INTRODUCTION

A decision support tool for river infrastructure planning has been developed to optimise trade-offs involving river connectivity, hydropower generation, and various types of upfront and ongoing costs, including structural engineering works, installation and retrofitting of hydropower, and annual cross-port shipping of goods.

The planning tool extends previous work (King and O'Hanley, 2016; Ioannidou and O'Hanley, 2018) by considering (i) *multithreaded river sections*, essential for estimating river connectivity in the presence of diverted channels for hydropower and shipping, (ii) *backwater effects* caused by the lowering or raising of artificial in-stream structures, which , in turn, affect hydropower generation potential and transport capacity of shipping vessels, and (iii) the integration of *realistic cost functions* for estimating the cost of hydropower installation/retrofitting and cross-port shipping of goods by a heterogeneous fleet of vessels. All of these aspects are novel research contributions not presently incorporated in existing river infrastructure planning tools.

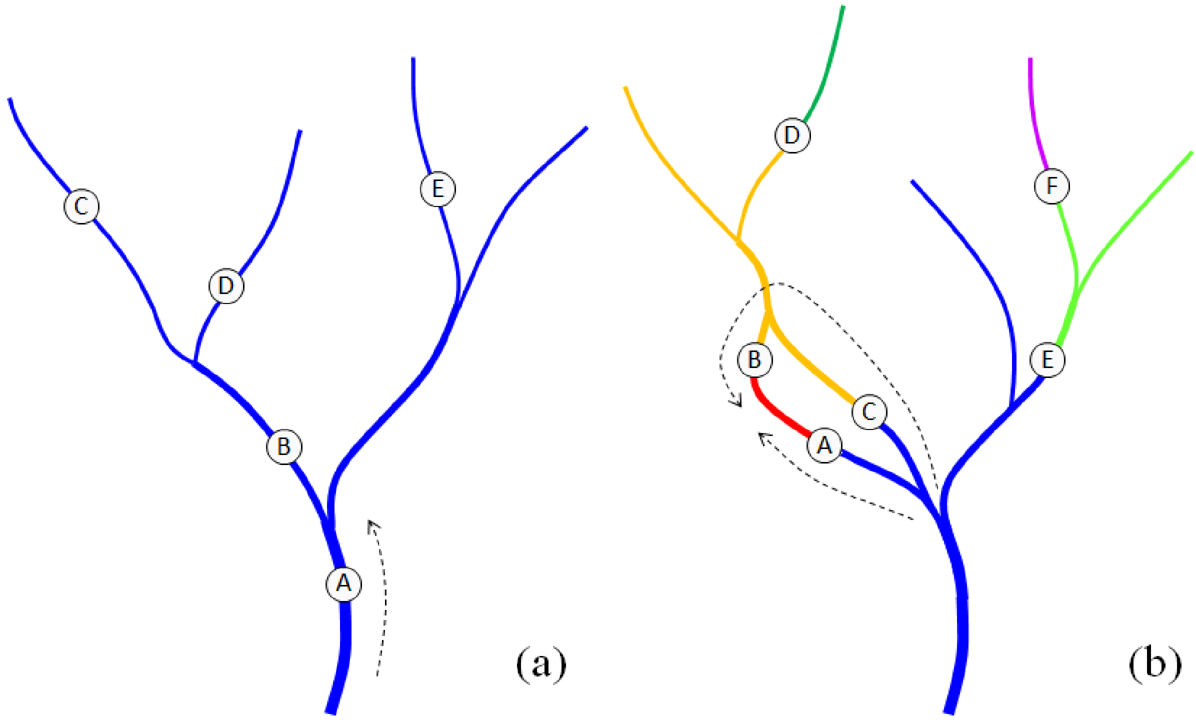


Figure 1. Examples of dendritic (a) and multithreaded (b) river networks. Lettered nodes represent artificial in-stream structures (for example, dams and weirs). Note how in the dendritic network (a), there is only one dispersal path between the areas below and above structure A, while in the multithreaded network (b), there are two paths available for reaching the area above structure A starting from below A, either by directly passing structure A or by passing structures C and B.

The ability of the planning to tool to handle multithreaded river sections is particularly noteworthy. Existing connectivity metrics make the very strong, simplifying assumption that rivers are strictly dendritic, meaning that a river never diverges as it flows in the downstream direction. This assumption is frequently made, not because it actually holds in practice but because it greatly simplifies the way connectivity is conceptualised and modelled. More specifically, if and when a river is dendritic, then there is necessarily one and only one dispersal path between any two sections of river (**Figure 1**). In heavily modified rivers systems, which are common across Europe, diversions have been constructed for hydropower, shipping, or other purposes (for example, milling). The presence of diversions introduces multiple dispersal pathways between different sections of river (**Figure 1**) and potentially makes existing connectivity metrics unsuitable for characterising the functional connectivity of rivers. Real-world planning, particularly in the context of Europe and other industrialised regions, necessitates moving away from the use of overly simple connectivity metrics and instead developing new, more robust metrics to describe complex, interconnections between river areas formed by the presence of diversions.

To validate the planning tool and demonstrate its functionality, a database for the Neckar River catchment in Germany has been created. The planning tool is well suited the Neckar study area, as hydropower and river transport are the two main human uses of rivers within the catchment. It is worth noting that the planning tool can be readily modified to consider other environmental and socioeconomic factors, which may be important in other planning areas, such as irrigation, drinking and industry water supply, fishing, recreation, and water purification.

A variety of planning scenarios were generated with the planning tool for the Neckar catchment to illustrate environmental and socioeconomic trade-offs involved with barrier modification, mitigation and removal actions. Results are detailed in Section 4. Before this, further details about the study area, primary objectives and outputs of the planning tool, and some basic modelling assumptions are provided.

2.1 Neckar database

A geospatial database was created in Task 3.1.1 (AMBER D3.3, 2019) for the navigable portion of the Neckar between river kilometres 0.0 and 201.5 along with its main tributaries, the Jagst and Kocher, and minor tributary streams. Various spatial and hydrologic information was extracted from publically available sources.

The database contains:

1. A total river length of 4,069km
2. A total of 1069 weirs, dams, and culverts and 27 ship locks located across the Neckar catchment
3. Information on low and medium river flow
4. Estimated low and medium natural water depth below existing structures
5. Shipping data consisting of laden/unladen vessel counts on transported amounts between different ports
6. Installed hydropower capacity at existing dams and weirs

A subset of 536 barrier points was extracted by snapping geospatially referenced weirs, dams, culverts and locks points to the river network using a 100m snapping distance. A map view of the Neckar catchment area and the position of artificial structures within it is shown in **Figure 2**.

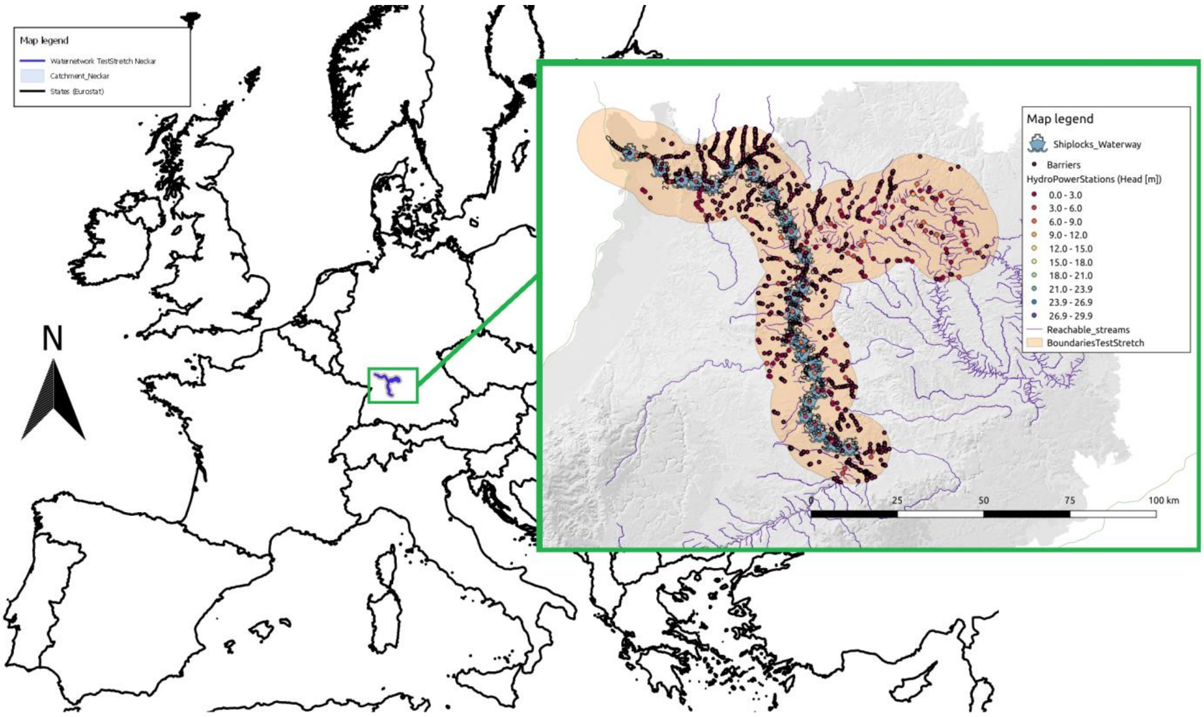


Figure 2. Map view of the Neckar test stretch.

2.2 Planning tool objectives and outputs

The planning tool considers the following three primary objectives or key performance indicators (KPIs).

1) Connectivity for aquatic species defined on the range 0.0 to 1.0, with 1.0 representing a fully connected river catchment and 0.0 a completely disconnected river catchment
2) Hydropower generation potential under medium flow conditions (kW)
3) Total (real) cost, which includes:
    a. Costs for structural engineering works related to modification, mitigation, or removal of artificial structures (€M)
    b. Annual costs for waterborne transport of goods based on low flow conditions (€M/year)
    c. Costs for installation and retrofitting hydropower turbines (€M)

Since structural engineering works and hydropower installation/retrofitting costs are incurred only once (at the beginning), while shipping costs are ongoing, total cost is computed over a 30-year time horizon and discounted using a 3% discount rate. A fourth KPI, total hydropower revenue (€M) discounted over 30 years, also using a 3% discount rate, is derived directly from hydropower potential (assuming 5000 hours of hydropower production per year and an electricity price of €0.122 per kWh). The planning tool has been specially configured in four ways to prioritise certain KPIs. The four configurations, also referred to as models, are listed in **Table 1**.

