Decision support tools for balancing multiple objectives in river infrastructure planning

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Outline

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- Graph theory models
- Optimisation models

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PART 1
Prioritisation Methods

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What are the options?

1. The status quo is not an option

2. Get rid of barriers or least mitigate their negative impacts on longitudinal connectivity
   - The real trick is to doing this cost-efficiently!

Ways of going about barrier mitigation planning

- Informal methods
  - Rely on expert judgement
- Formal methods
  - Involves some sort of quantitative analysis
  - Scoring-and-ranking
  - Graph theory models
  - Optimisation models

Informal methods

- Informal methods are common place
- Get a bunch of “experts,” often biologists, into a room and brainstorm what to do
- Usually easy enough to figure out the initial set of barriers to repair/remove for a given catchment
- Example: the English “Divide and Conquer / Filter” approach
  - Get different regions to come up with a list of priorities
  - Apply a filtering process at the national level to the regional priorities

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The drawbacks of going informal

Informal methods fall short on a number of grounds

- Lacks rigour
  - Heavily reliant on local knowledge and opinion
  - Often very subjective
  - No common yardstick for comparing options (e.g., value of partial vs full remediation?)
- Unmanageable at large spatial scales
  - Looking at multiple watersheds is generally too difficult
  - Even if you try to break the problem down by watershed, how do you compare priorities across watersheds?
- Doesn’t get at the problem of how to allocate funds efficiently

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Formal methods

- Formal methods require coming up with a structured/systematic way of making assessments
- From the get go, need to establish one or more <u>measurable</u> criteria to be applied to barrier mitigation decisions
- Ideally, should:
  - Have clear and objective goals
  - Allow for coordinated action
  - Be cost-efficient

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Framing the problem

- Goal: maximise the amount of accessible (possibly quality-weighted) upstream habitat for one or more fish species, guilds, taxa, etc.
- Constraints: limited budget, minimum requirements for hydropower potential and water storage capacity
- Problem statement: which barriers should be repaired/removed in order to maximise net habitat gain subject to a budget and/or other requirements?

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Barrier passability

- First off, we need a way of quantifying how much a barrier inhibits fish dispersal
- For our purposes, passability defined as the fraction (in the range 0-1) of fish that are able to pass through, over, or around a barrier while migrating upstream or downstream
  - Full barriers have passability 0
  - Partial barriers have values between 0 and 1 (e.g., 0.5 for a moderately impassably barrier)

Single vs multiple barriers

- Barrier passability applies to an individual barrier
- When multiple barriers are present, need to think about cumulative passability
- For simplicity, cumulative passability normally taken as the product of individual barrier passability values

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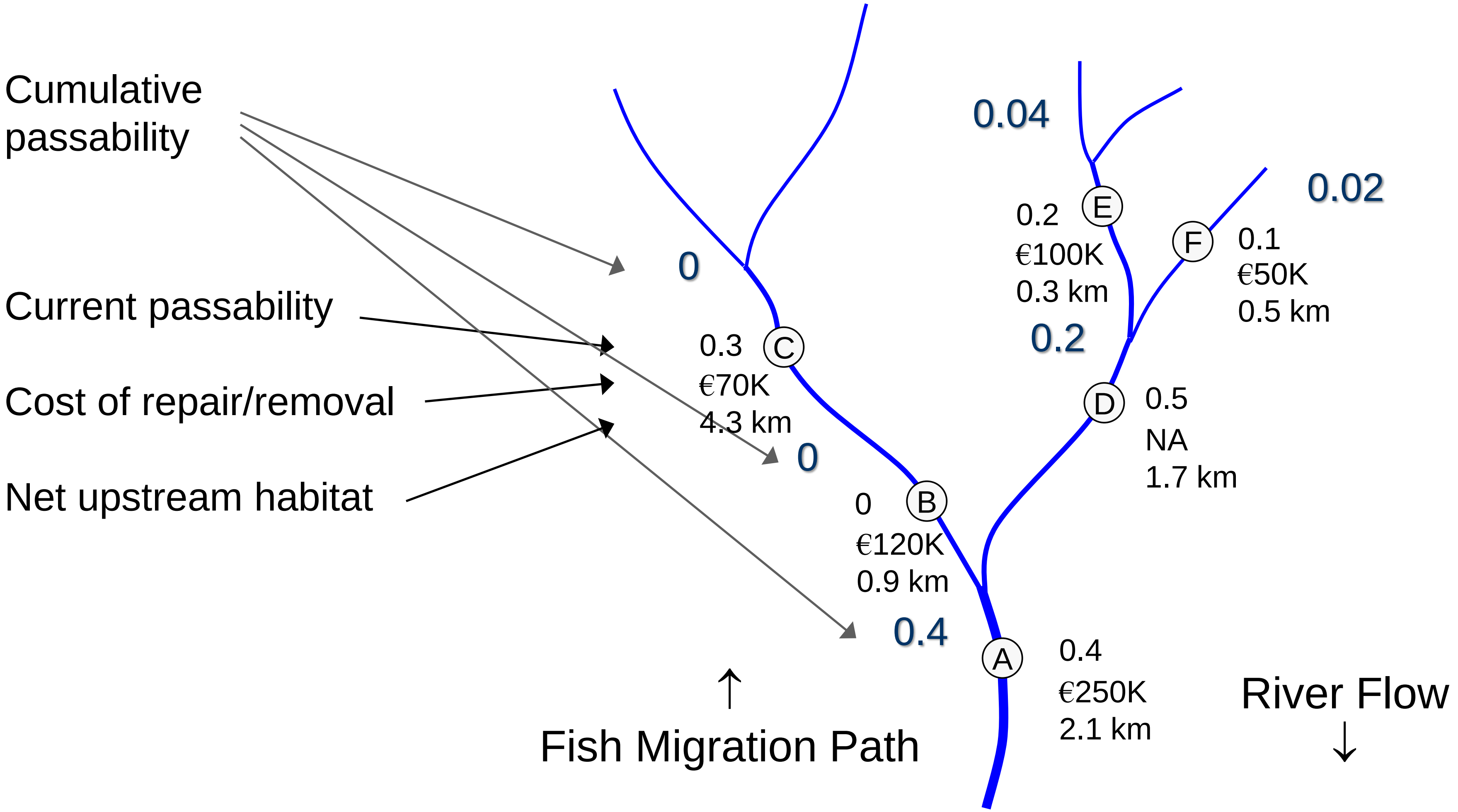
Example barrier network



Scoring and ranking

- Scoring & Ranking procedures far and away the most common approach
- The main appeal of Scoring & Ranking lies in its simplicity
- The problem with Scoring & Ranking is that it's <u>very</u> inefficient!

Scoring & Ranking methods

- Assign a score to each barrier
- Sort in decreasing order of score
- Fix barriers according to rank until you run out of money

$$S_j = \frac{U_j \times \Delta p_j}{c_j}$$

S_j = score of barrier *j*
U_j = total habitat upstream from barrier *j*
Δp_j = increase in barrier *j*'s passability after mitigation
c_j = cost of mitigating barrier *j*

