*Danube Commission · Working Group on Technical Issues*

# Assessment of Energy Efficiency of Heavy Convoy Trains on the Danube

*Methodological framework with probabilistic and forecasting extension*

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# Why a Danube-specific approach is needed

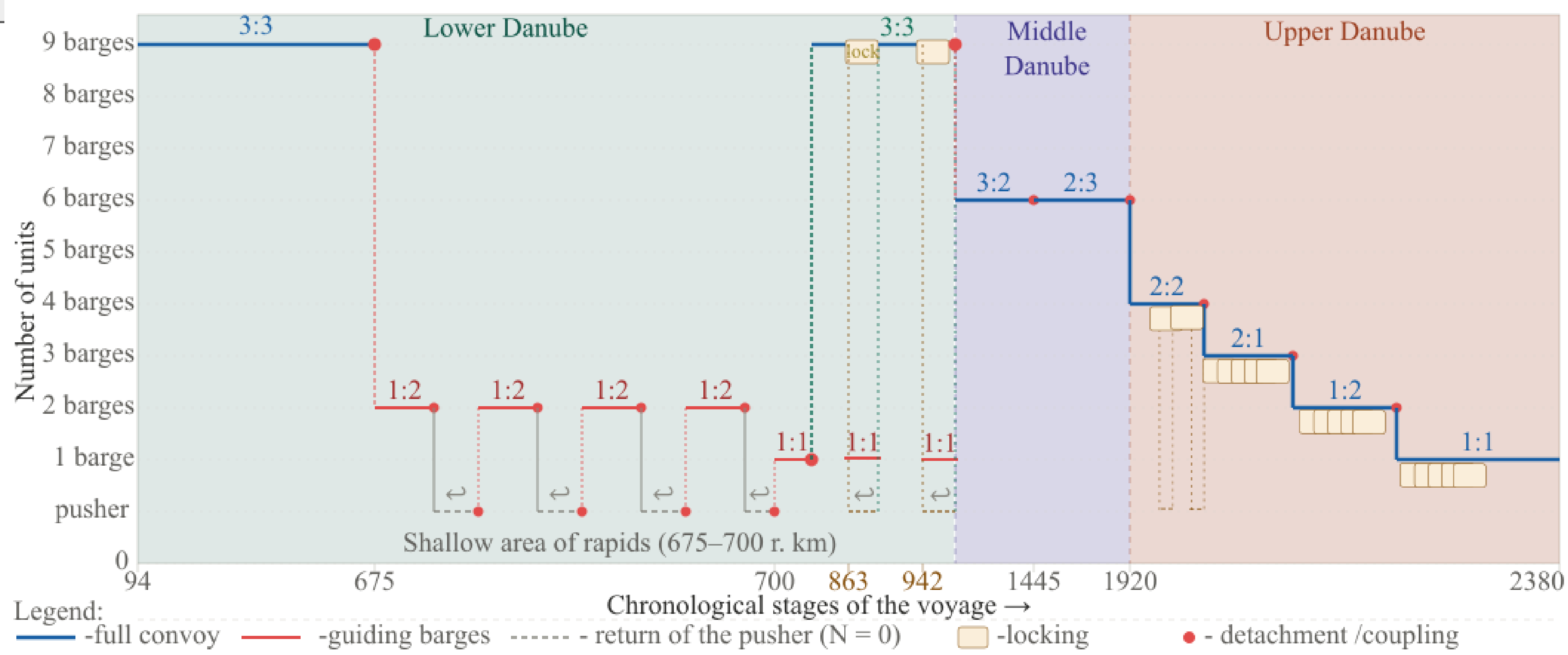
## Existing instruments

**EEDI / EEXI (IMO)** — designed for sea-going vessels in steady-state cruise conditions

**Roadmap on environmentally friendly navigation** (Danube Commission) — Attachment 5 calls for harmonised methodology of energy assessment

## Danube-specific factors

1. Significant hydrological variability — depth and current
2. Lockages and convoy escorting in piecewise-non-uniform conditions
3. Frequent reconfiguration of caravans en route
4. Direct shaft-power measurement is impractical on inland fleet
5. Need for indices that integrate depth, current and trip time structure



# Object of study: self-propelled vessel with caravan

*A self-propelled vessel performing a trip along the Danube waterway with a caravan of non-self-propelled barges*

