

Modelling lake futures

Cumbrian Lakes Research Forum 2026

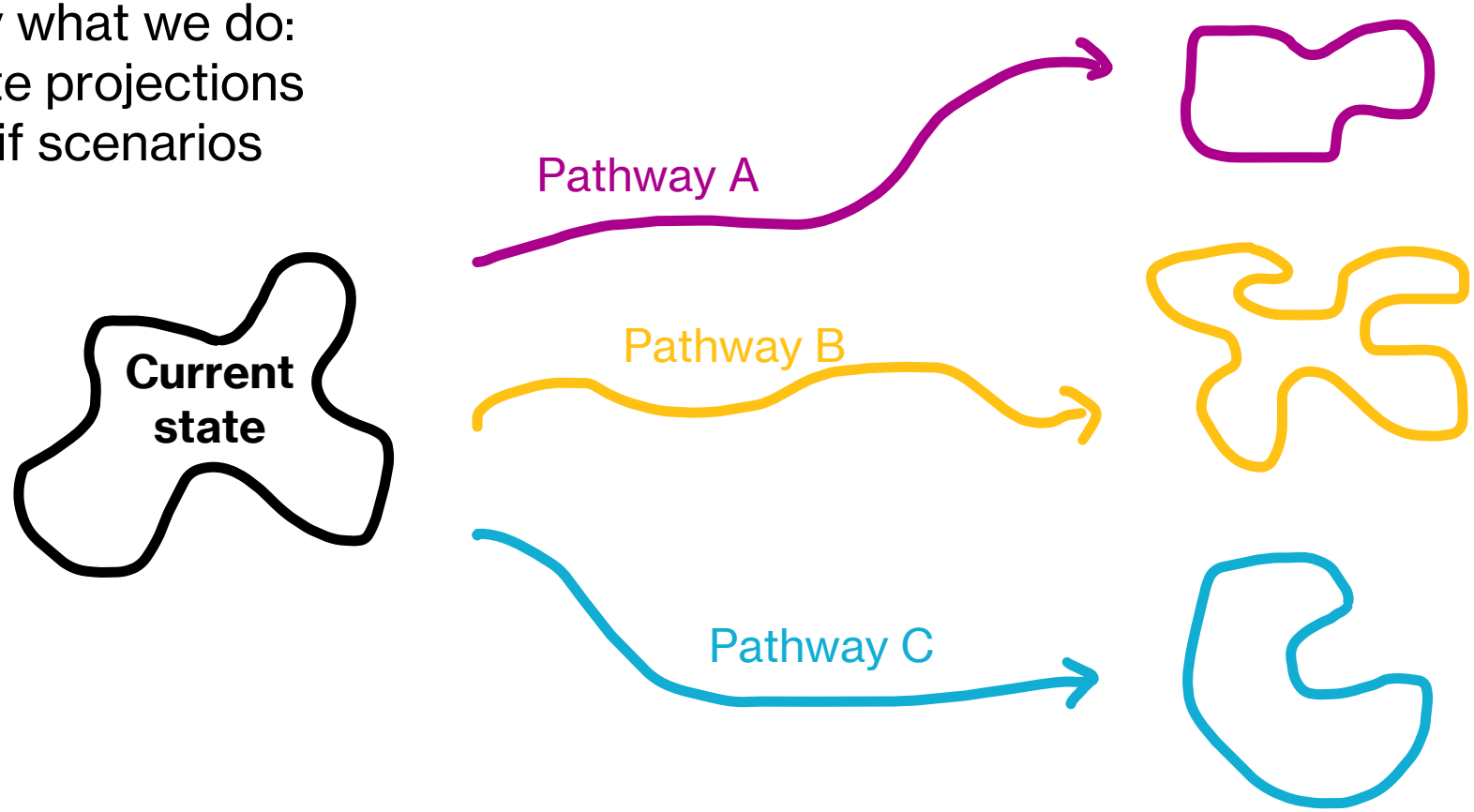
George Linney & Freya Olsson

PLURALAKES

What COULD the future look like?

Normally what we do:

- Climate projections
- What-if scenarios



What ~~COULD~~ *SHOULD* the future look like?

Instead:
Focus on the end goal
- Binding legislation
- Stakeholder values

A vision for the lake future state



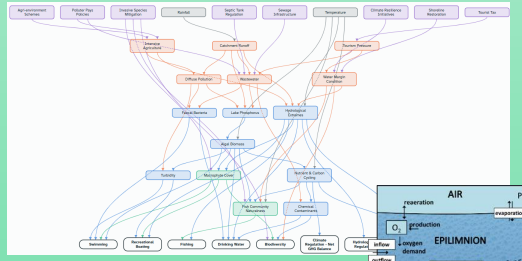
Models can be used to identify levers and pathways to reach desired goals



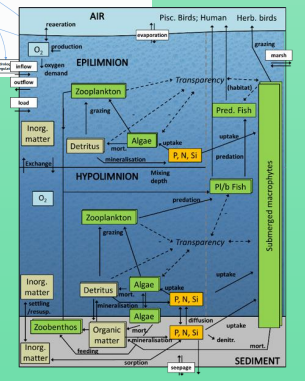
1. **What** measures should we use?
2. **When** and **how** should we implement them?
3. **Can we** reach our desired future given the constraints and opportunities?

Aim: use a range of models to identify levers and pathways for achieving lake future targets

Part 1: Linking **policy levers to ecosystem services** at Windermere using **Bayesian belief networks**



Part 2: combining **process-based models** with **optimisation algorithms** to identify the management pathways for Windermere