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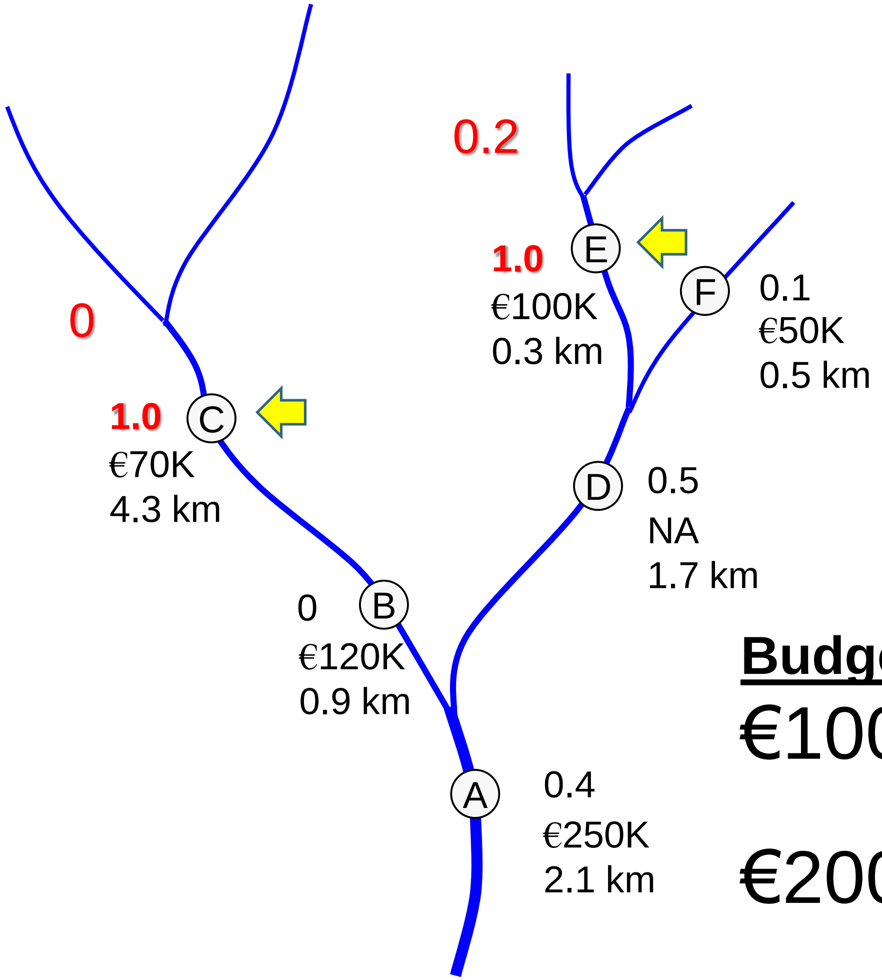
Scoring & Ranking in action



Barrier	Score	Cost
C	43.00	€70K
E	9.60	€100K
F	9.00	€50K
B	7.50	€120K
A	5.04	€250K

Budget	**S&R**	**Optimal**
€100K	Soln: C Gain: 0 km	Soln: E Gain: 0.192 km
€200K	Soln: C & E Gain: 0.192 km	Soln: B & C Gain: 3.318 km

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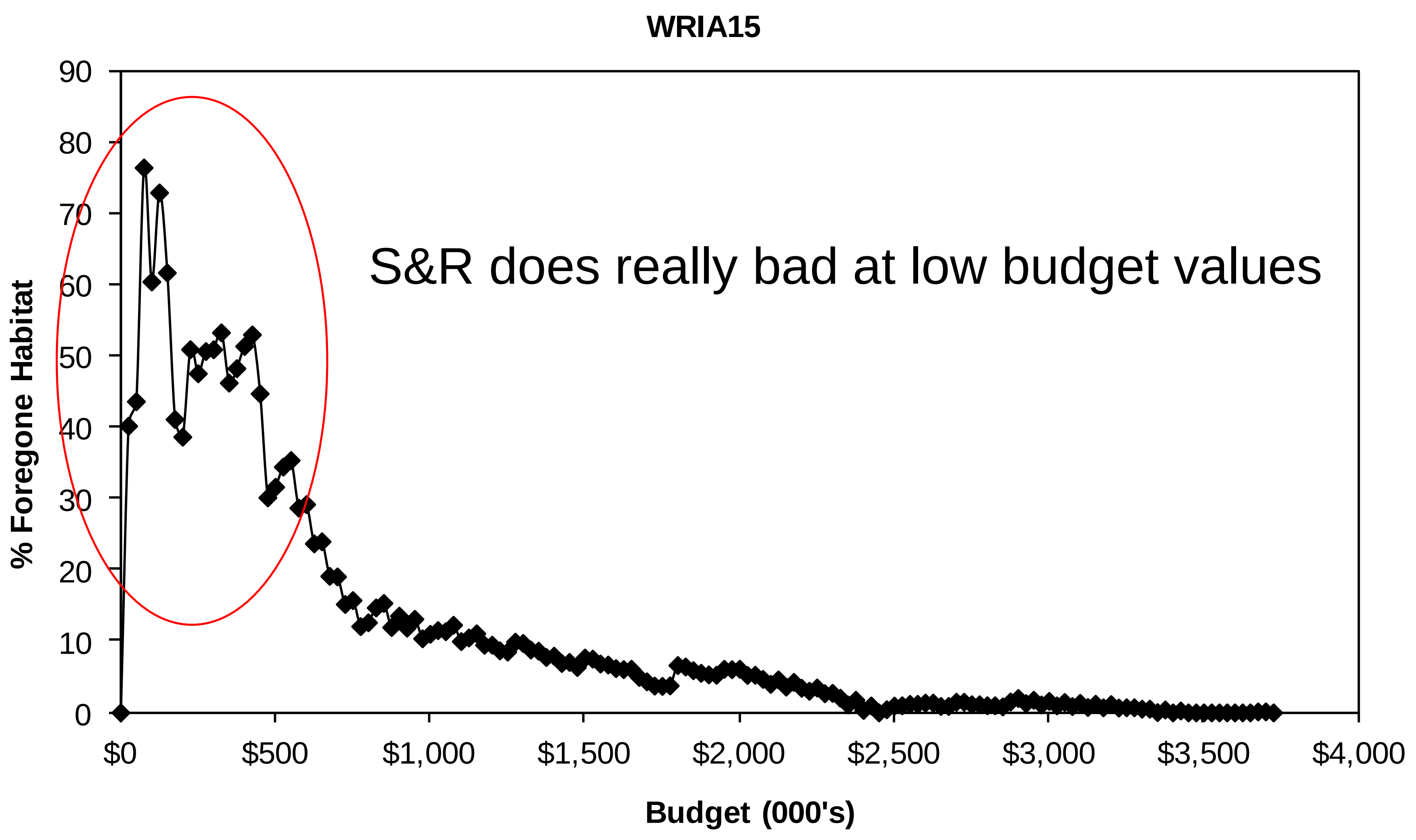
A concrete example



What's wrong with Scoring & Ranking?

- Usually ignores the spatial structure of barrier networks
  - I.e., downstream barriers
- Mitigation decisions made independently rather than in an adaptive and coordinated manner
  - I.e., assumes that passability at other barriers is constant
- Put another way, S&R ignores the interactive effects that multiple barrier mitigation actions have on cumulative passability

Can we do things better?

In short, YES

- Option 1: Graph theory models
- Option 2: Optimisation models

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Graph theoretic approaches

- Graph theory models incorporate:
  - Spatial structure of barrier networks
  - Interactive effects of barrier mitigation on cumulative passability / connectivity
- Involves 2 steps (done in tandem):
  1. Create a graph (node and arc) representation of a river barrier network
  2. Develop and apply an index to understand how well “connected” a river network is