Table 1. Planning tool configurations.

No.	Model	Objective
1	Model 1	Maximise river connectivity only (see Section 3.3 for explanation of how connectivity is determined)
2	Model 2	Maximise hydropower only
3	Model 3	Minimise total cost (including shipping costs) with secondary objectives for maximising connectivity and hydropower (implemented as constraints requiring these KPIs to be greater than or equal to user-defined thresholds)
4	Model 4	Minimise total cost (including shipping costs) with additional constraints requiring structural engineering works and hydropower installation/retrofitting costs to be zero (required for estimating the current situation)

3 BASIC MODELLING ASSUMPTIONS

In developing the river infrastructure decision support tool and applying it to the Neckar catchment study area, various modelling assumptions and simplifications were necessary. Some of the more important assumptions are discussed below.

3.1 Barriers located on multithreaded river sections

For the purposes of placement, modification, mitigation, or removal, artificial river structures are treated collectively in groups, termed hydrologic modelling units. A hydrologic modelling unit consists of a single structure if located on a non-divergent section of river, or as a set of barriers if they are arranged along parallel river channels having the same upstream divergence point. Most hydrologic modelling units in the Neckar consist of a single barrier, but there are some 2-barrier hydrologic modelling units and a small number of units with three or even four barriers. With reference to **Figure 1(b)**, structures A, E, D, and F all form single-barrier hydrologic modelling units, while structures B and C form a 2-barrier hydrologic modelling unit.

3.2 Available modification, mitigation, and removal options

Up to six planning options were available for each hydrologic modelling unit within the Neckar. These are as follows:

1) Do nothing.
2) Install a fish pass if none currently exist (for dams and weir-like structures only) to increase passability of a given structure.
3) Raise head by 0.5m (for barriers on the main stem Neckar only) to: (i) increase hydropower potential of a given structure; (ii) raise water depth upstream to reduce the cost of shipping; (iii) possibly increase passability of barriers upstream; or (iv) any combination thereof. Note that an increase in passability is only achieved if and when the upstream barriers lie within the backwater of the downstream barrier and head is reduced sufficiently (see Sec. 3.3 for explanation of how passability is estimated as a function of head).
4) Lower head by 0.5m (for barriers on the main stem Neckar only) to possibly increase fish passability at a given structure.
5) Remove structures completely (for barriers on major/minor tributaries only) to increase fish passability of a given structure.
6) Culvert replacement (for culverts on minor tributaries only) to increase fish passability of a given structure.

Due to the high economic importance of the shipping (PLANCO 2006), structures along the main stem Neckar, which are essential for maintaining navigation, were not considered for complete removal. There are only a handful of culverts with limited upstream habitats upstream in the Neckar study area. This may be entirely different in other river systems, so consideration of culverts within the decision support tool is an important feature in general.

Removal and mitigation costs for the various options list above were as follows.

- Cost of removal = $\begin{cases} €400{,}000 & \text{if located on the Neckar} \\ €302{,}422 & \text{if located on a major tributary} \\ €208{,}908 & \text{if located on a minor tributary} \end{cases}$

- Cost of raising/lowering head height (weirs and dams) = $\frac{1}{3}c_j + \frac{2}{30}c_j \times \Delta head$

  where $\Delta head$ is the head change in meters and

  $c_j = \begin{cases} €15{,}400{,}000 & \text{if located on the Neckar} \\ €2{,}850{,}000 & \text{if located on a major tributary} \\ €580{,}000 & \text{if located on a minor tributary} \end{cases}$

- Cost of raising head height (locks) = $€3{,}276{,}953 + €5{,}022{,}602 \times \Delta head$

- Cost of installing a fish pass = $c_j = \begin{cases} €1{,}200{,}000 & \text{if located on the Neckar} \\ €1{,}000{,}208 & \text{if located on a major tributary} \\ €289{,}610 & \text{if located on a minor tributary} \end{cases}$

- Cost of culvert replacement = €49,000

3.3 Estimation of barrier passability and river network connectivity

Passability for aquatic species, typically fish, is defined on the scale from 0.0 (not passable) to 1.0 (fully passable). For fish, passability usually represents the fraction of individuals that are able to successfully navigate an artificial barrier in the upstream and/or downstream direction, though other definitions are sometimes used (Kemp and O'Hanley 2010). For the Neckar case study, upstream passability of barriers was estimated based on the swimming/jumping abilities of cyprinid fish, the most common group of fish found within the catchment. More specifically, the following rule base, informed by the work of Kemp et al. (2008), was used to classify the upstream passability of barriers:

1) For barriers without a fish pass, a passability score of 1.0 (fully passable) was assigned if head height was 0.2m or less, 0.0 (impassable) if head was greater than 0.2m.
2) Barriers with a fish pass were given passability scores of:
   a. 1.0 (fully passable) if head was 0.2m or less
   b. 0.75 (high passability) if head was above 0.2m but less than 10m (a fairly conservative estimate for new, state-of-the-art fish passes)
   c. 0.5 (medium passability) if head was over 10m.
3) Locks were assigned a 0.1 passability score in all cases.
4) On combined weir and lock structures along the Neckar, the higher passability of the weir or lock was chosen.

It should be noted that passability for barriers without a fish pass was treated as binary (passable or impassable) based on head height. Also, passability scores are for a single fish taxa (cyprinids) and do not take into account the risk of injury or mortality (especially important for downstream passage). Given the availability of more fine-scale structural and flow data or expert evaluation for all barriers within the catchment, a more sophisticated implementation of the planning tool can be easily devised to incorporate a wider range of passability scores, for example, allowing passability to vary on a sliding scale based on head height and/or vary for multiple fish taxa/guilds.

Individual barrier passabilities were integrated together to estimate the overall connectivity of the catchment based on a generalisation of the well-known Dendritic Connectivity Index (DCI). DCI, which estimates the degree to which any section of river is connected to the river mouth, is the best known and most commonly used metric within the academic literature (Cote et al., 2009). The metric was adapted to account for threaded sections of river by including all possible dispersal pathways between any two subparts of a river network bounded by artificial barriers. To do this, a specially coded C++ programme was developed to isolate the river into self-contained units called river subnetworks. A river subnetwork is delineated by one or more downstream barriers and one or more upstream barriers such that all internal river segments within a given subnetwork share the same downstream and upstream barriers. With reference to **Figure 1**, each of the different coloured portions of the river network correspond to different subnetworks. After decomposing the river network into subnetworks, dispersal pathways were enumerated for each pair of subnetworks and cumulative passability for pathway evaluated in an iterative manner using the probability chain method of O'Hanley et al. (2013).

4 SCENARIOS

The four different configurations of the river infrastructure decision support tool were used to generate a total of 10 planning scenarios. These planning scenarios describe various possible current and future states of the catchment based on desired objectives, including the current situation, maximisation of connectivity or hydropower, minimisation of total cost (including shipping), and combinations thereof. The 10 planning scenarios are listed in **Table 2.**

Table 2. Scenarios evaluated using the river infrastructure planning decision support tool.

No.	Scenario
1	Current situation
2	Maximise connectivity
3	Maximise hydropower
4	Minimise cost given: i) no decrease in connectivity and ii) no decrease in hydropower
5	Minimise cost given: i) no decrease in connectivity and ii) a 10% increase in hydropower
6	Minimise cost given: i) a 200% increase in connectivity and ii) no decrease in hydropower
7	Minimise cost given: i) a 200% increase in connectivity and ii) a 10% increase in hydropower
8	Minimise cost given: i) a 400% increase in connectivity and ii) a 10% decrease in hydropower
9	Minimise cost given: i) a 400% increase in connectivity and ii) no decrease in hydropower
10	Minimise cost given: i) a 400% increase in connectivity and ii) 10% increase in hydropower

5 RESULTS

The results for the different planning scenarios are explained below. For each scenario, a bar chart shows percentages for the KPIs relative to the current state. These are:

1. Percent river connectivity relative to the current state
2. Percent hydropower generation potential relative to the current state
3. Percent total cost (including cost of structural engineering works, discounted shipping cost over 30 years, and cost of hydropower installation/retrofitting) relative to the current state
4. Percent total hydropower revenue (discounted over 30 years) relative to the current state

Connectivity, hydropower generation potential, total cost, and total hydropower revenue are cross-compared between the current state and the respective scenarios.

Also shown are polar bar charts (Nightingale Rose chart) that plot scores for connectivity, hydropower potential, total cost, and total hydropower revenue KPIs relative to the optimum. The bigger (more outward) a radial bar for a particular KPI, the better. Scores are based on taking raw KPI values (i.e. as measured in their respective units) and rescaling them based on the best a KPI could potentially achieve. Since connectivity, hydropower potential, and hydropower revenue should all be maximised, radial bars increase as these KPIs increase. For cost, however, the goal is to minimise it, so radial bars increase if cost decreases.

The abbreviations used in the bar and polar bar charts are summarised in **Table 3**.

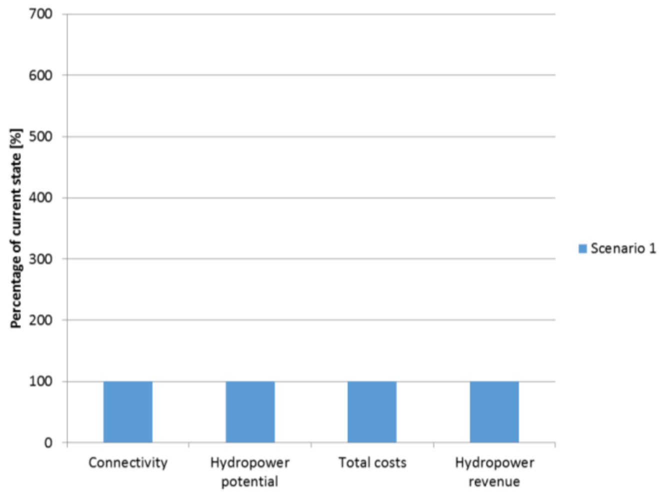
Table 3. Scenarios evaluated.

No.	Abbreviation	Explanation
1	Conn	River connectivity
2	Hydro	Hydropower potential
3	Cost	Total cost associated with structural engineering works, discounted shipping cost over 30 years, and cost of installing/retrofitting hydropower turbines
4	Rev	Total hydropower revenue discounted over 30 years

Map views for the respective scenarios show the river connectivity in connection with the necessary mitigation action to reach the connectivity state.