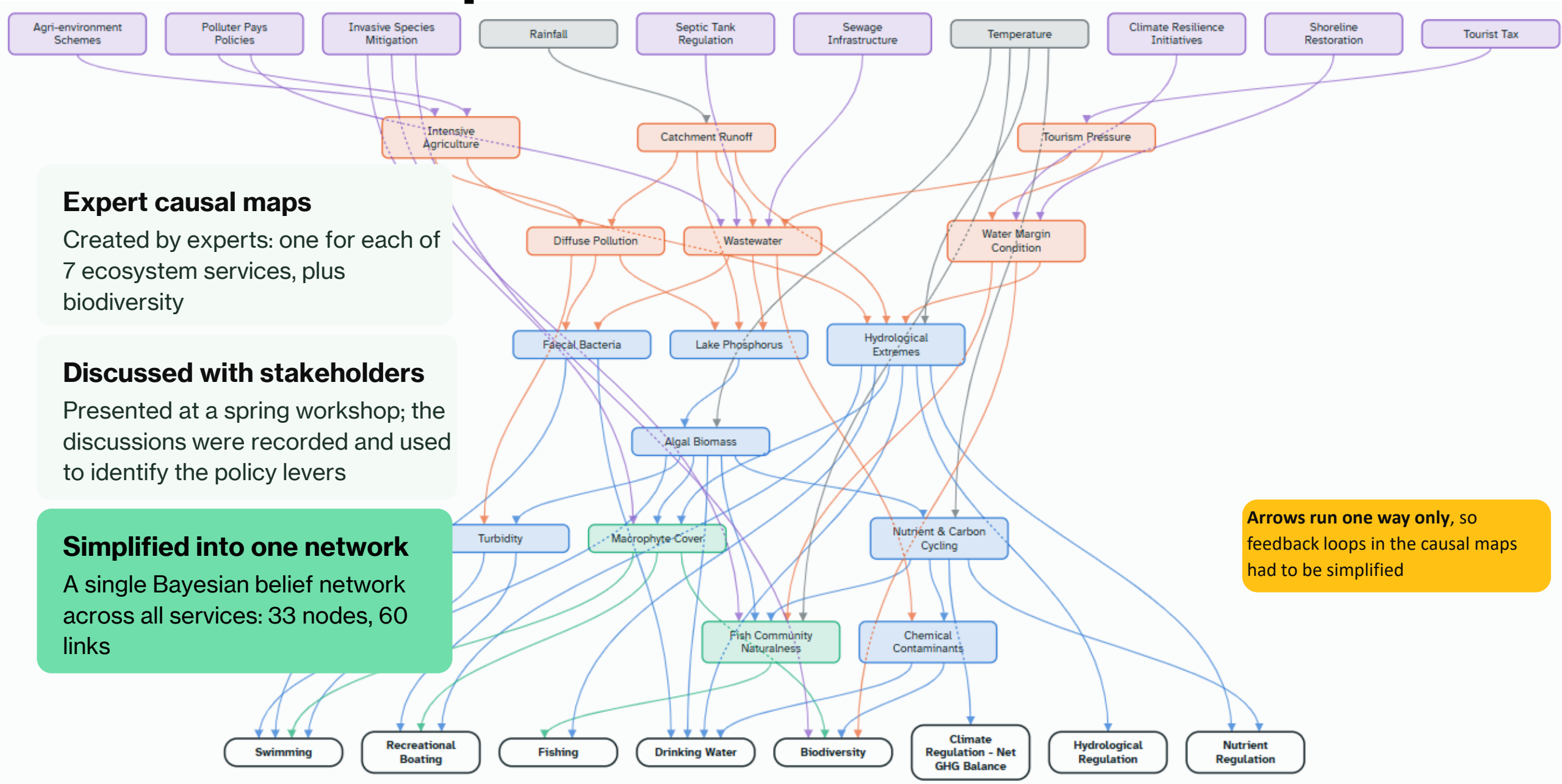
Part 1: Which levers should we pull for swimming?

Linking policy levers to ecosystem services at Windermere, starting with open-water swimming



Photo: © Steve Ashworth, Great North Swim 2017 (Lake District National Park, 2023)

From causal maps to one network



Expert causal maps

Created by experts: one for each of 7 ecosystem services, plus biodiversity

Discussed with stakeholders

Presented at a spring workshop; the discussions were recorded and used to identify the policy levers

Simplified into one network

A single Bayesian belief network across all services: 33 nodes, 60 links

Arrows run one way only, so feedback loops in the causal maps had to be simplified

What is a Bayesian Belief Network?

Each node has states

Sewage Infrastructure

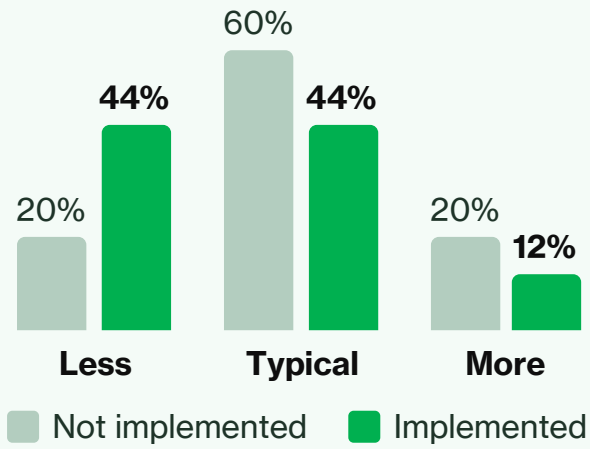
Not implemented

Implemented

A policy lever, switched on or off

Pull the lever: probabilities shift

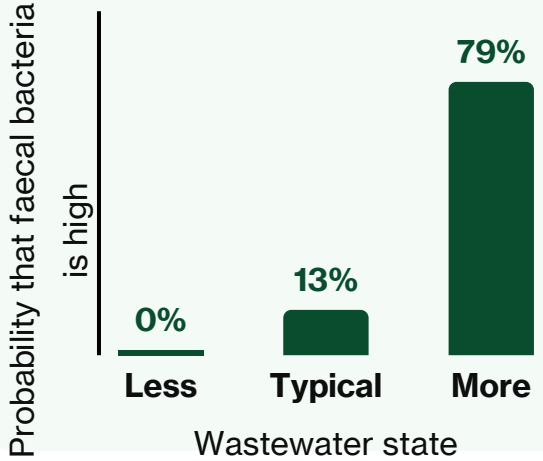
Wastewater



Links carry probabilities

Faecal Bacteria

Probability Faecal Bacteria is **High**, when wastewater is less, typical or more