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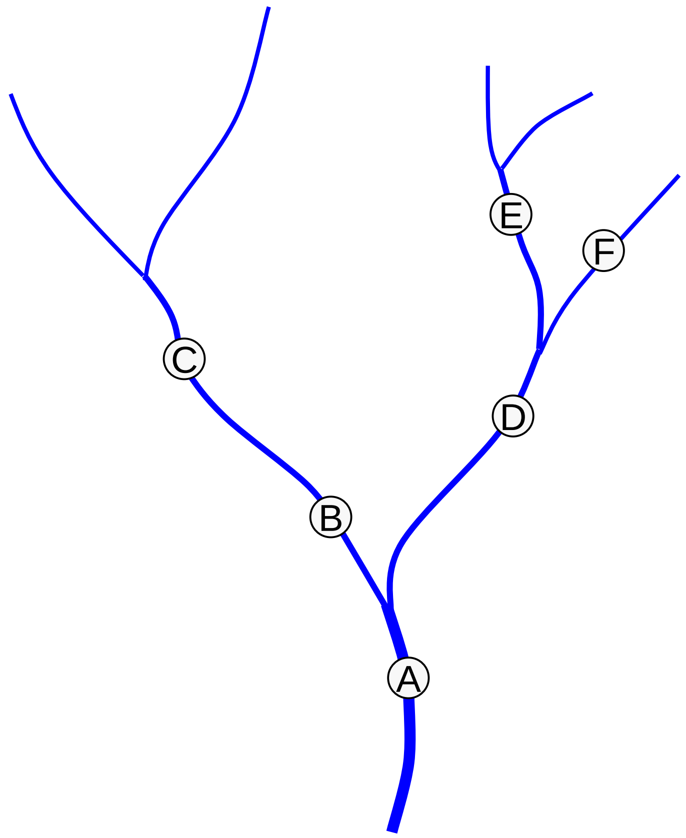
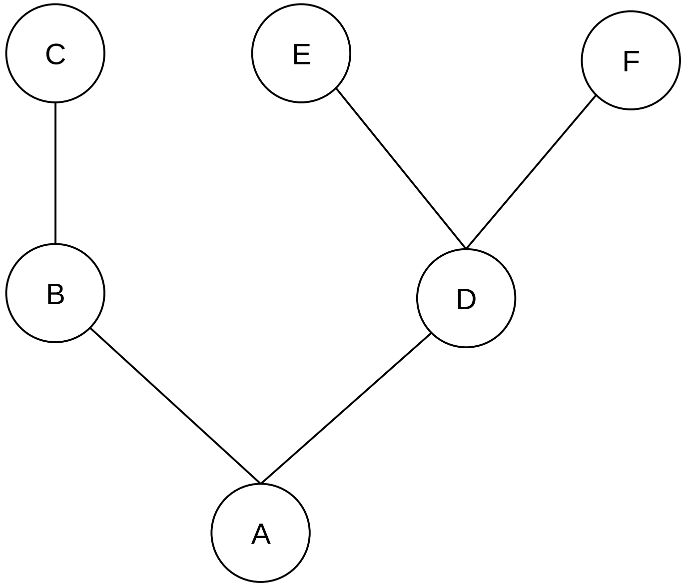
A graph theoretic perspective

River/Barrier Network



Graph Representation



Node = Barrier

Dendritic Connectivity Index

Cote et al. (2008)

$$DCI_D = \sum_{j=1}^{n} \frac{l_j}{L} \left(\prod_{k \in D_j} p_k^u p_k^d \right) \cdot 100$$

Diadromous species

Normalized stream length

Cumulative upstream/ downstream passability

Dynamics

Mitigation increases the passability of barriers

↓

Affects cumulative passability of barriers

↓

Affects cumulative passability of any upstream barriers

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Graph theory pluses and minus

- On the upside, graph theory takes a holistic view:
  - Handles the interactive effects of barrier mitigation
  - Allows for coordinated action
- But (and this is a big but) it's only designed to do simple "what-if" type analyses
  - E.g., What happens if I mitigate this barrier or this set of barriers?
- Doesn't provide any guidance on how to mitigate barriers cost-effectively
  - Entirely up to the user to come up with a realistic and cost-effective mitigation portfolio

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Optimisation based methods

- Optimisation goes a considerable step further than graph theory approaches by actually optimising mitigation decisions!
- Offers an objective and systematic framework for thinking about the problem
- Makes the most efficient use of limited resources
- Can balance multiple, possibly competing, objectives and constraints
- Key uncertainties can even be incorporated in a coherent fashion

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I assume this is clear to everyone!

A basic optimisation model

O'Hanley and Tomberlin (2005)

$$\max z = \sum_{j \in J} v_j \alpha_j$$

Maximise connectivity-weighted habitat

$$s.t. \qquad \alpha_j = \prod_{k \in D_j} \left(p_k^0 + \sum_{i \in A_k} p_{ik} x_{ik} \right) \forall j \in J$$

Connectivity of habitat above barrier *j*

$$\sum_{i \in A_j} x_{ij} \leq 1 \quad \forall j \in J^{Art}$$

Can only carry out one mitigation project at an artificial barrier *j*

$$\sum_{j \in J^{Art}} \sum_{i \in A_j} c_{ij} x_{ij} \leq b$$

Limited budget for mitigation

$$x_{ij} \in \{0,1\} \forall j \in J^{Art}, i \in A_j$$

Either mitigate a barrier or not

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My personal take

Method	Objective Goals	Coordinated Action	Cost-Efficient	Grade
Informal Methods	✗	?	✗	C-
Scoring & Ranking	✓	✗	✗	F
Graph Theory Models	✓	✓	✗	B
Optimisation Models	✓	✓	✓	A

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PART 2
River Infrastructure Planning Tool Overview

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Drum roll please …

- The AMBER River Infrastructure Planning (RIP) Tool is a decision support tool for optimising barrier mitigation
- Identifies cost-efficient mitigation actions to maximise the amount of accessible, possibly quality-adjusted, river habitat while balancing trade-offs with:
    - project implementation cost
    - hydropower generation potential
    - water storage capacity

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How does it work?

- Integrates information on
  - Barrier passability
  - Potential habitat
  - Mitigation cost
  - Hydropower potential
  - Water storage capacity
- Crucially, accounts for:
  - Spatial structure of barrier networks
  - Interactive effects of barrier mitigation decisions on longitudinal connectivity

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Key RIP Tool functionalities

- Friendly graphical user interface (GUI)
- Performs optimisation runs for any specified budget and desired targets for hydropower potential and water storage
- Can carry out basic "what-if" analyses
  - Create user-defined solutions in which one or a handful of barriers are forced <u>in</u> or forced <u>out</u> of the final solution
- Handles
  - Multiple alternative mitigation projects at any given barrier (e.g., fix a barrier a little or fix it a lot)
  - Can focus on diadromous and or potadromous fish