5.1 Scenario 1

Current connectivity within the Neckar is very low at just 0.11 (i.e. 11% of the river catchment connects through the river outlet to the Rhine). The most well connected river sections are along the main stem Neckar, which has a fair number of fish passes and semi-passable locks. There are no project implementation costs and no costs for retrofitting or renewing of hydropower plants, so the only costs for this scenario are for shipping (**Figure 3** and **Figure 4**).



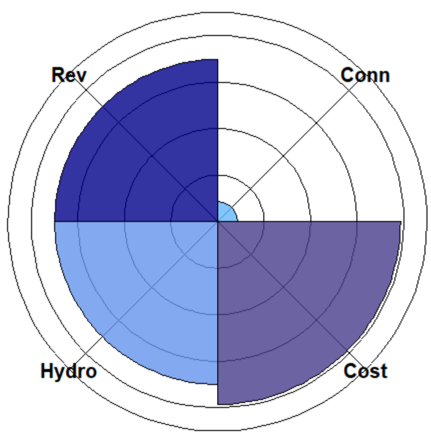


Figure 3. Scenario 1 percentage KPI scores (left) and relative KPI scores (right).

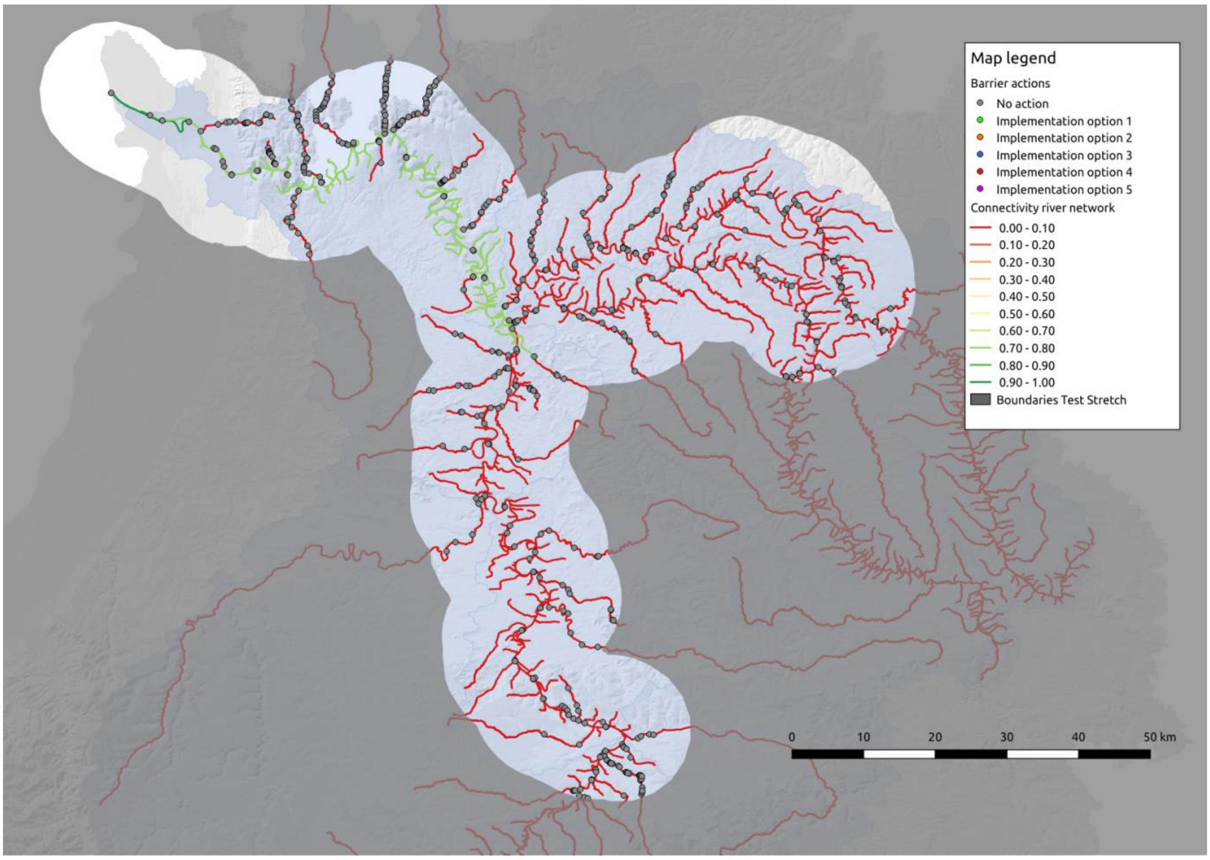
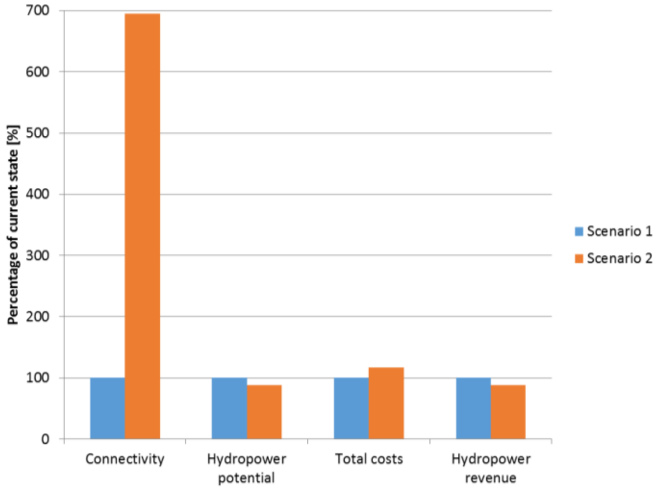


Figure 4. Map view for Scenario 1.

5.2 Scenario 2

Connectivity can be increased to a maximum of 0.75 (i.e. 75% of the catchment could be connected to the Rhine) by removing/mitigating nearly all barriers along the Jagst and Kocher (the main tributaries to the Neckar) and minor tributaries. The choice of removing versus mitigating a barrier depends on which option provides better connectivity; if both options achieve the same level of connectivity, then the cheaper options is selected.

Barriers on the Neckar cannot be removed due to the need to maintain shipping and can only be mitigated by the construction of fish passes or by lowering/raising head, which never achieves full connectivity. Project implementation costs are relatively high, but due to increases in head of specific barriers designed to increase water level and passability at barriers upstream, the cost of shipping could be reduced by 20%. At the same time, hydropower potential and total hydropower revenue would noticeably decrease, both due to head decreases and as a result of the diversion of flow into fish passes (**Figure 5** and **Figure 6**).



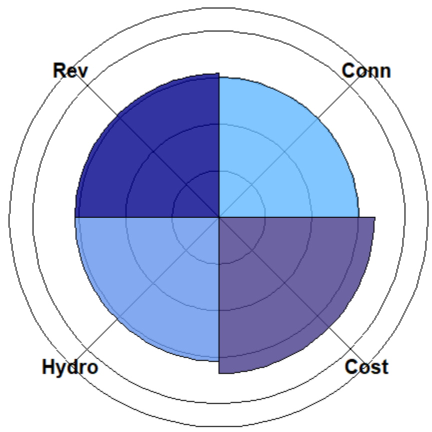


Figure 5. Scenario 2 percentage KPI scores (left) and relative KPI scores (right).

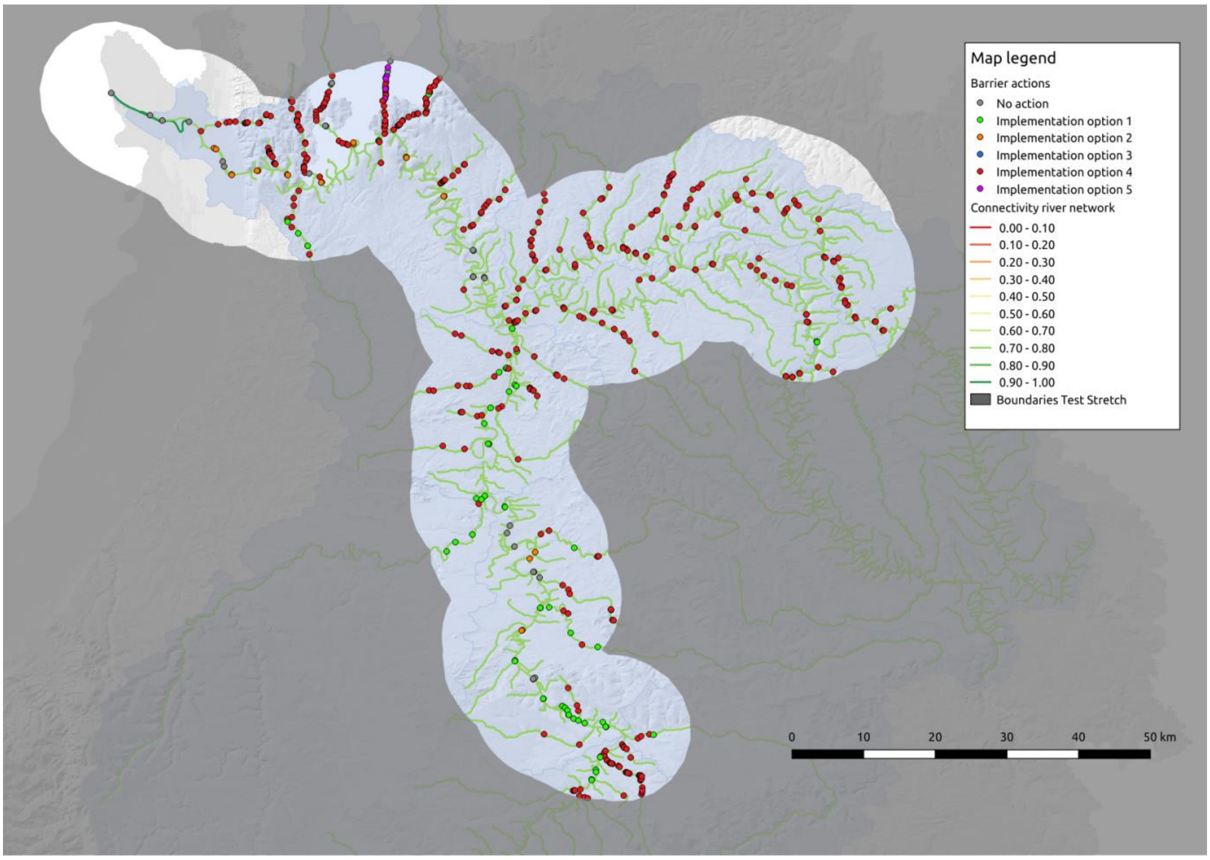


Figure 6. Map view for Scenario 2.