Combine them

Faecal Bacteria **High**

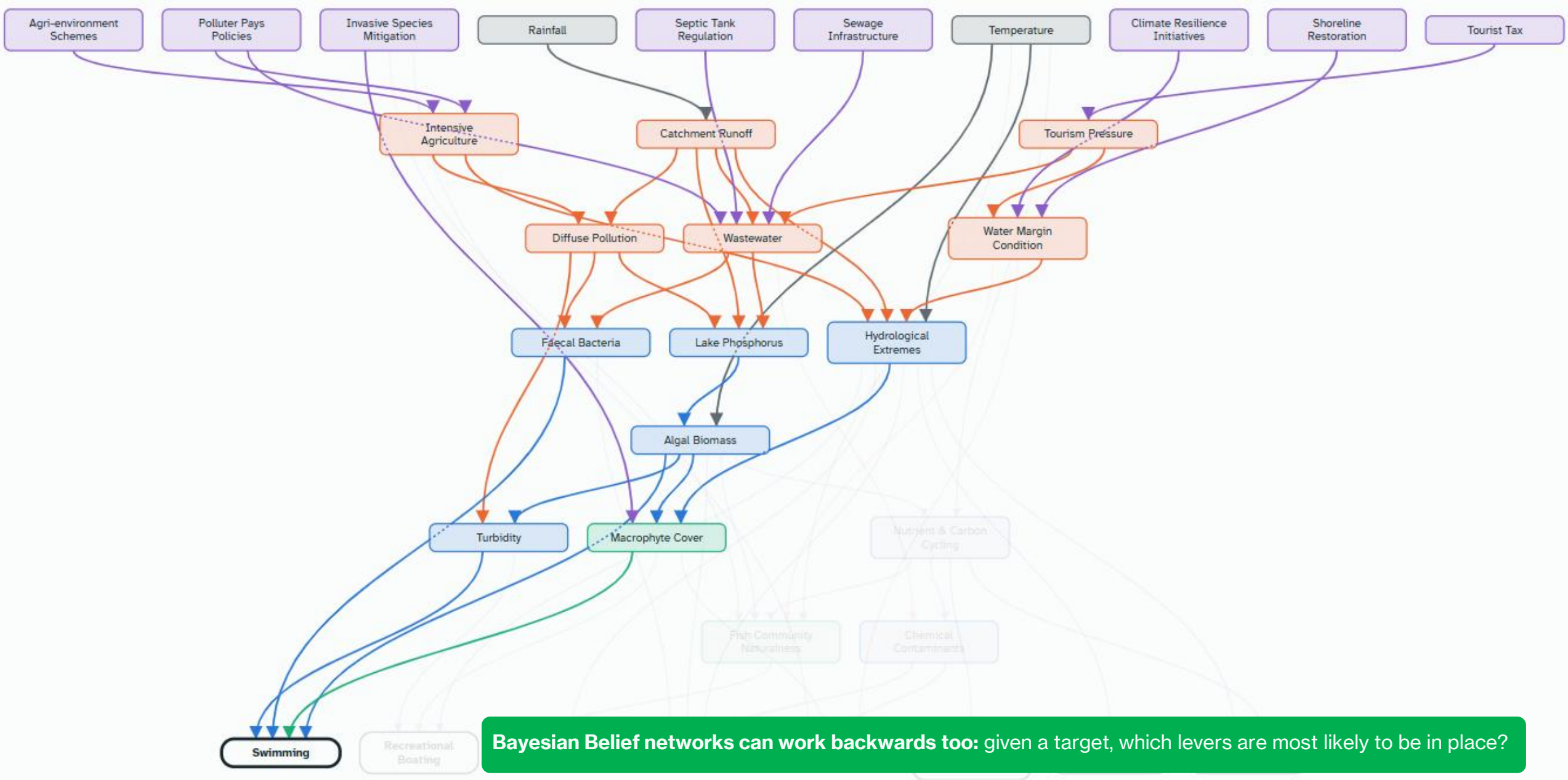
24% → 15%

For each Wastewater state, multiply its probability by the link probability, then add them up.

About 1 year in 4 → about 1 year in 7

High means the worst seasons in Windermere's own record (2012–2025)

Swimming pathway



Bayesian Belief networks can work backwards too: given a target, which levers are most likely to be in place?

Swimming pathway - simplified

The eight policy levers were identified through conversations with stakeholders at a workshop in spring

POLICY LEVERS

- **Sewage Infrastructure**
- **Septic Tank Regulation**
- **Polluter Pays Policies**
- **Invasive Species Mitigation**
- **Agri-environment Schemes**
- **Tourist Tax**
- **Shoreline Restoration**
- **Climate Resilience Initiatives**

→

PRESSURES

- Catchment Runoff
- Wastewater
- Diffuse Pollution
- Intensive Agriculture
- Tourism Pressure
- Water Margin Condition

→

LAKE & FLOW

- Hydrological Extremes
- Faecal Bacteria
- Lake Phosphorus
- Algal Biomass
- Turbidity
- Macrophyte Cover

→

ECOSYSTEM SERVICE



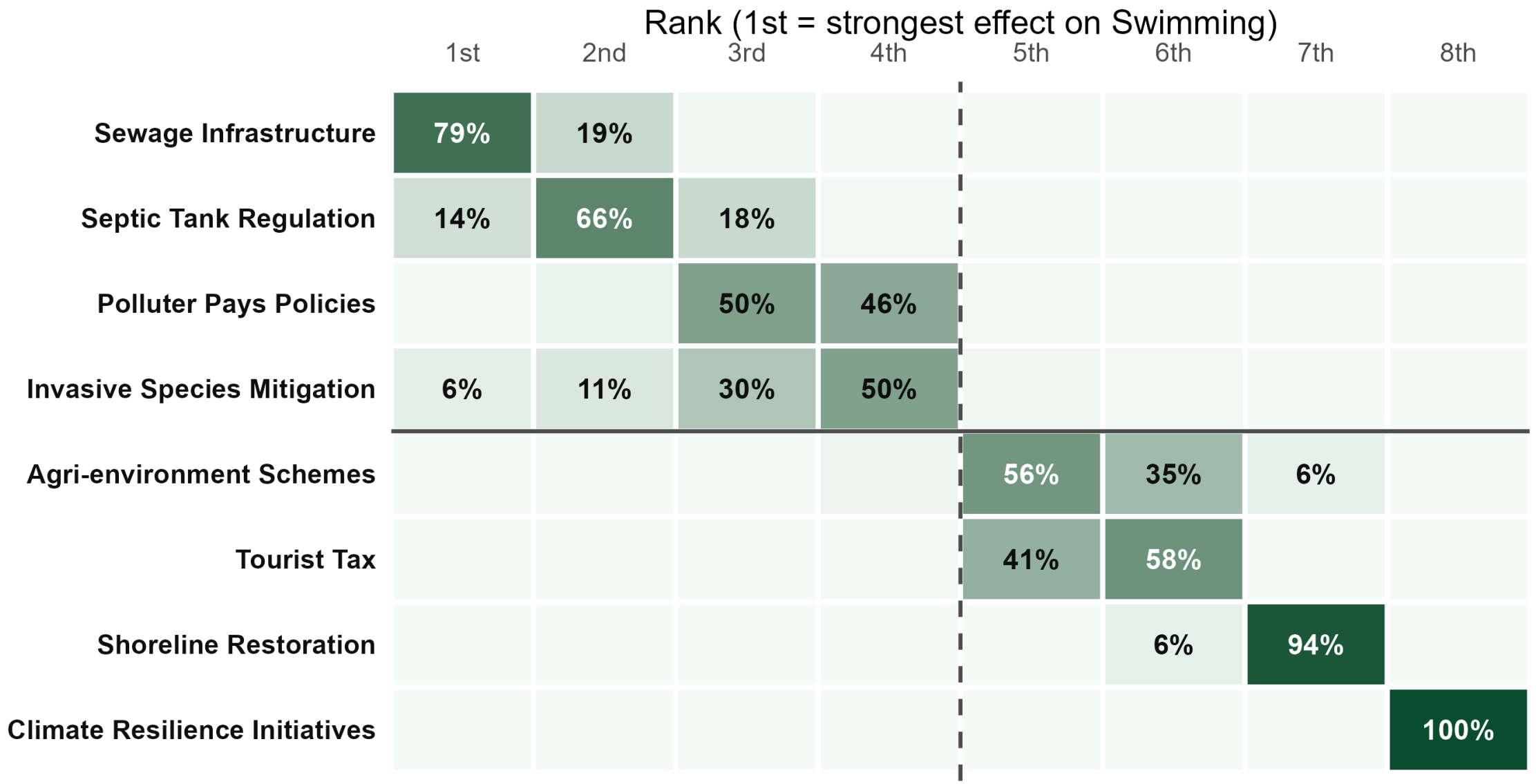
How we tested the levers

1. Switched each policy on in turn, then every combination of all eight (256), and measured the change in the chance Swimming is High (a good swimming year)