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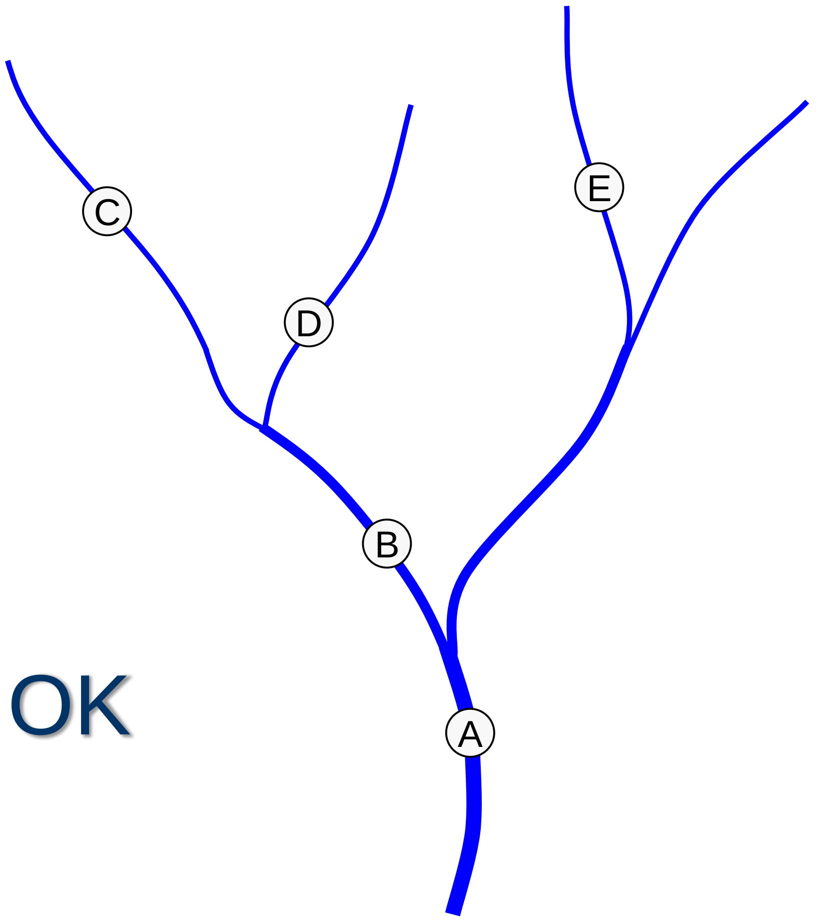
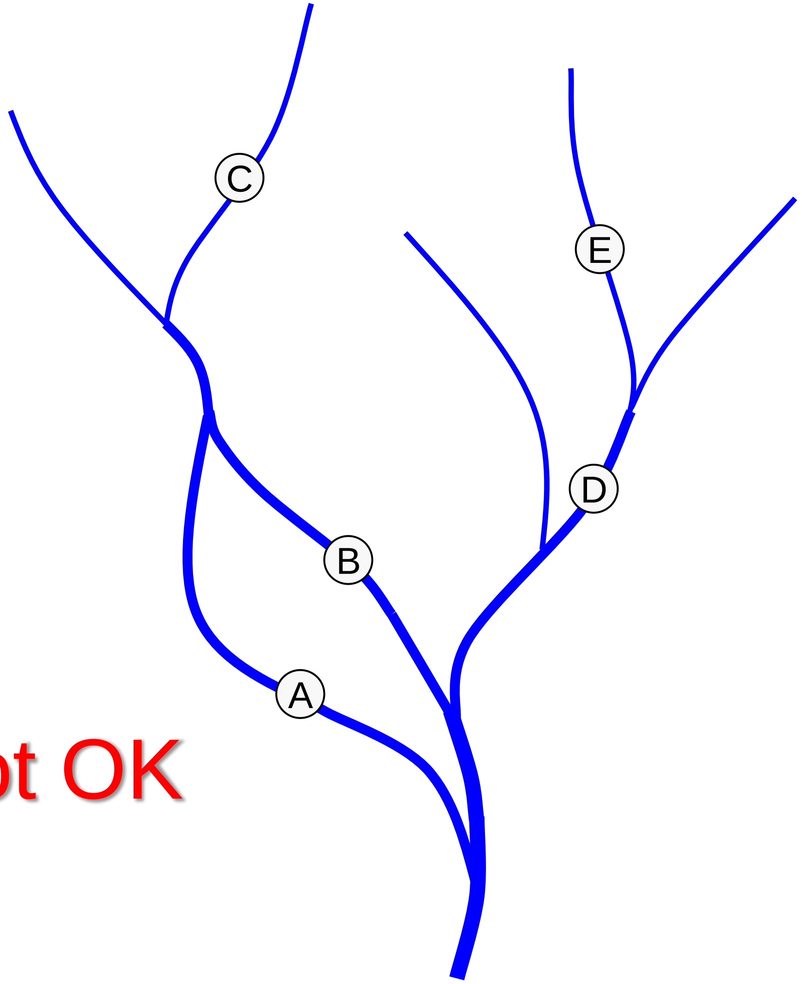
Barriers must form simple trees!

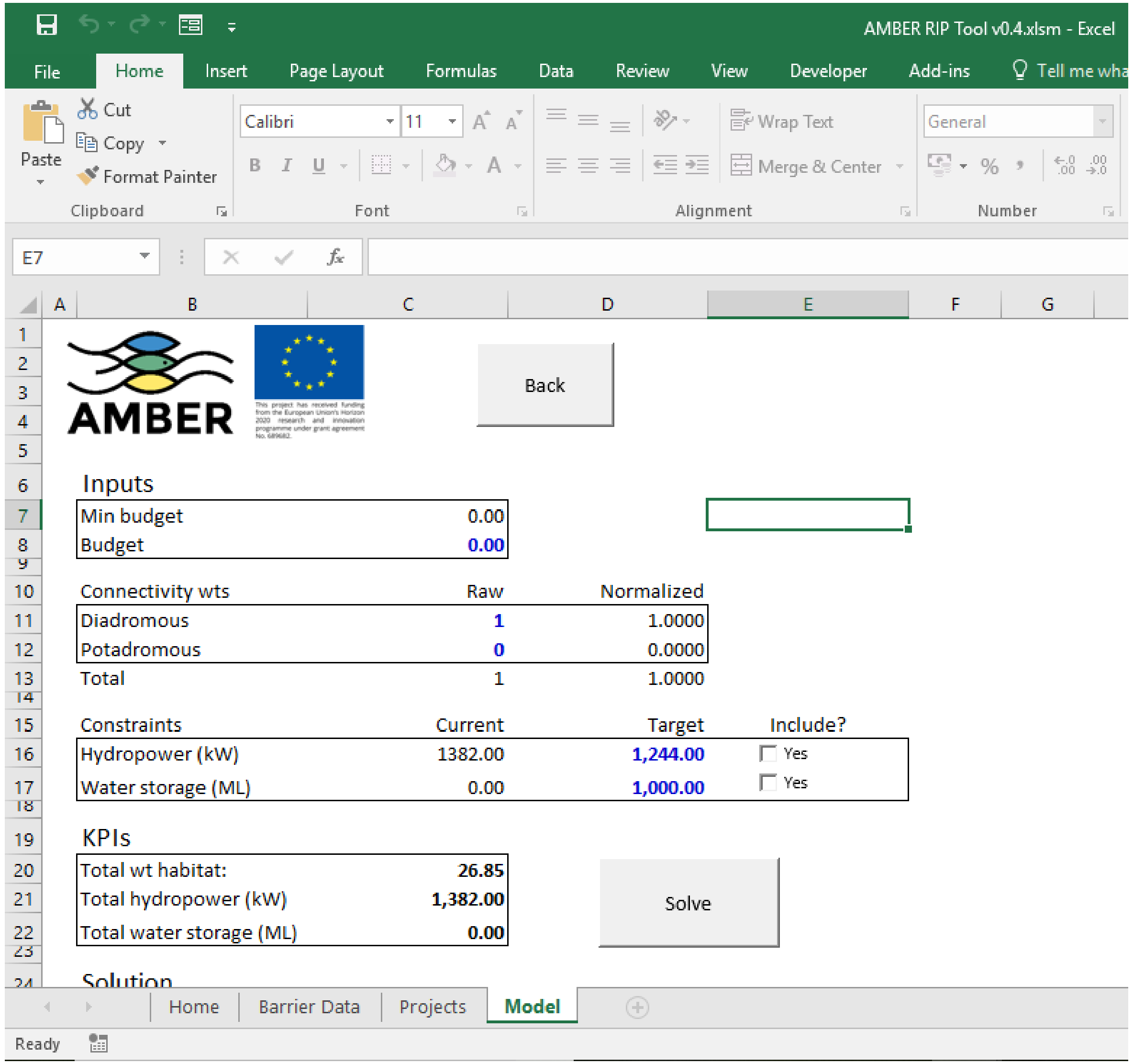


OK



Not OK

RIP tool demo



PART 3
River Wey
Case Studies

Case study 1

Let's consider a real-world barrier dataset from the Wey River in England. To get our feet wet, we'll answer the following questions.

a) What is the current amount of habitat available above barriers?

   Answer: 26.85 km of accessible habitat

a) Given a budget of £250k, what is the net gain in accessible habitat and which barriers would you mitigate?

   Answer: gain of 38.06 – 26.85 = 11.21 km by mitigating barriers W56, W622, and W636

a) If the budget were to increase to £1 million, what would the plan be then?

   Answer: accessible habitat goes up to 93.92 km by mitigating barriers W13, W21, W61, W152, W309, W367, W466, W505, W569, W622 (note W56 and W636 no longer chosen)

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Case study 2

Some follow-up analysis …

a) With a budget of £500k, the recommendation was that barriers W56, W622, and W636 should be mitigated. What if barrier W56 can't actually be mitigated because it's on Mr Johnson's farm and everyone knows that working with him is a nonstarter?

   Answer: instead of 38.06 km, get 37.72 km of accessible habitat (not much of a difference)

a) With a budget of £1 million, hydropower potential goes down to 1163 kW, equivalent to a 16% reduction. What if hydropower should only be reduced by 10% (i.e. no less than 1244 kW)?