5.3 Scenario 3

For a scenario designed to maximise hydropower production, generation potential (based on medium flow conditions) could be increased by a maximum of 14.5% across the catchment. The cost for structural engineering works and turbine installation/retrofitting are the second highest of all considered scenarios. Revenue from electricity generation would increase but does not fully offset costs (**Figure 7** and **Figure 8**).

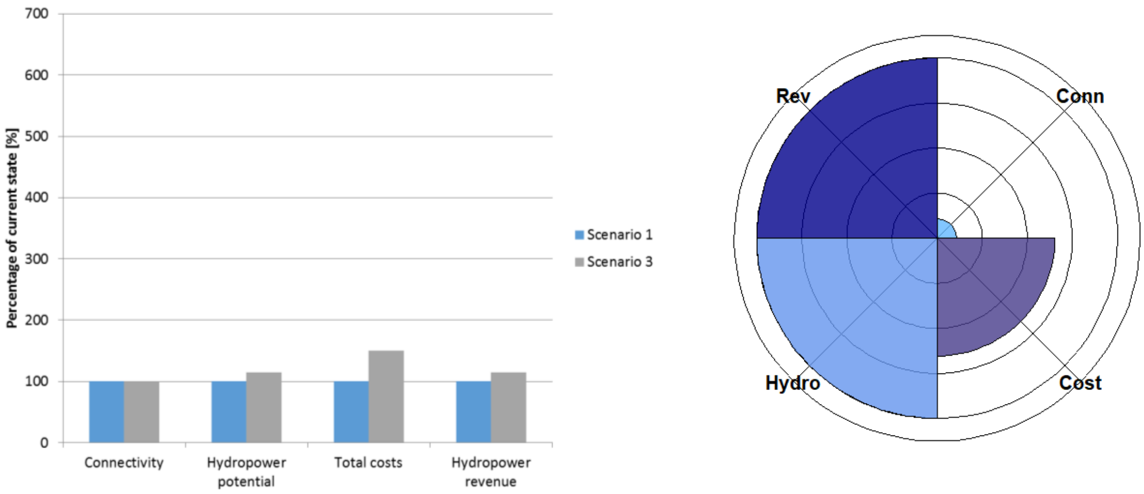


Figure 7. Scenario 3 percentage KPI scores (left) and relative KPI scores (right).

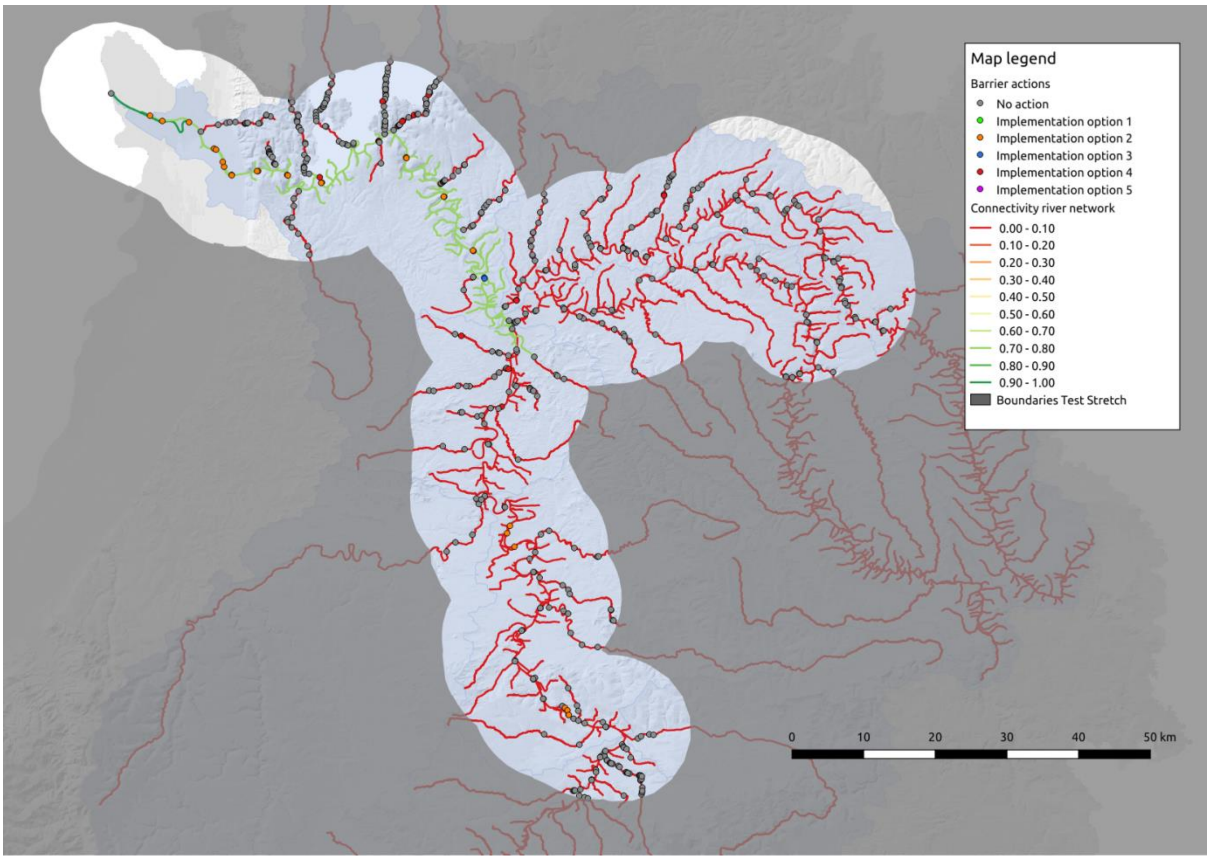


Figure 8. Map view for Scenario 3.

5.4 Scenario 4

For the Neckar catchment, minimising total costs necessitates reducing annual shipping costs. Analysis with the infrastructure planning tool shows that the only way to achieve this is by increasing the head height of dams along the main stem Neckar, which would increase water depth along the navigable portion of the river and thereby allow a fewer number of more heavily laden vessel to transport goods (**Figure 9** and **Figure 10**). While hydropower potential and total revenue could also be increased by increasing head height, this could only be achieved by simultaneously installing/upgrading turbines to increase installed capacity, which is not prescribed under this scenario as this would entail additional costs.

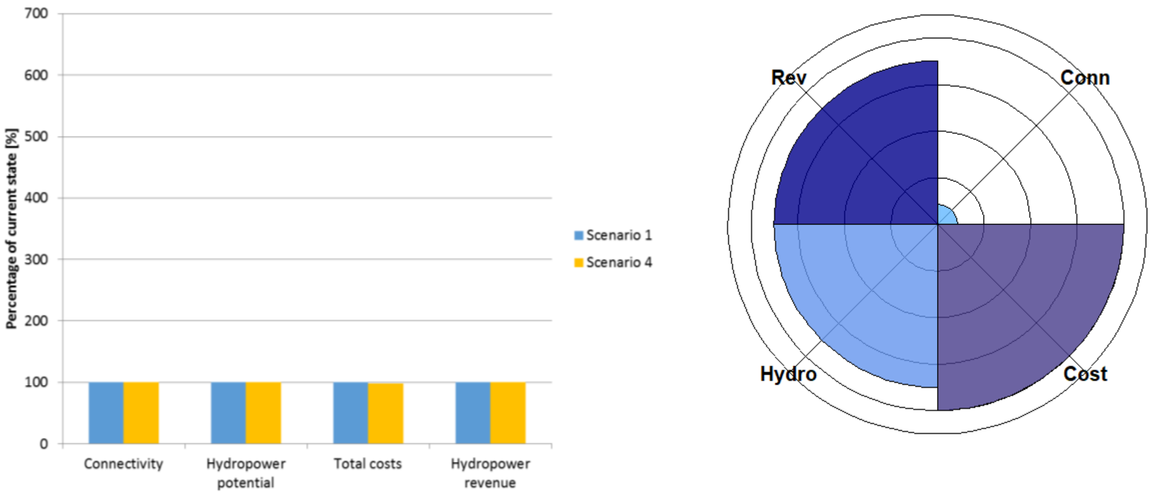


Figure 9. Scenario 4 percentage KPI scores (left) and relative KPI scores (right).

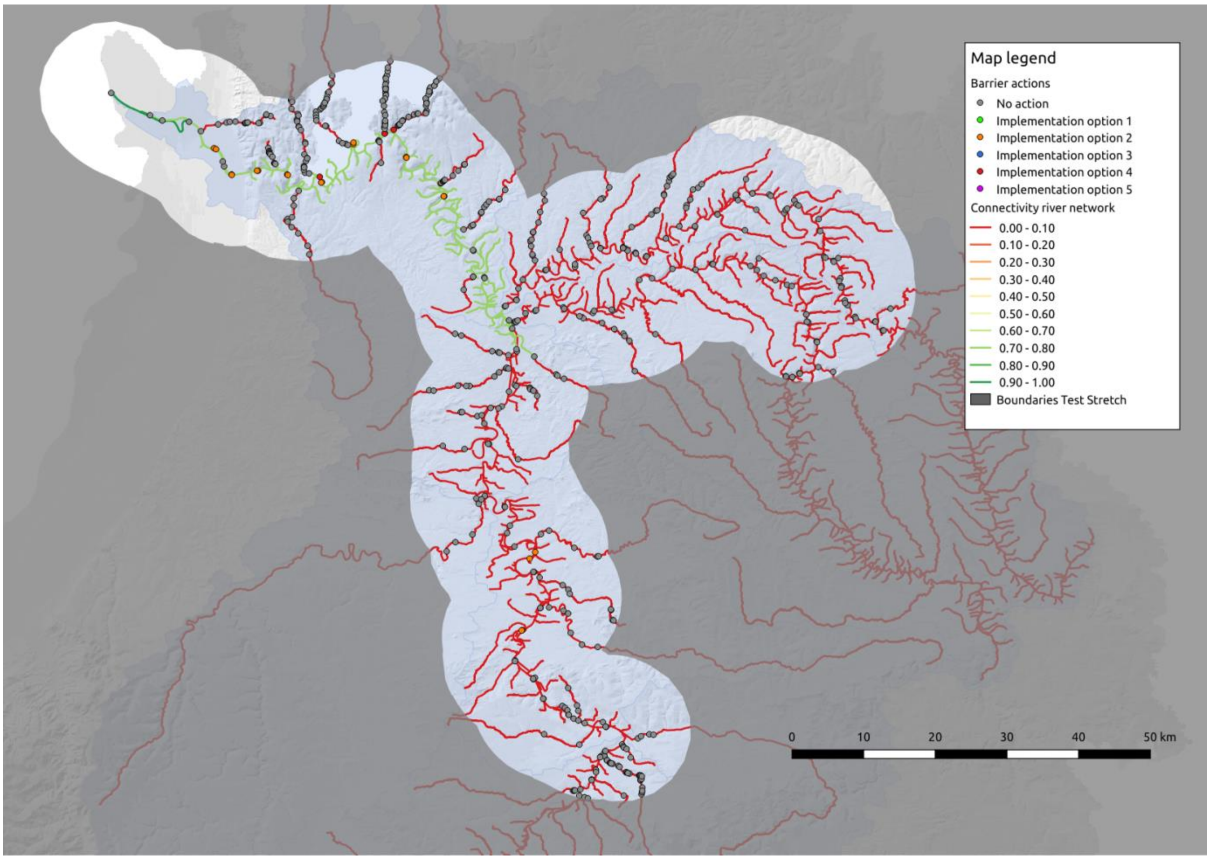


Figure 10. Map view for Scenario 4.