2. Re-ran the model 200 times with every uncertain number (the policy effects and the weights) set anywhere from half to double its best estimate

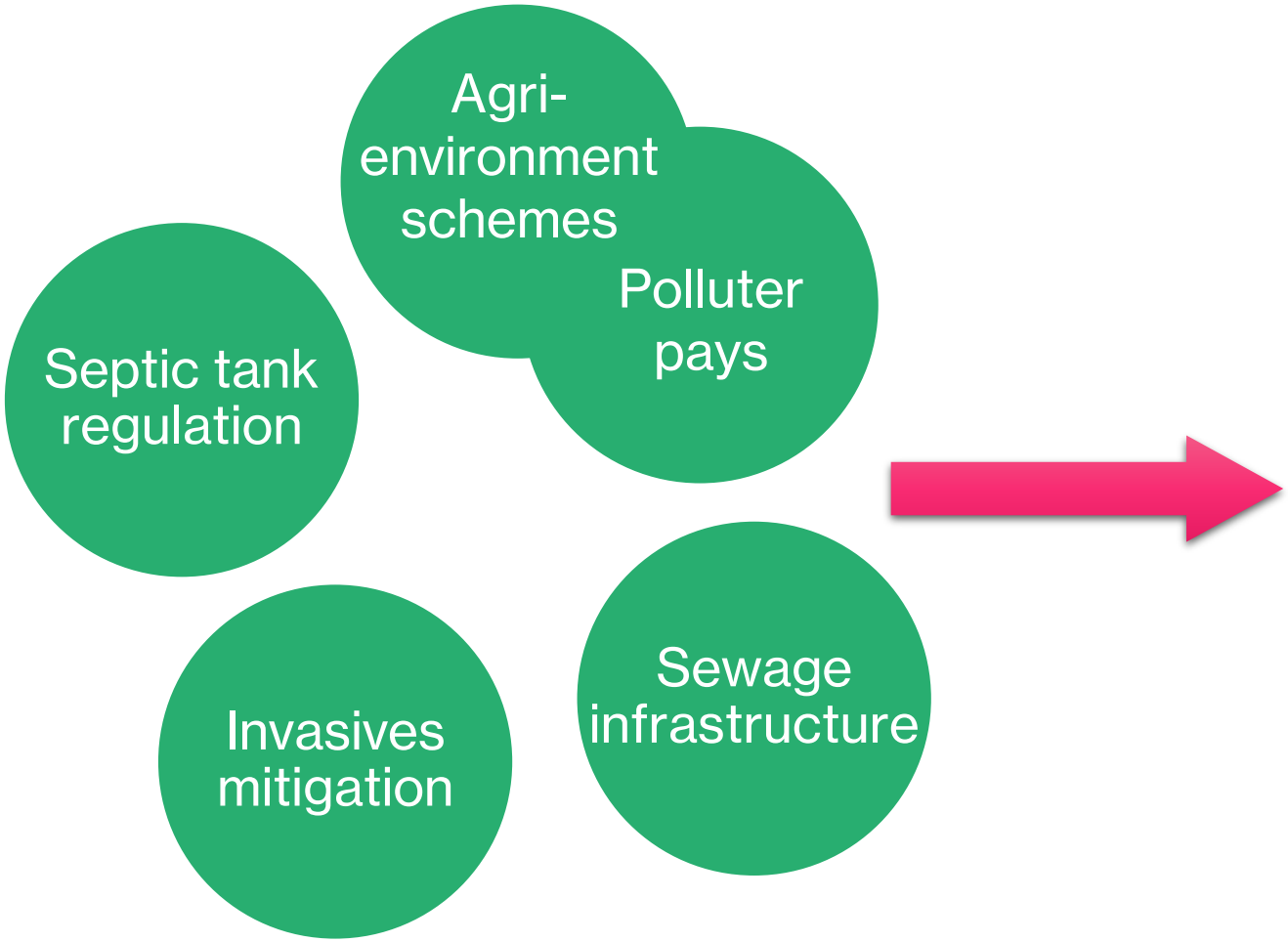


Most important levers for swimming



Share of 200 runs in which each lever got each rank (every uncertain number varied from half to double).