   Answer: hydropower now at 1276.23 kW (8% reduction), but instead of 93.92 km of accessible habitat, only get 82.15 km of accessible habitat (13% reduction)

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PART 4
Neckar Catchment Case Study

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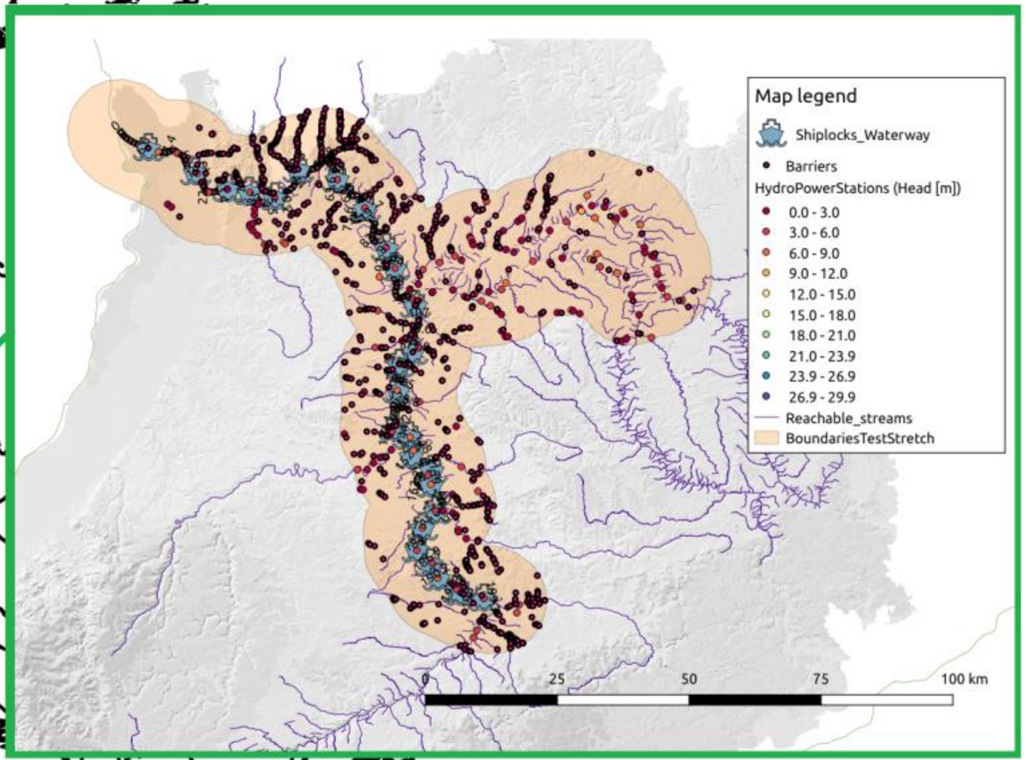
Neckar River catchment

Neckar Database

- 4,069km of river
- 1069 weirs, dams, and culverts and 27 shipping locks
- Installed hydropower capacity at existing hydropower plants
- Med. flow estimates
- Low / medium / natural water depth estimates
- Shipping cost data
    - Fleet make-up
    - Cross-port distances and shipping volumes
    - Shipping cost equations as functions of: max. eff. draft, travel distance, laden vs. unladen returns



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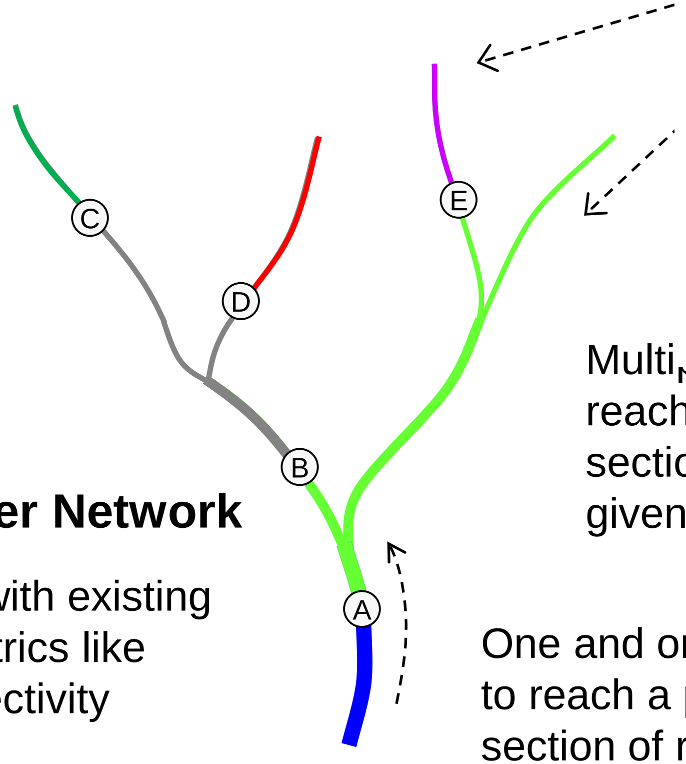
River connectivity

Take-home message: Modelling of multithreaded river systems opens up a lot of new possibilities

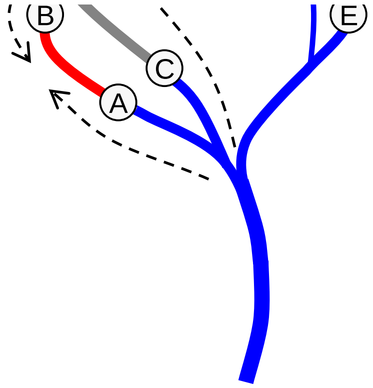


Dendritic River Network

Easy to model with existing connectivity metrics like Dendritic Connectivity Index (DCI)

One and only one way to reach a particular section of river from a given starting point

Multiple ways of reaching a particular section of river from a given starting point



Multithreaded River Network

Difficult to model. Requires novel ways to measure connectivity.

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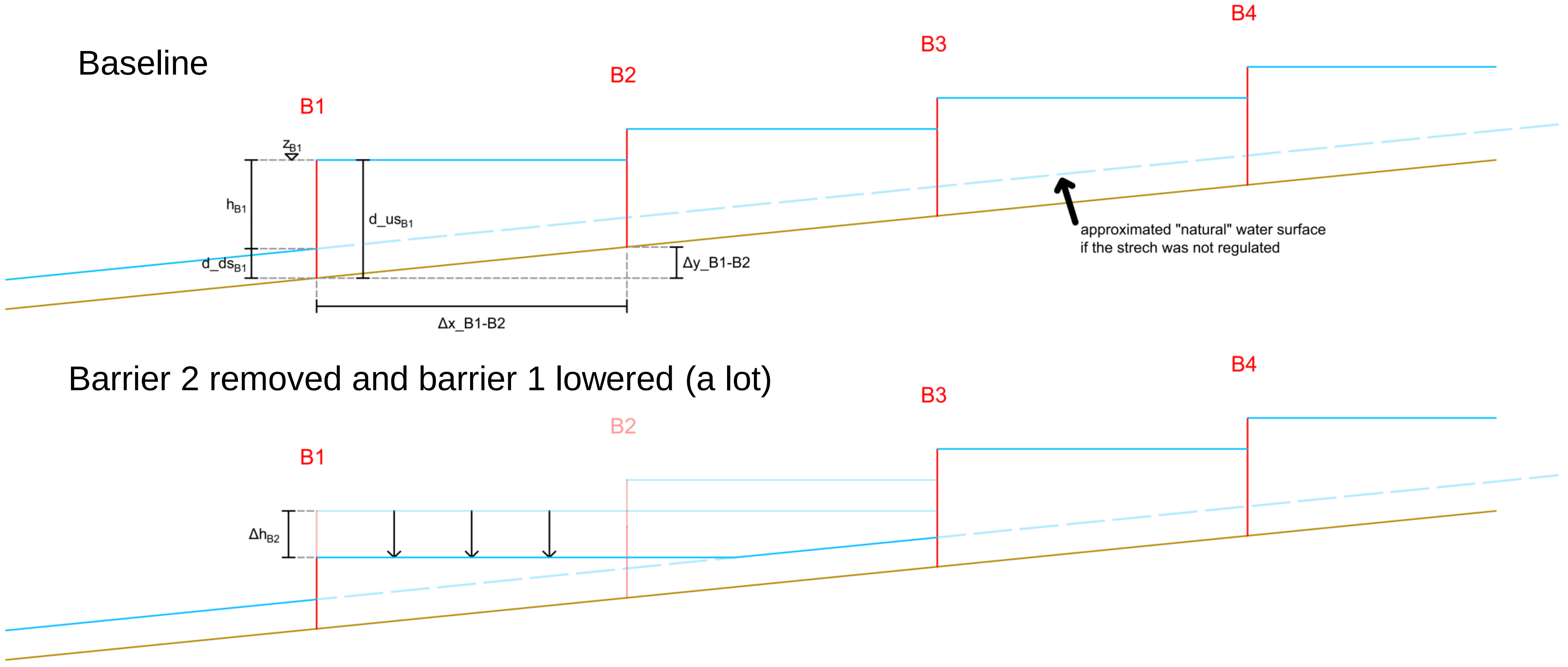
Backwater effects