5.5 Scenarios 5-10

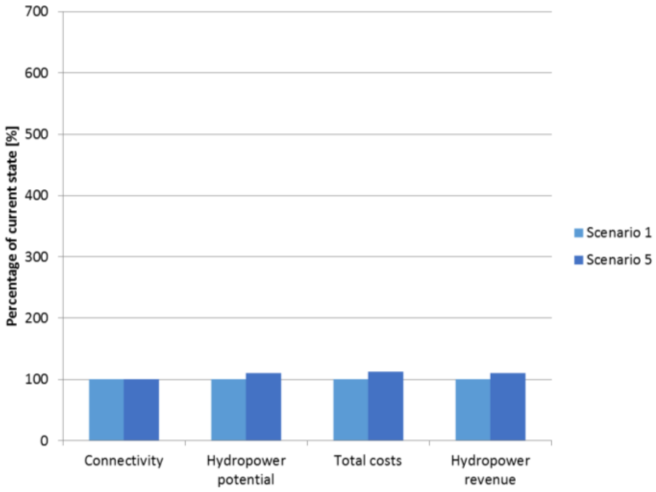
For Scenarios 5-10, trade-offs are found among river connectivity, hydropower potential, total cost, and total hydropower revenue (**Figures 11** to **22**). Increasing hydropower potential is costly, but revenue from electricity generation either partially compensates for or, in one case, produces an overall benefit (the difference between net increase in hydropower revenue and plus net decrease in shipping costs minus the cost of structural engineering and hydropower turbine installation/retrofitting).

Scenario 5 provides the most cost-effective way of increasing hydropower (by 10%) by raising the head of dams along the main stem Neckar. Despite the high cost for engineering works and installing/retrofitting hydropower turbines, this scenario provides the highest net benefit (hydropower revenue plus reduction in shipping cost minus cost of engineering works minus cost of installing/retrofitting hydropower turbines) compared to the current state, while marginally increasing connectivity. Maximising hydropower production (Scenario 2) yields a lower net benefit than Scenario 5, due to the extremely high cost of engineering works and hydropower installation/retrofitting involved with modifying all existing structures suitable for hydropower production, including all those located along main and minor tributaries of the Neckar. River flow within tributary rivers is much lower than in the main stem Neckar, so the relatively small increases in hydropower potential and total revenue produced by raising the head of tributary dams are not justified based on cost considerations.

Increasing connectivity by 200% to 0.33 with no loss of existing hydropower generation potential (Scenario 6) would reduce net benefit by 5% due to the cost of engineering works and replacement of lost hydropower potential (**Figures 13** to **14**). With a simultaneous increase of 10% in energy production, reduction of net benefit could be improved from 5% to 4% by Scenario 7 (**Figures 15** to **16**).

Increasing connectivity by 400% to 0.542 (Scenarios 8, 9, and 10) is yet more costly (**Figures 17** to **22**). The cheapest way to achieve this level of connectivity is to keep energy production at current levels (Scenario 9). Engineering works and hydropower installation/retrofitting costs involved with simultaneously increasing energy production (Scenario 10) do not exceed additional benefits.

The changes in connectivity, hydropower potential, total cost, and total revenue for all 10 scenarios are summarised in **Figure** and **Table 4**.



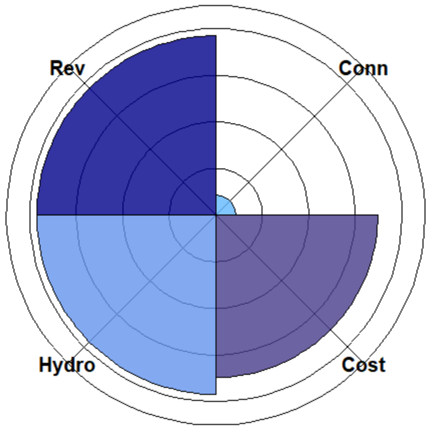


Figure 11. Scenario 5 percentage KPI scores (left) and relative KPI scores (right).

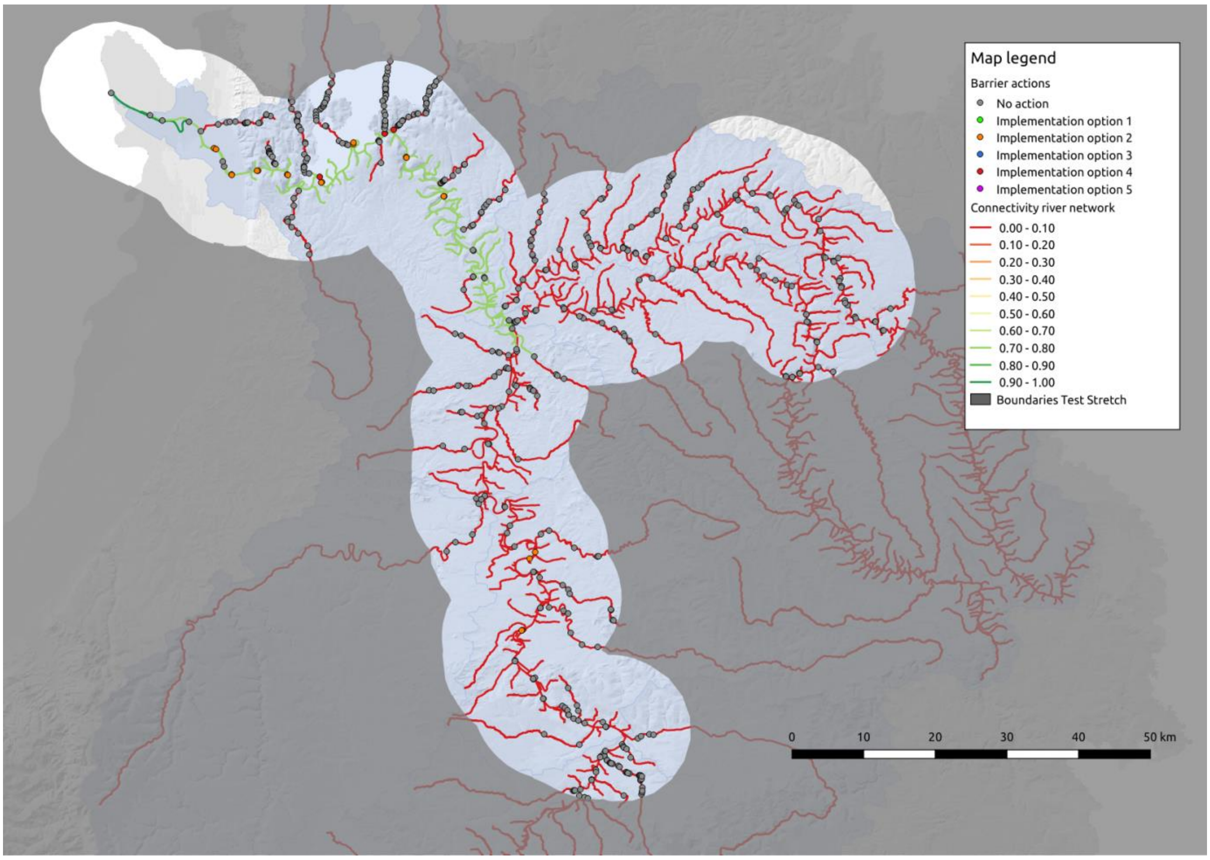
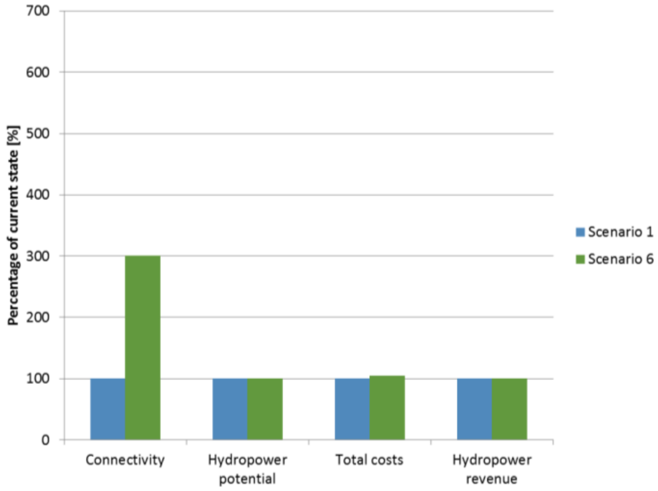


Figure 1. Map view for Scenario 5.



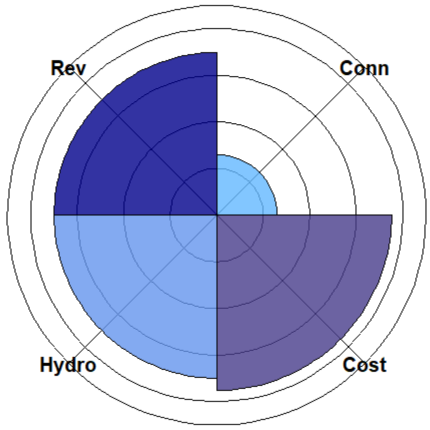


Figure 13. Scenario 6 percentage KPI scores (left) and relative KPI scores (right).