Part 2: From levers to pathways

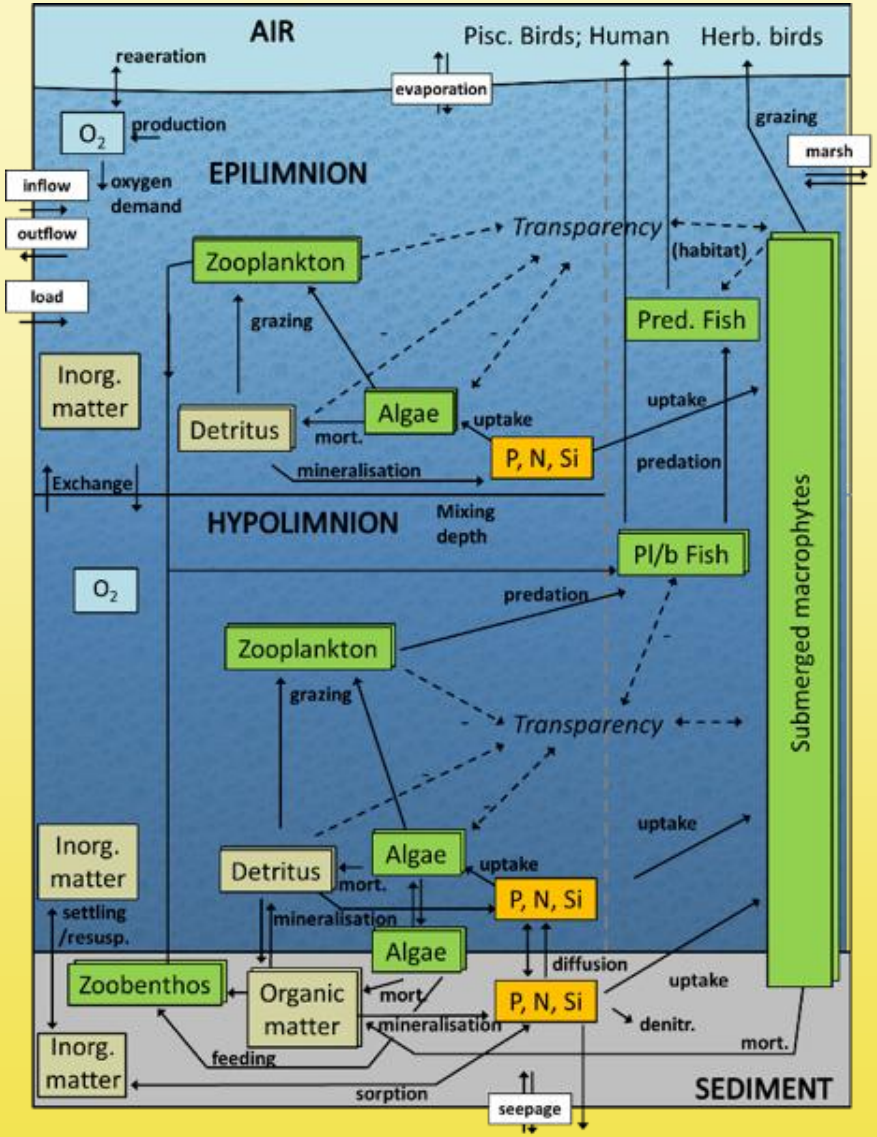


Next step: finding the pathways

*How can we **use** these levers to achieve the target ecosystem service (swimming)?*

Levers

Apply



Compare

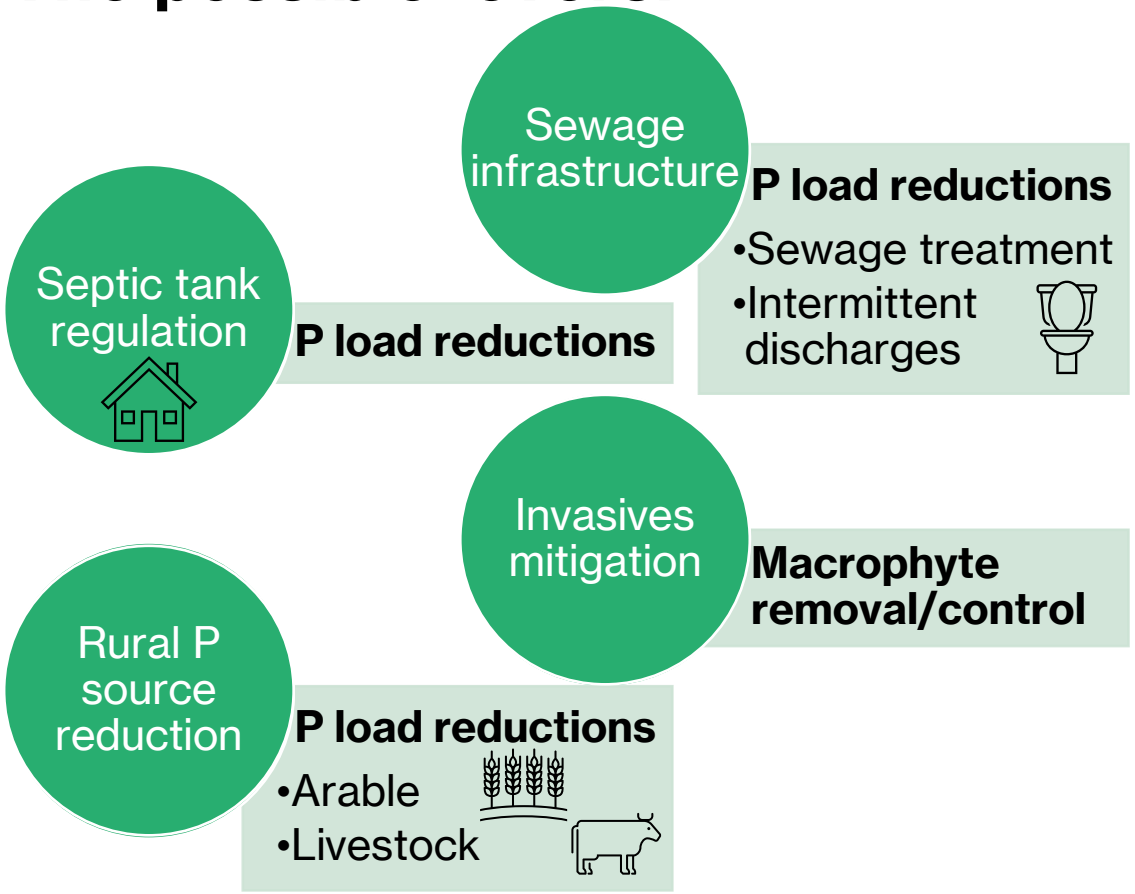


The possible pathways are constrained by our future targets and possible levers

The future targets:



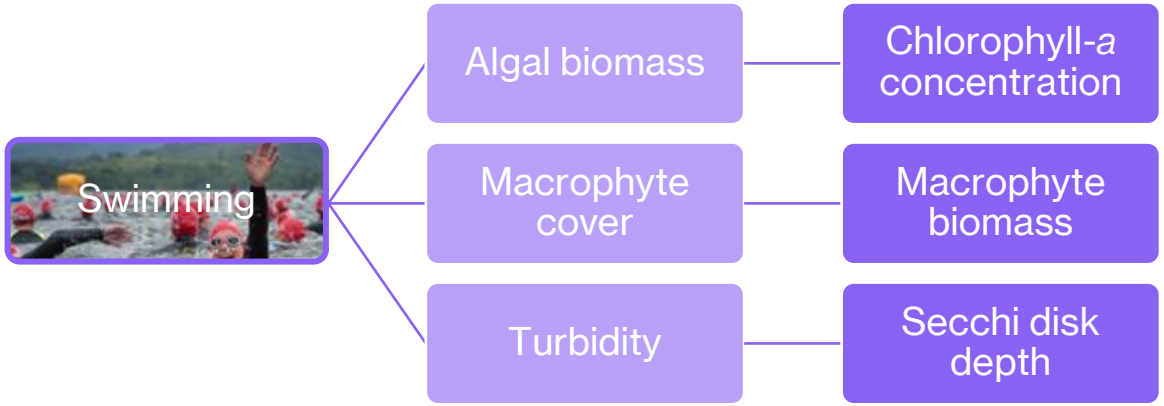
The possible levers:



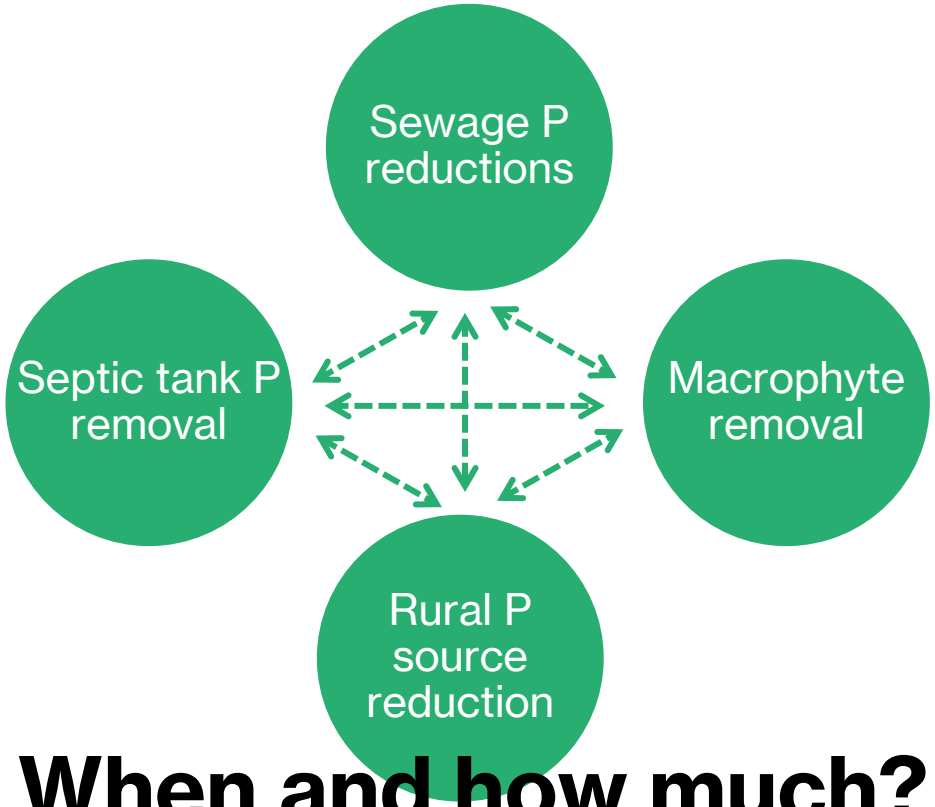
Zhan, Q., et al., 2023. https://doi.org/10.1016/j.jenvman.2023.119163

The possible pathways are constrained by our future targets and possible levers

The future targets:



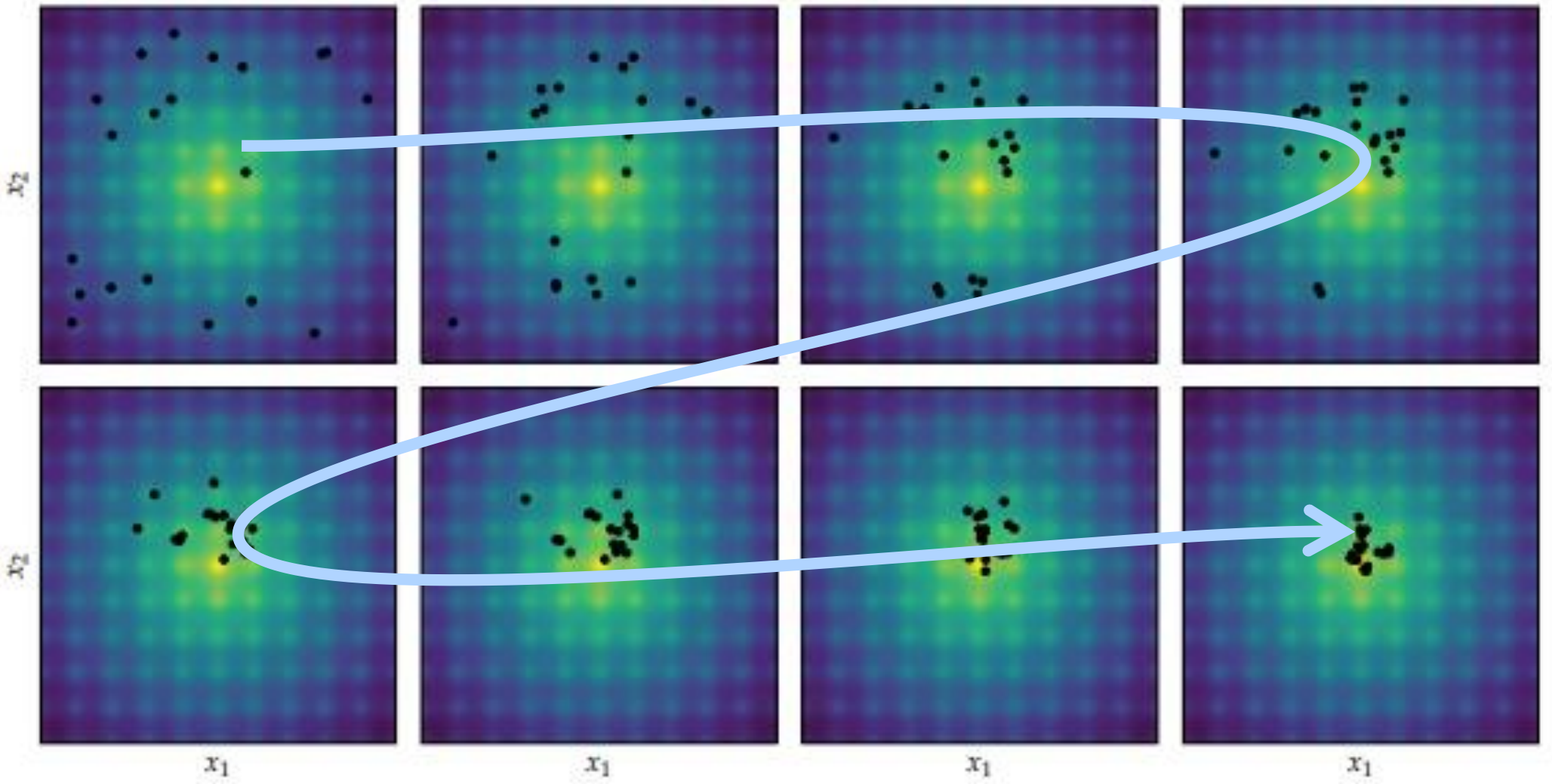
The possible levers:



When and how much?