Incorporating backwater effects essential for determining passability and for assessing hydropower potential



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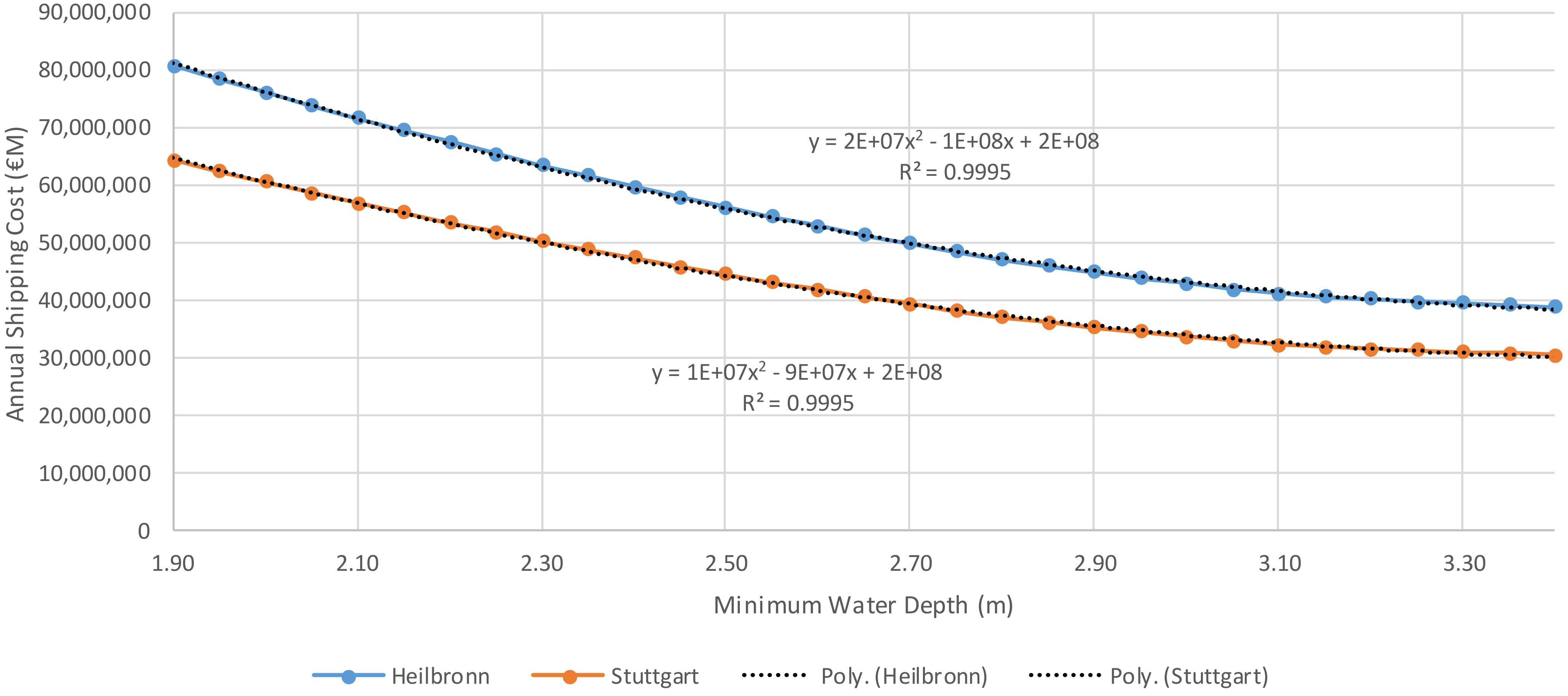
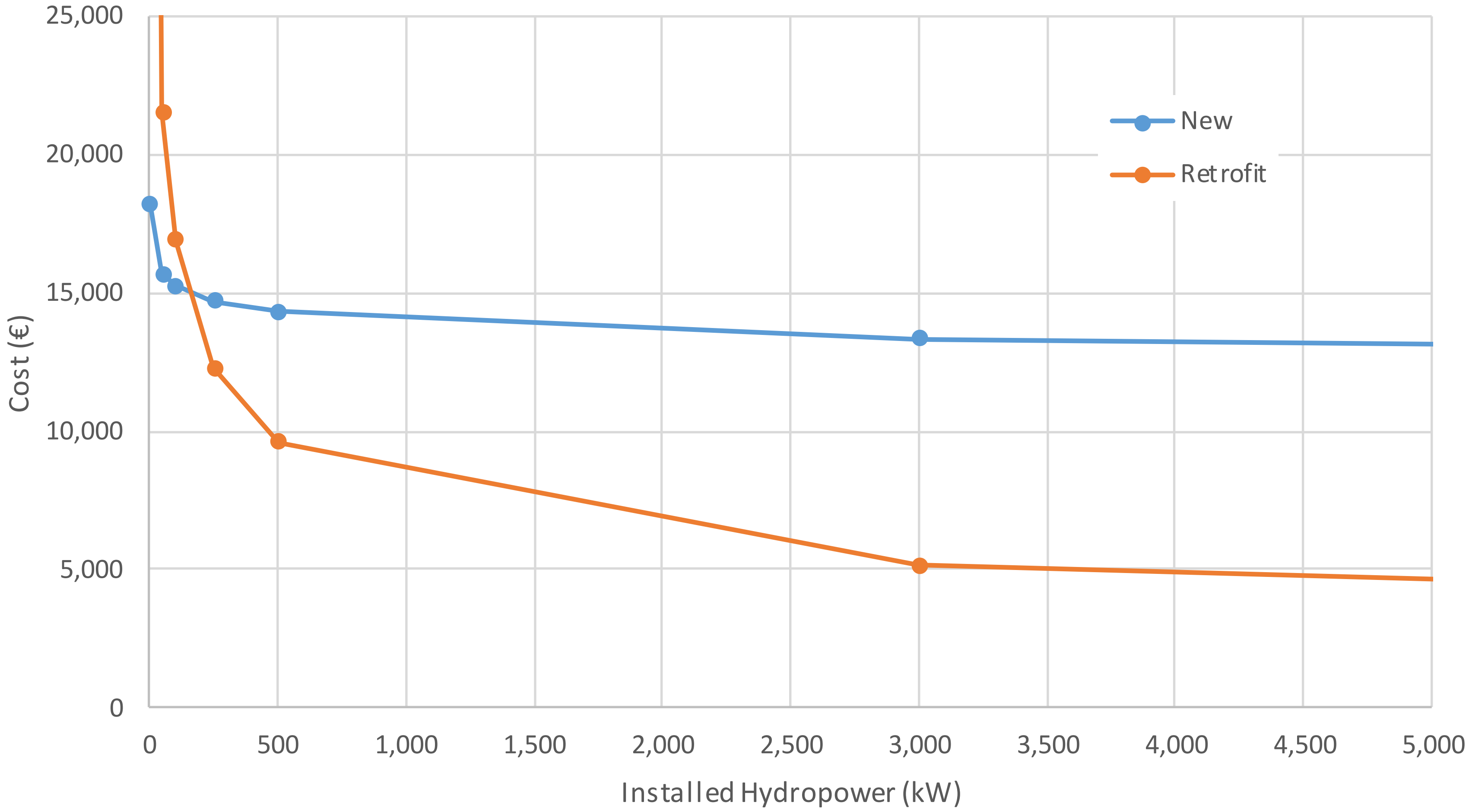
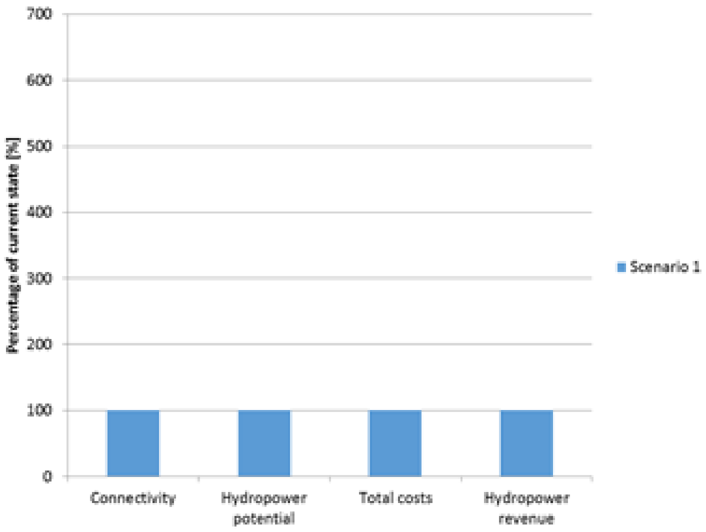
Shipping cost curves