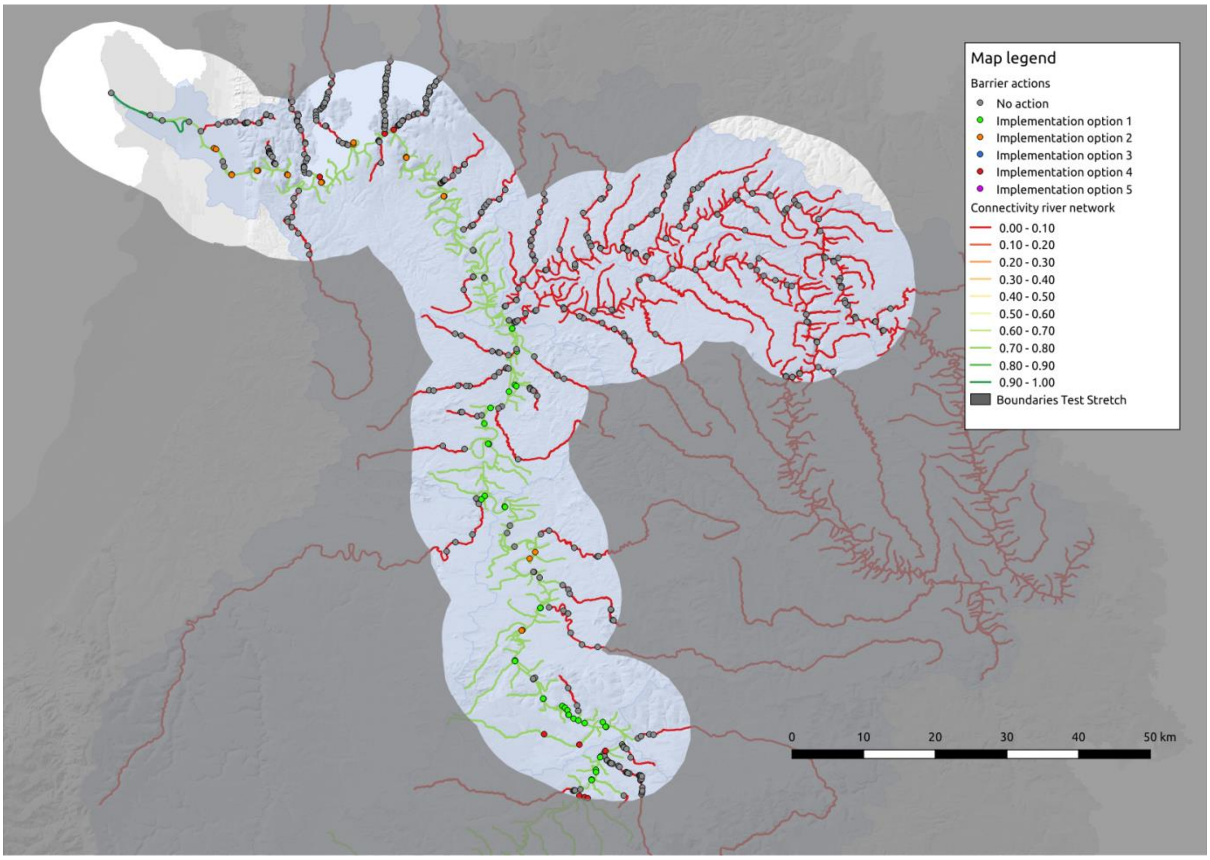


Figure 14. Map view for Scenario 6.

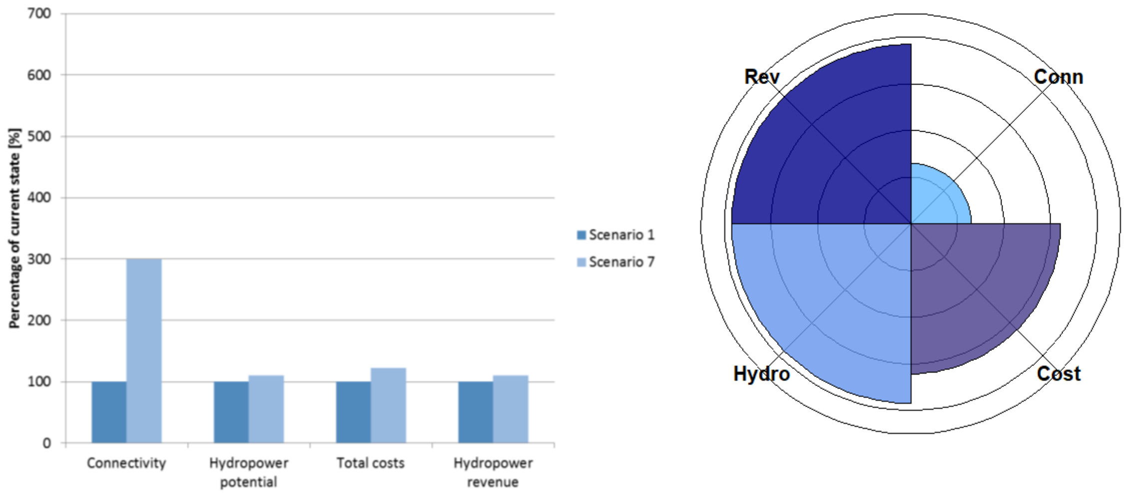


Figure 15. Scenario 7 percentage KPI scores (left) and relative KPI scores (right).

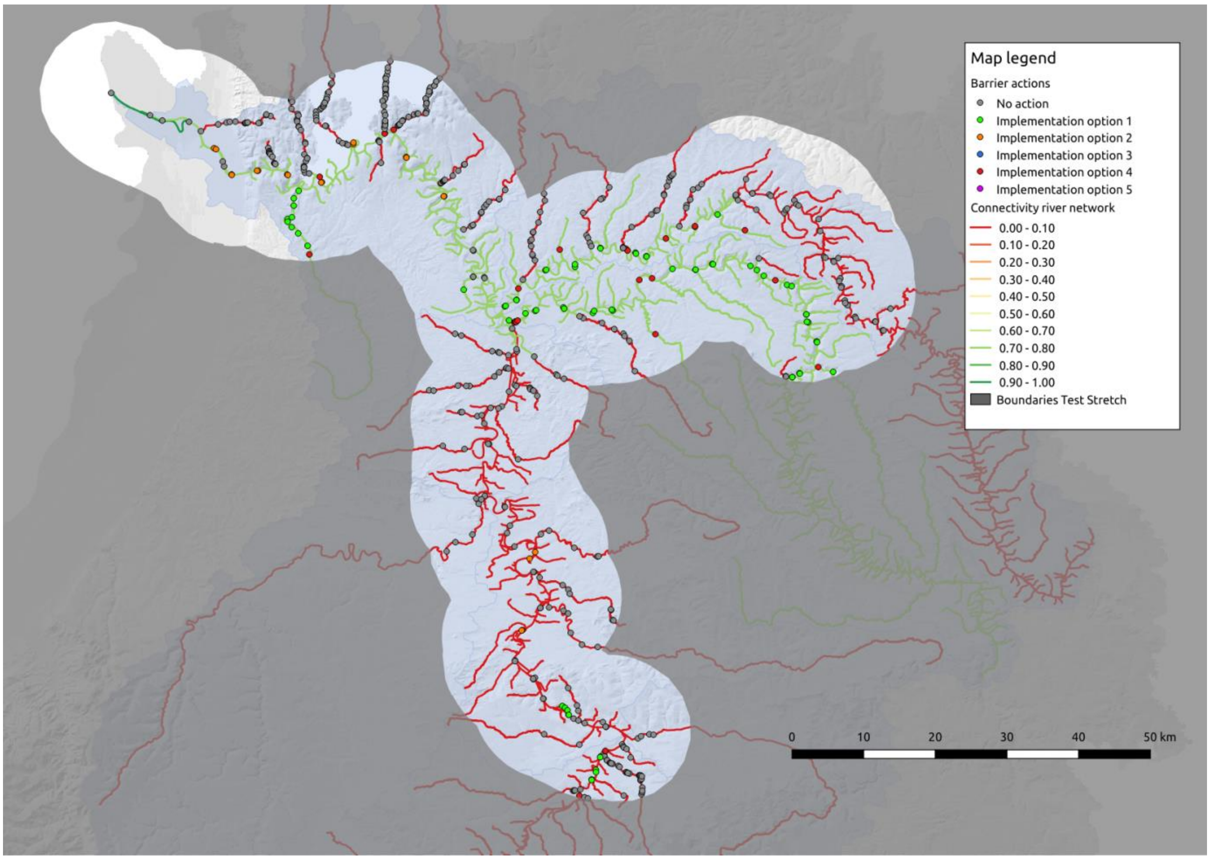


Figure 2. Map view for Scenario 7.

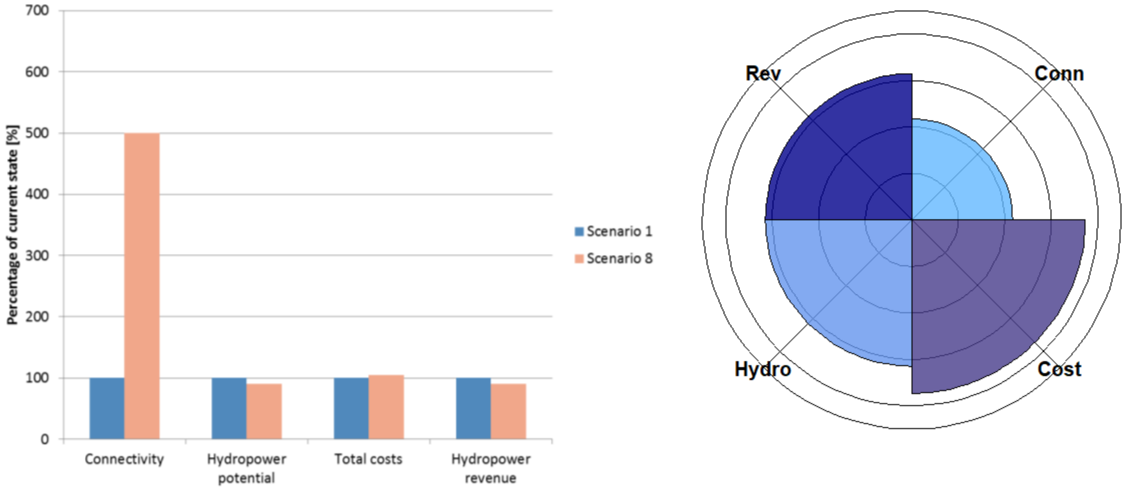


Figure 17. Scenario 8 percentage KPI scores (left) and relative KPI scores (right).