Zhan, Q., et al., 2023. https://doi.org/10.1016/j.jenvman.2023.119163

Th



removal/
control

lition or
expansion
of marsh
area

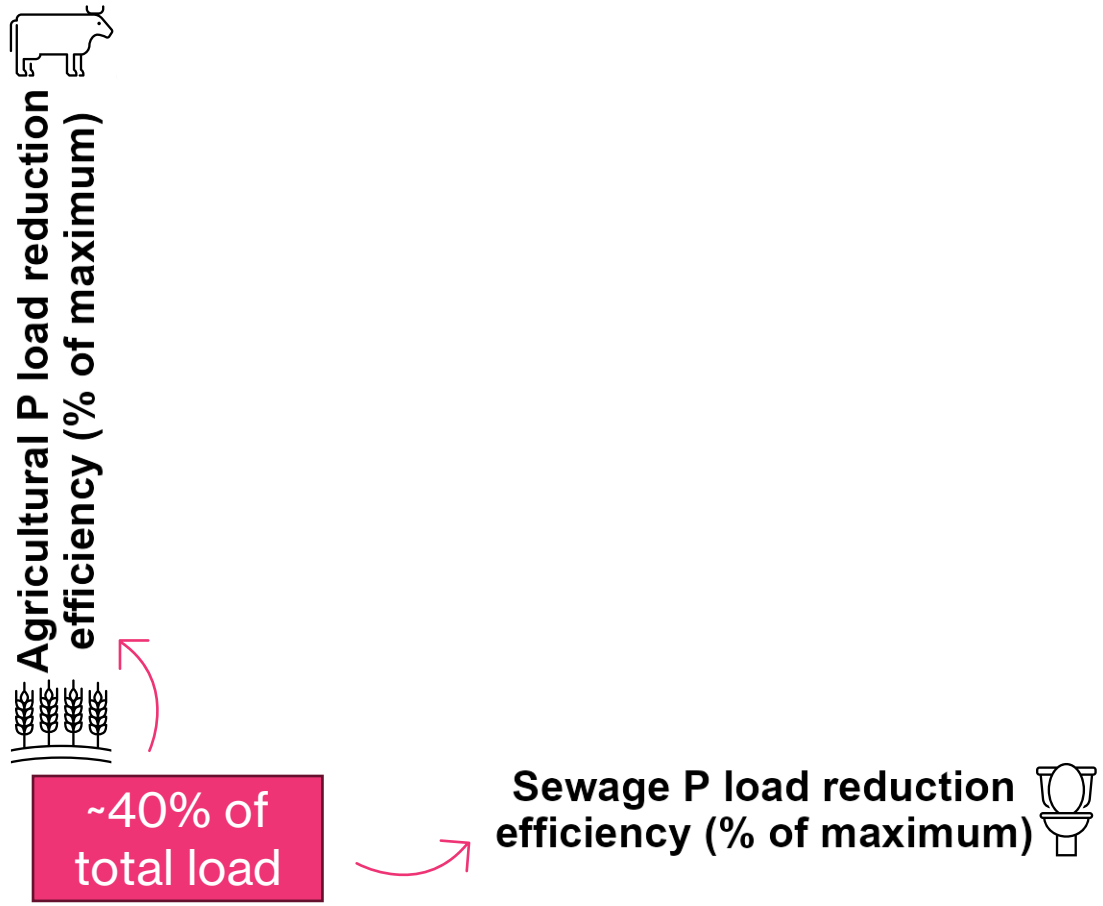
The model framework identified pathways to achieve the swimming ES

Identified (at least) 131 possible pathways

Combination of actions needed

Total P reductions combined sources

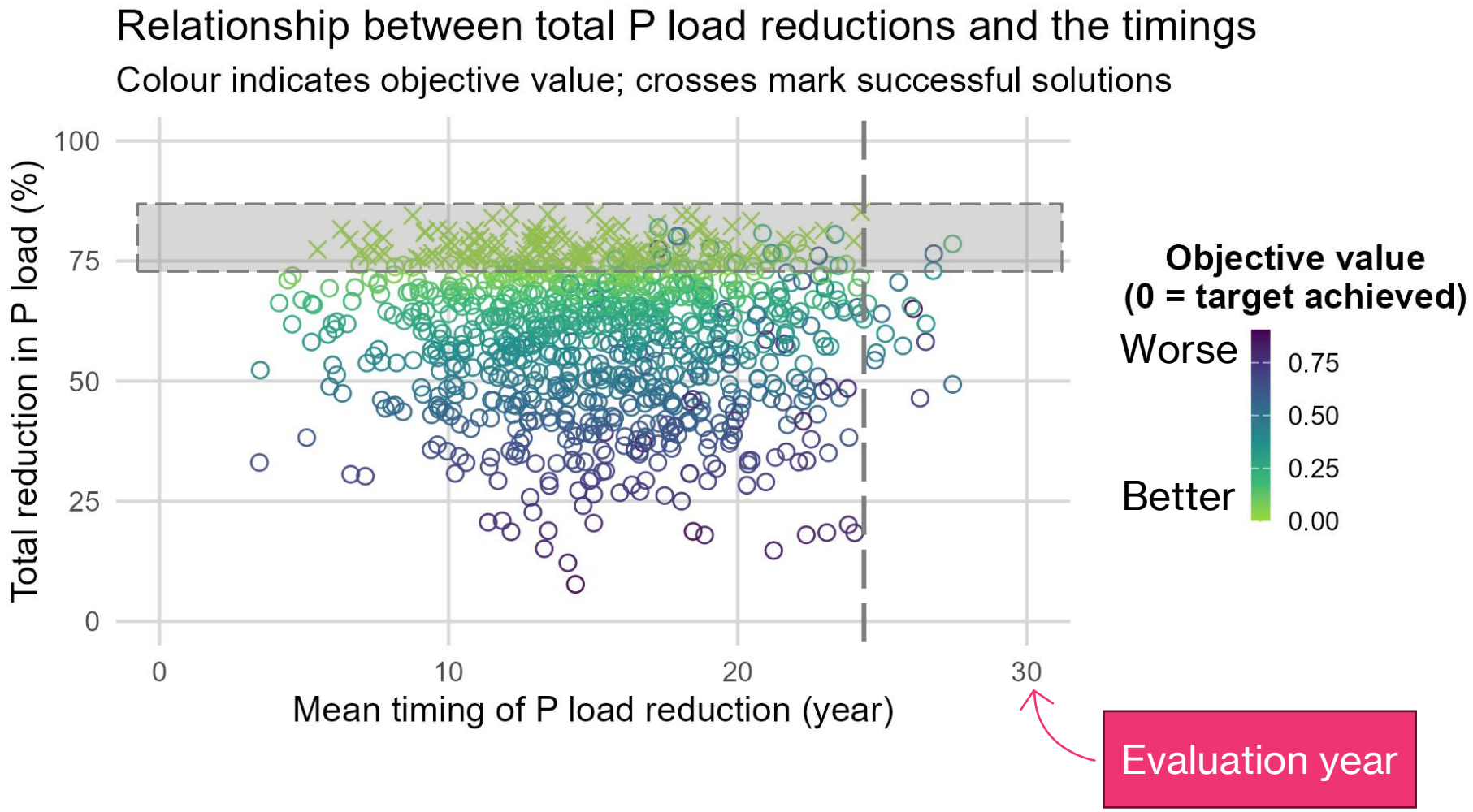
No effect of macrophyte removal → low macrophytes already