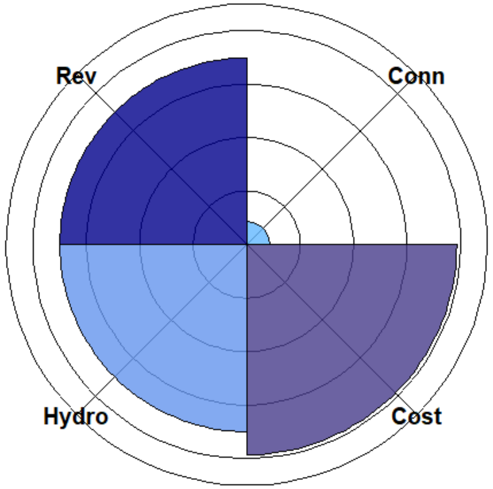


Hydropower unit installation cost

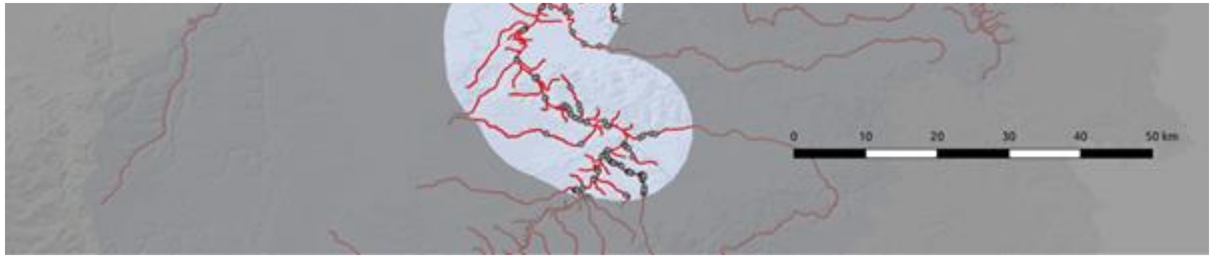


Current situation





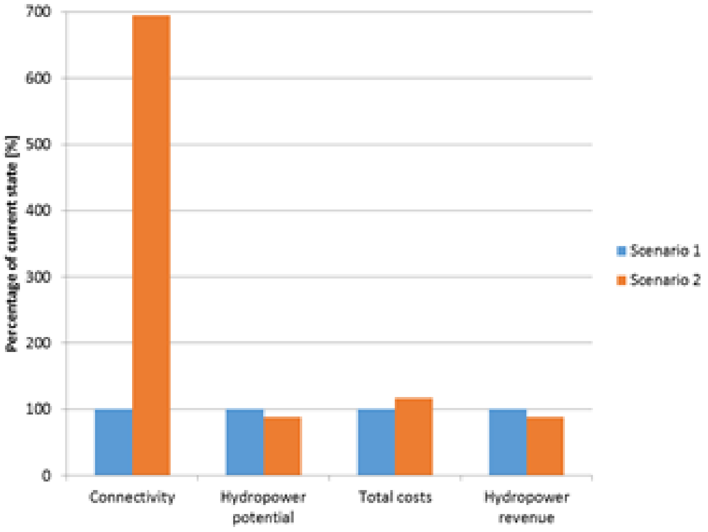
Take-home message: Like most places across Europe, the Neckar has been heavily impacted by barriers

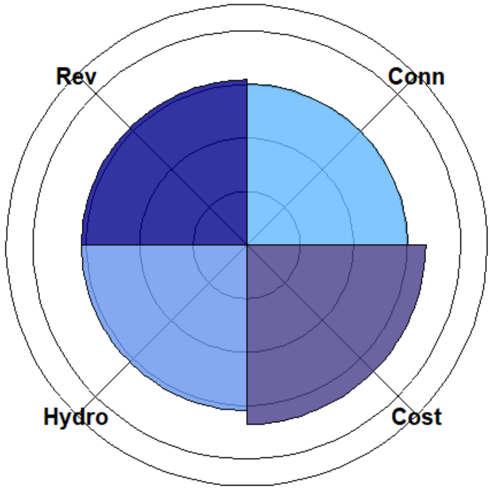


Observations:

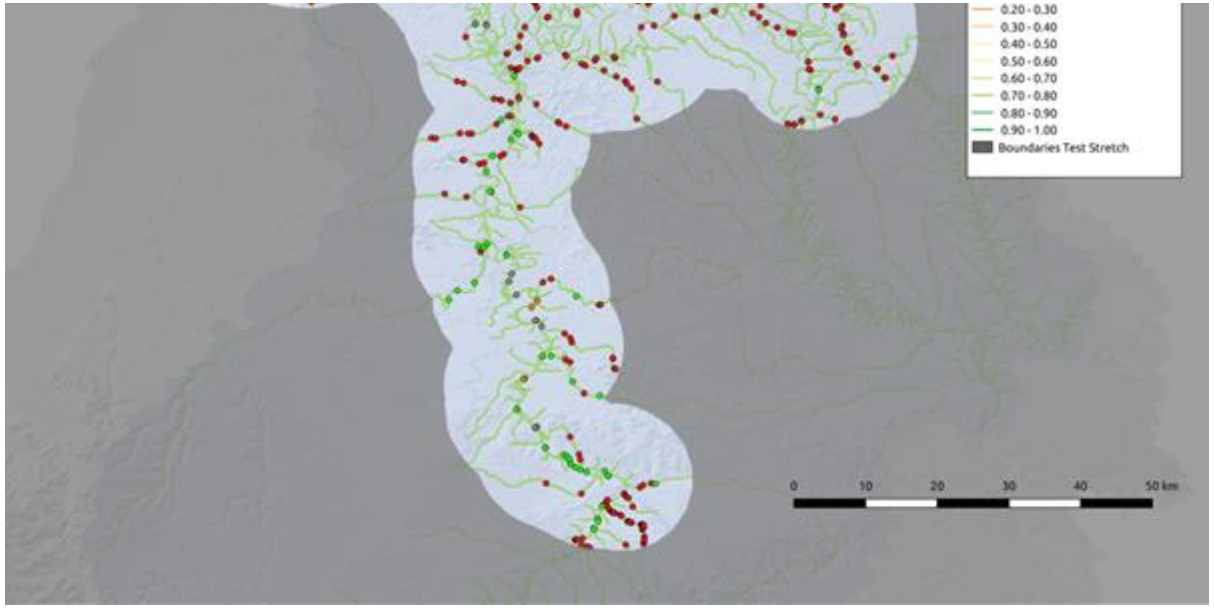
- Current connectivity in the Neckar is deficient.
- Most well-connected river sections along the main Neckar because of existing fish passes and semi-passable locks.