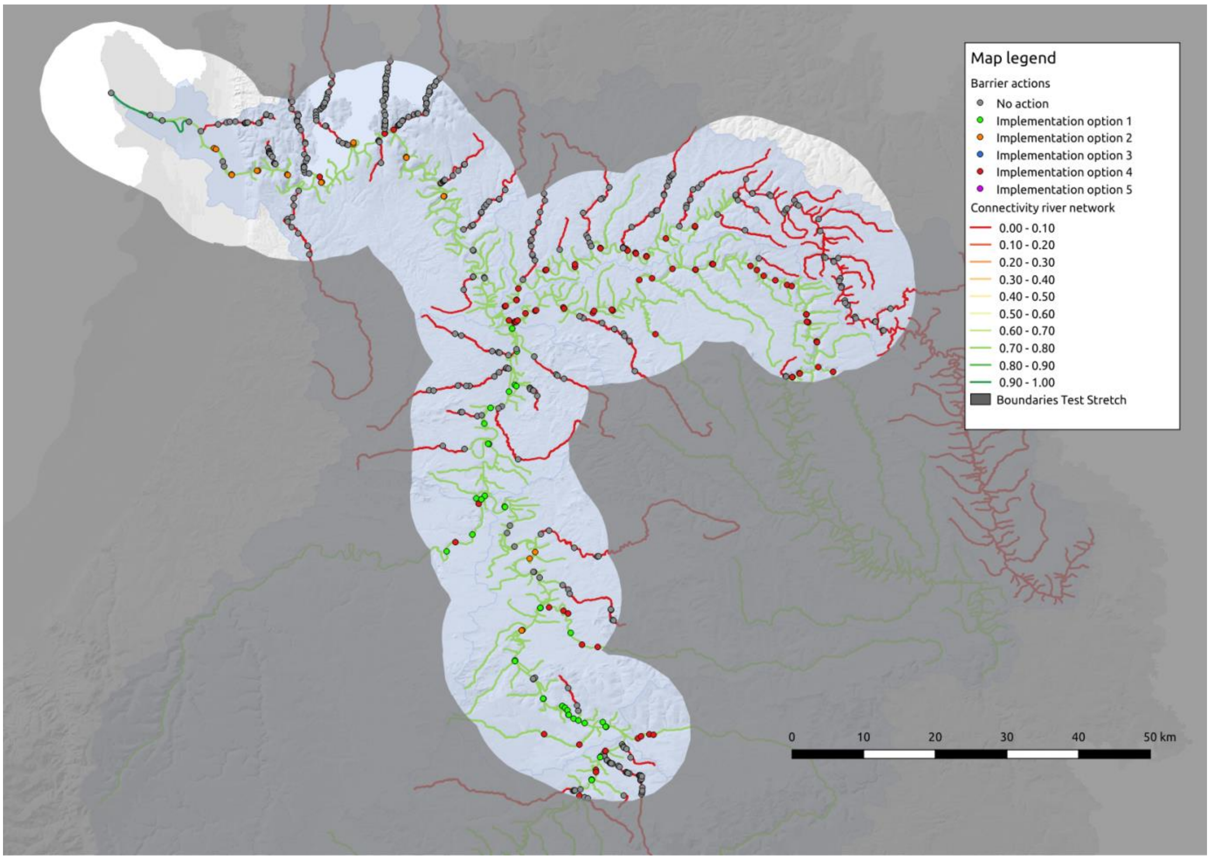


Figure 3. Map view for Scenario 8.

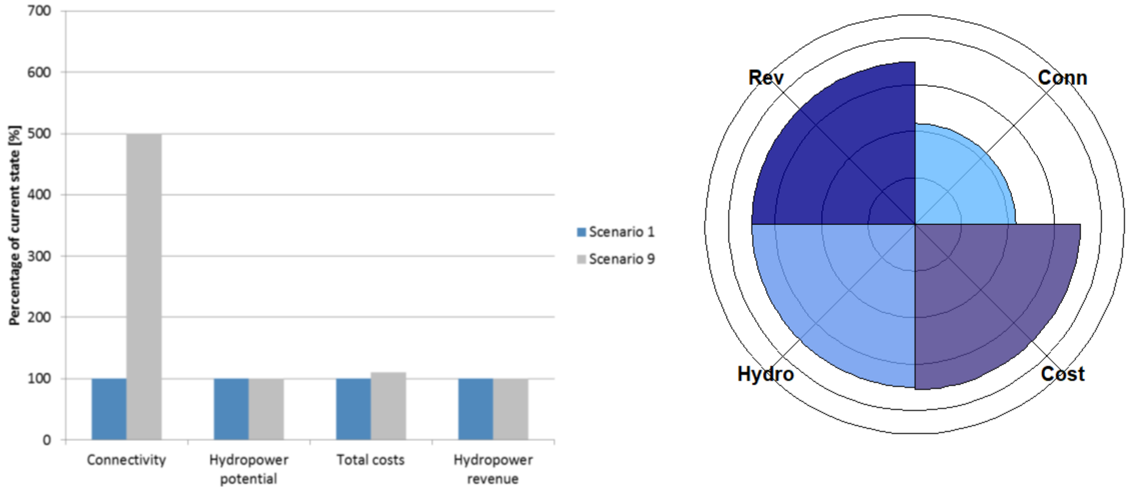


Figure 4. Scenario 9 percentage KPI scores (left) and relative KPI scores (right).

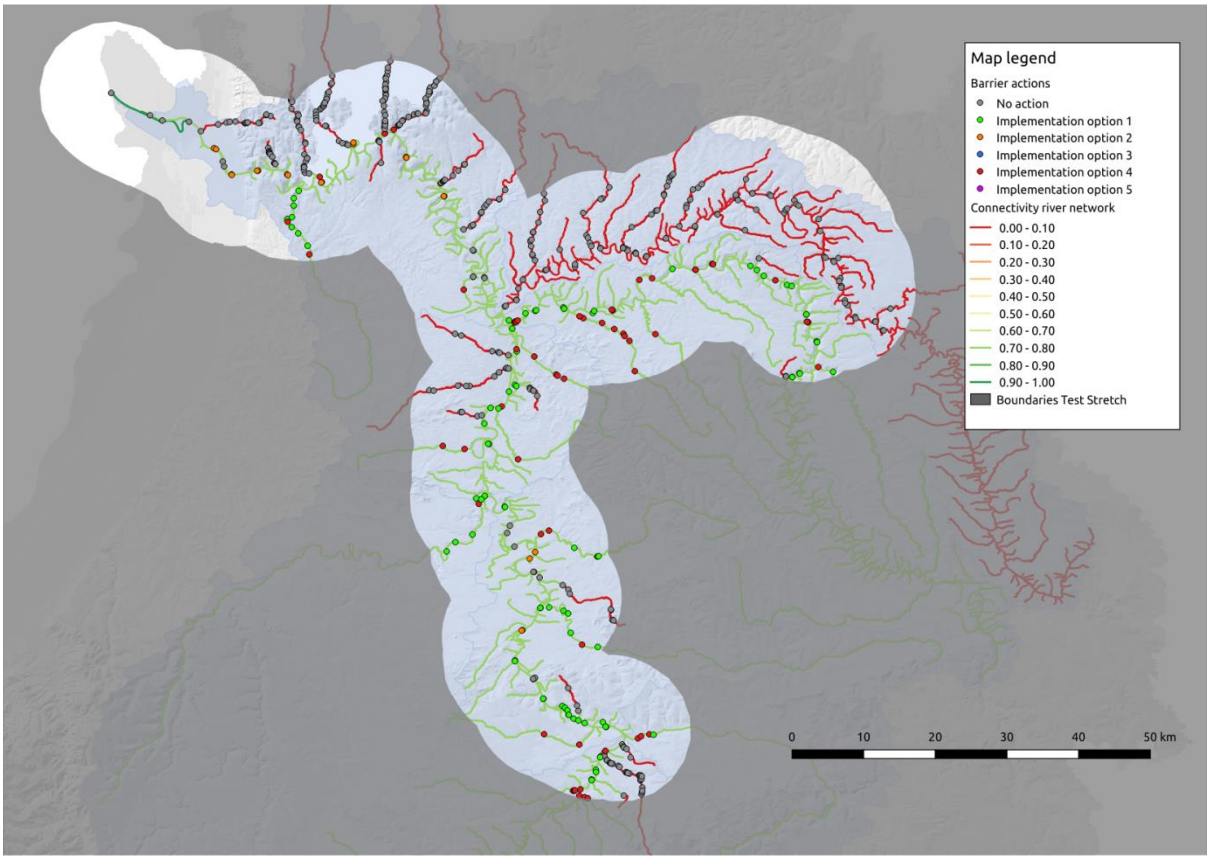


Figure 50. Map view for Scenario 9.

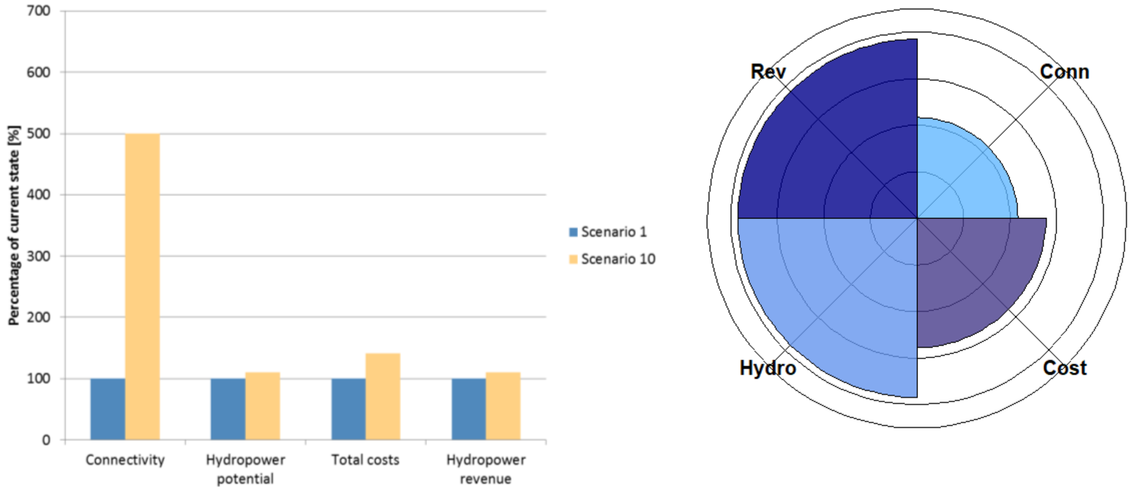


Figure 21. Scenario 10 percentage KPI scores (left) and relative KPI scores (right).