Timing and loads (partially) related

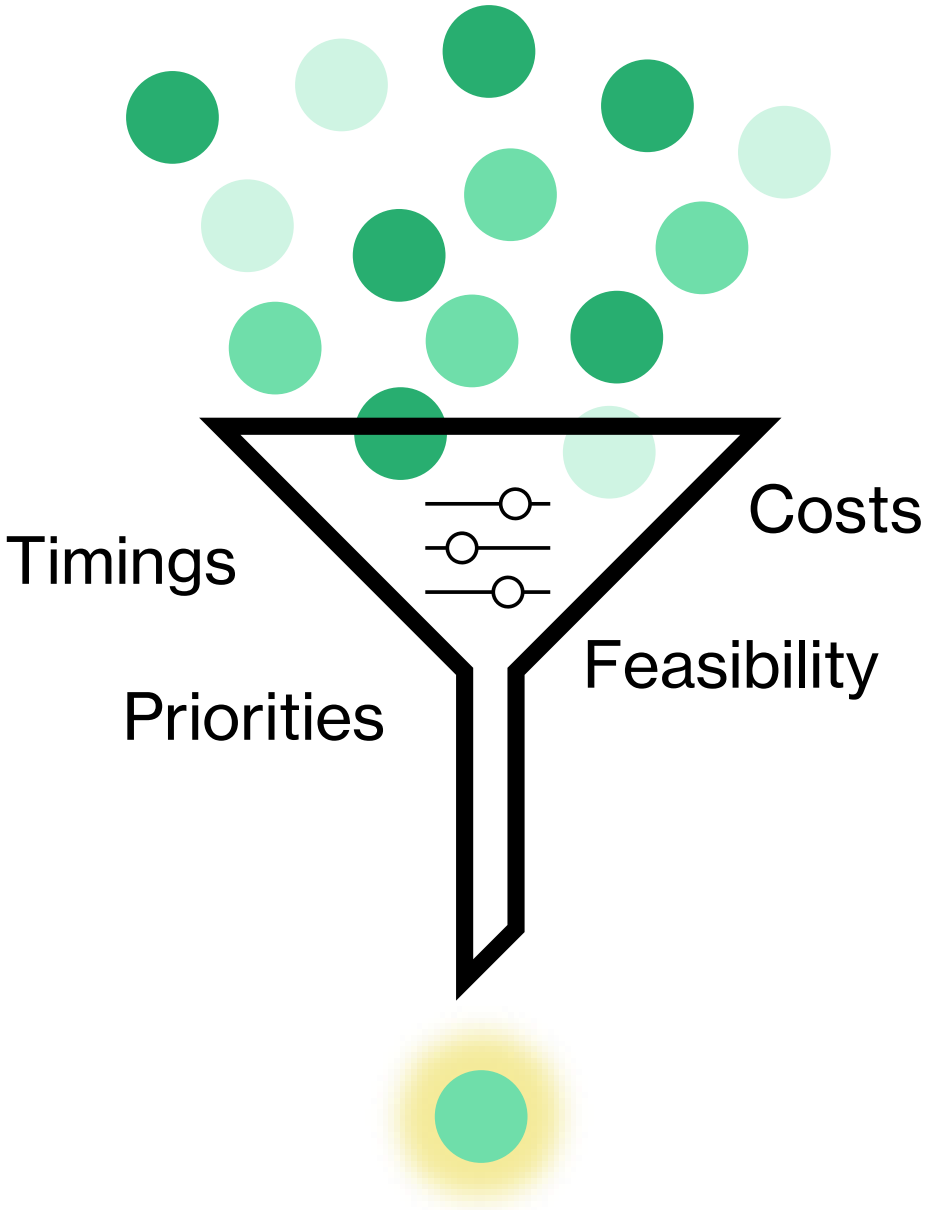
74-85% reductions in successful pathways

Timings need to account for lags in responses



Selecting a *preferred* pathway for implementation

- Model identified lots of possible lever combination
- Potential critical limit in P loading
- Timing is important

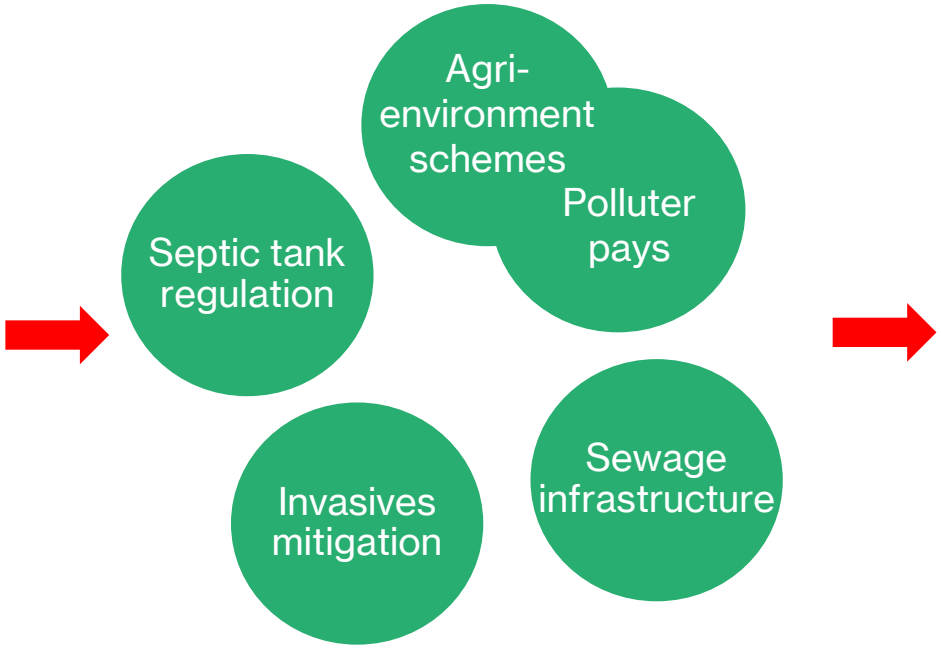


See the whole system, then model the pathways

Two **complementary** methods to explore how Windermere provides the ecosystem services of swimming, now and into the future.

Bayesian belief network

- Captures the whole system
- Diverse data inputs
- Identified levers that matter most swimming



Process model

- Dynamic over **time**
- Identified **optimal timing** and magnitude of levers

Further work: multiple services in multiple futures

A future Windermere may provide many services:

Swimming ✓ | **Drinking Water** | **Fishing** | **Recreational Boating** | **Biodiversity**

Hydrological Regulation | **Climate Regulation** | **Nutrient Regulation**

1. **Levers with multiple benefits:** which levers improve several services?
2. **Trade-offs and synergies:** where does improving one service help or harm the others?
3. How does future **climate change** influence the success of management levers and pathways to achieve a desired state?
4. Do we need more transformative, systemic change?

Acknowledgements and Thanks

PLURALAKES

Water4All
Water security for the planet

pluralakes.eu

Radboud Universiteit

UKCEH

NWO

UKRI
Engineering and Physical Sciences Research Council

- **PLURALAKES team**
- **Stakeholder participants**