Maximise connectivity





Take-home message: There's no free lunch!



Observations:

- Possible to increase connectivity considerably.
- High project cost, but partly offset by lower shipping cost.
- Hydropower potential and revenue both reduced.

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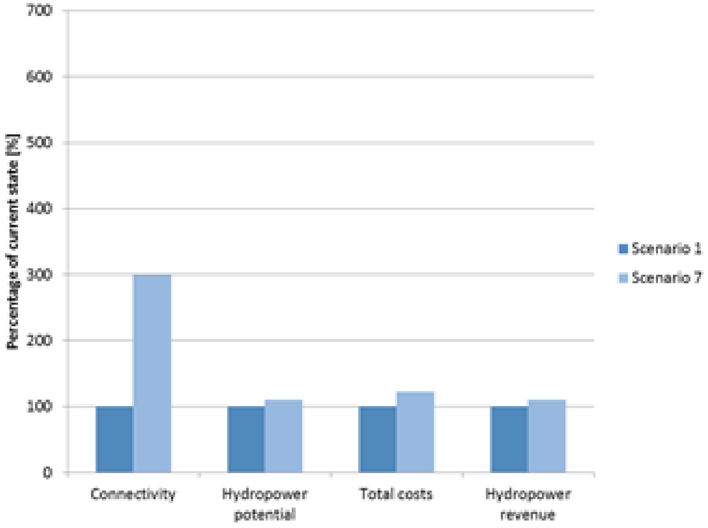
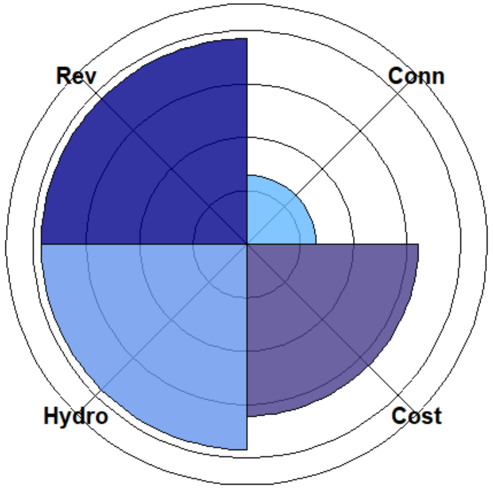
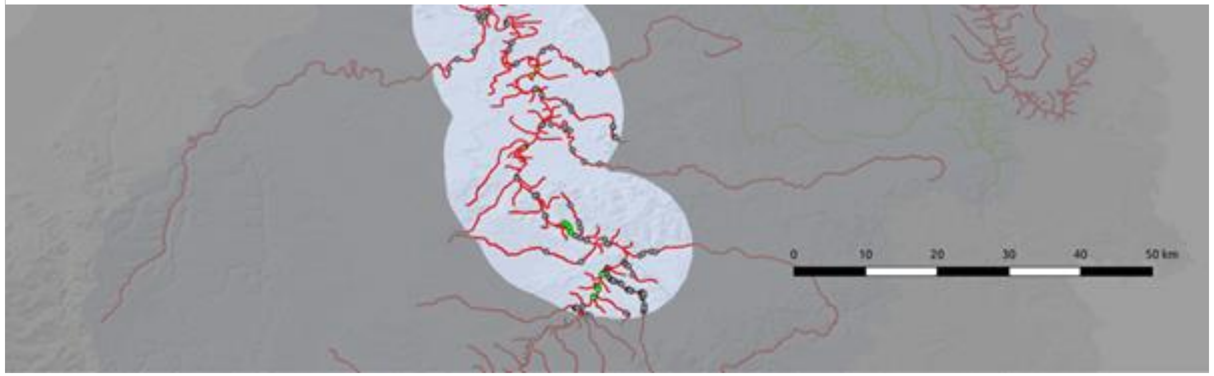
+200% conn. & +10% hydropower





Take-home message: Still no free lunch, but maybe possible to find a happy tradeoff



Observations:

- Much better connectivity along main Neckar and main tributaries (still low in minor tributaries).
- Increased hydropower potential/revenue (10%).
- Total cost 22% higher but only a 3.7% dec. in net benefit.

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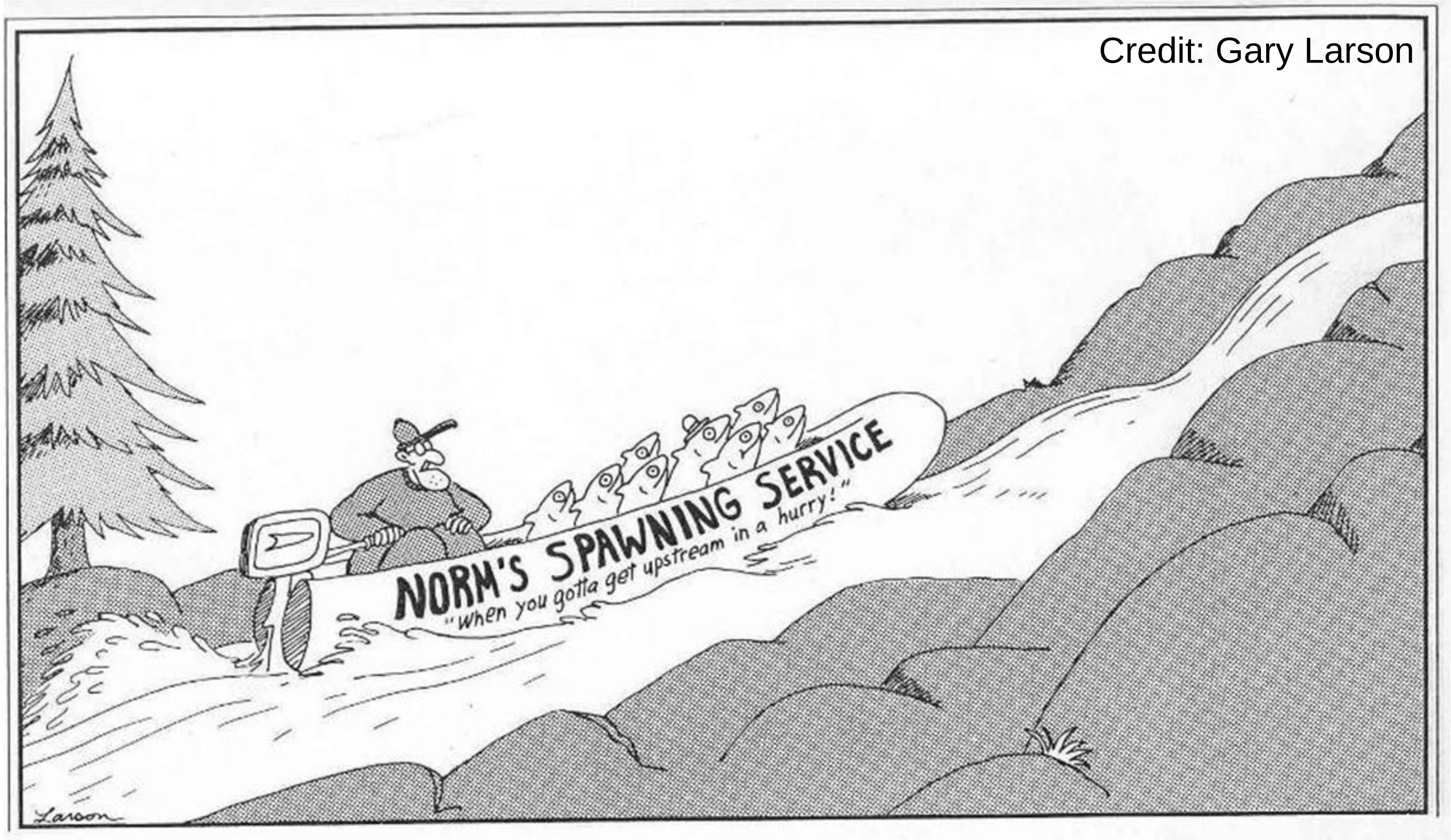
Optimisation – making the world a better place

Credit: Gary Larson



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