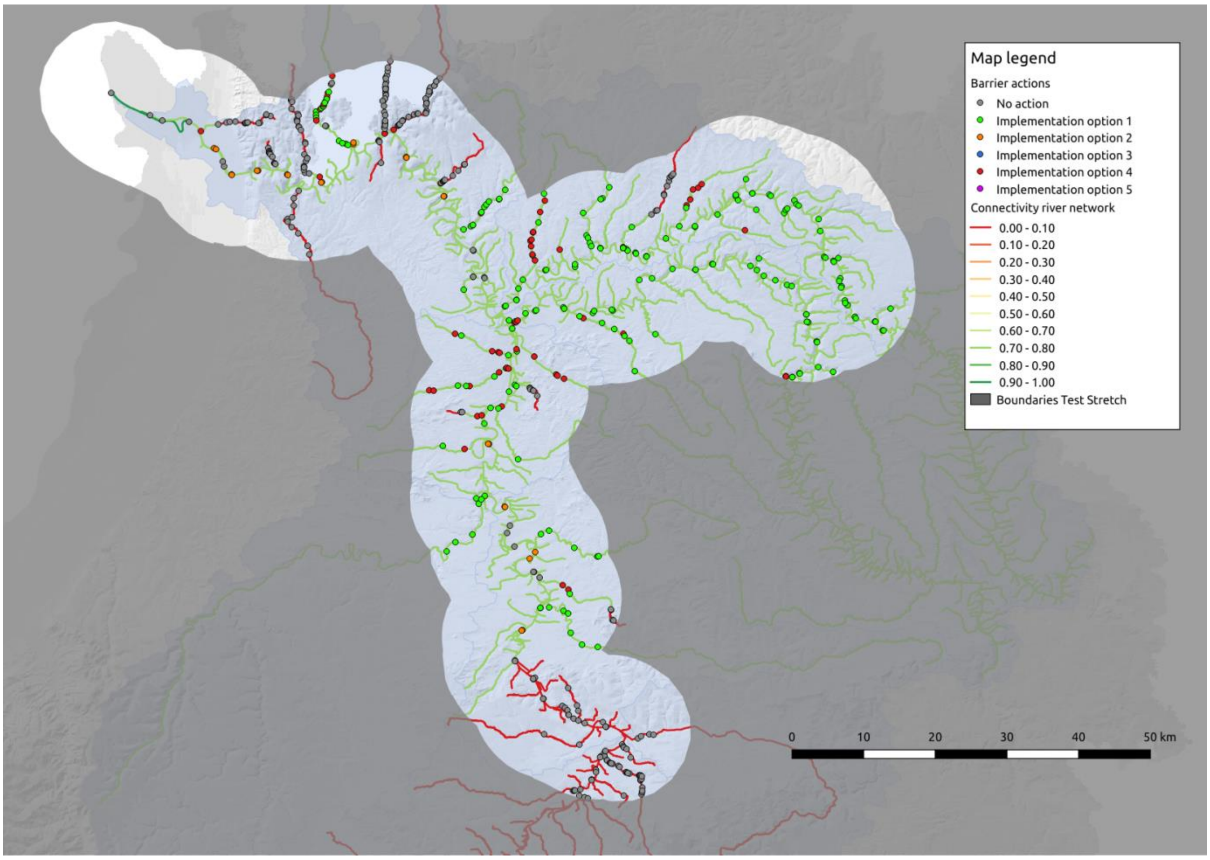


Figure 6. Map view for Scenario 10.

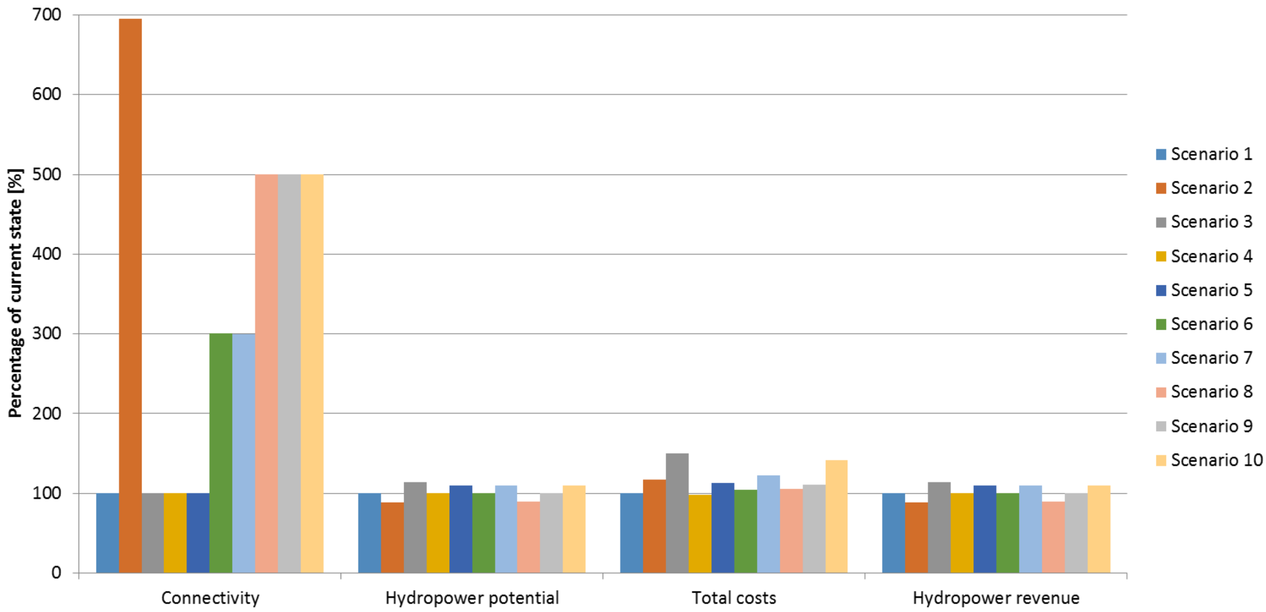


Figure 7. Comparison of results of all scenarios.

Table 4. Results of calculation runs.

No.	Scenario	Model	Connectivity	Hydropower potential	Total cost	Hydropower revenue
[-]	[-]	[-]	[%]	[%]	[%]	[%]
1	Current condition	4	100	100	100	100
2	Max connectivity	1	695	88	117	88
3	Max hydropower	2	100	114	150	114
4	Min costs, +0% connectivity +0% hydropower	3	100	100	98	100
5	Min costs, +0% connectivity, +10% hydropower	3	100	110	113	110
6	Min costs, +200% connectivity +0% hydropower	3	300	100	104	100
7	Min costs, +200% connectivity +10% hydropower	3	300	110	122	110
8	Min costs, +400% connectivity -10% hydropower	3	500	90	105	90
9	Min costs, +400% connectivity +0% hydropower	3	500	100	111	100
10	Min costs, +400% connectivity +10% hydro power	3	500	110	142	110

6 CONCLUSION

The river infrastructure planning decision support tool described in this report is a powerful and helpful aid for practice-oriented adaptive barrier management. It is capable of optimising improvements in river connectivity even for complex, multithreaded rivers whilst simultaneously balancing relevant socioeconomic factors like hydropower production, shipping, and many more. Due to its ability to evaluate both benefits and costs, the tool provides an ideal means of systematically targeting river infrastructure modification, mitigation, and removal actions in the most cost-effective way. A demonstration of the tool for the Neckar River catchment identified various trade-offs for a candidate set of planning scenarios designed to optimise different goals for connectivity, hydropower potential, and total cost.

High quality outputs and results generated with the decision support tool depend highly on the data utilized. For application to any given study area, a reliable, detailed, and complete set of data needs to be available or acquired. If all barriers are not included in the dataset, then estimated connectivity will invariably be incorrect. Likewise, if cost information for modification, mitigation, and removal of infrastructure do not mirror reality, then gains from river restoration for a given cost amount may be less than calculated by the tool.

Future improvements to the planning tool might include considering additional ecosystem services derived from river infrastructure like flood regulation, outdoor recreation, and water purification. Work in this area is ongoing.

7 REFERENCES

AMBER D3.3 (2019). Deliverable 3.3. Inventory of barriers and river infrastructures at test catchment with demonstration of Integrated Agent Based Dispersal Model. This document is a deliverable of the AMBER project. The project is funded from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 689682.

Cote, D., Kehler, D.G., Bourne, C., and Wiersma, Y.F. (2009). A new measure of longitudinal connectivity for stream networks. Landscape Ecology 24 (1): 101–113.

Ioannidou, C., O'Hanley, J.R. (2018) Eco-friendly location of small hydropower. European Journal of Operational Research 264(3): 907–918.

Kemp, P.S., O'Hanley, J.R. (2010) Procedures for evaluating and prioritising the removal of fish passage barriers: A synthesis. Fisheries Management and Ecology 17: 297–322.

Kemp, P.S., Russon, I.J., Waterson, B., O'Hanley, J.R., Pess, G.R. (2008) Recommendations for a "Coarse-Resolution Rapid-Assessment" methodology to assess barriers to fish migration and associated prioritization tools, Final report. Scottish Environment Protection Agency, Stirling, UK.

King, S., O'Hanley, J.R. (2016). Optimal fish passage barrier removal – Revisited. River Research and Applications 32(3): 418–428.

O'Hanley, J.R., Scaparra, M.P., Garcia, S. (2013) Probability chains: A general linearization technique for modeling reliability in facility location and related problems. European Journal of Operational Research 230(1): 63–75.

PLANCO (2006) Entwicklungspotenziale von Güterschiffen über 110m Länge (Langfristprognose 2025) und Bewertung erwogener Ausbaumaßnahmen am Neckar (Schleusenkammerverlängerung). PLANCO Consulting GmbH, Essen, 54 pp.