**Pusher tug**

*specialised vessel for caravan propulsion*

**Cargo self-propelled vessel**

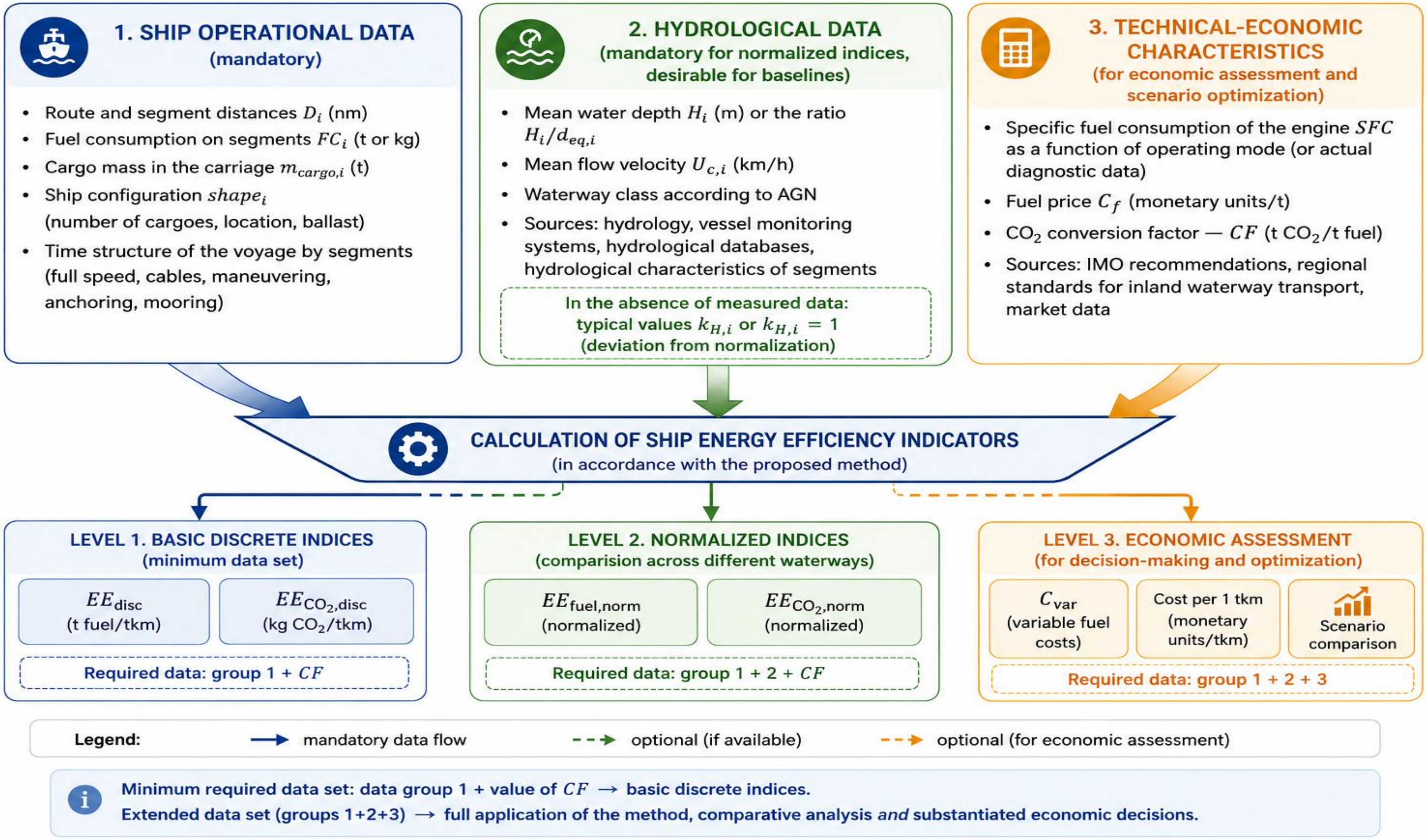
*with caravan attachment*

**Single voyage**

*degenerate case (caravan mass = 0)*

**Universal applicability:** the method covers the full range of voyage configurations of all Danube fleet operators, regardless of national affiliation or specific vessel type.

# System of energy-efficiency indices (based on *EEOI*)



**1. SHIP OPERATIONAL DATA**
**(mandatory)**

- Route and segment distances $D_i$ (nm)
- Fuel consumption on segments $FC_i$ (t or kg)
- Cargo mass in the carriage $m_{cargo,i}$ (t)
- Ship configuration $shape_i$ (number of cargoes, location, ballast)
- Time structure of the voyage by segments (full speed, cables, maneuvering, anchoring, mooring)

**2. HYDROLOGICAL DATA**
**(mandatory for normalized indices, desirable for baselines)**

- Mean water depth $H_i$ (m) or the ratio $H_i/d_{eq,i}$
- Mean flow velocity $U_{c,i}$ (km/h)
- Waterway class according to AGN
- Sources: hydrology, vessel monitoring systems, hydrological databases, hydrological characteristics of segments

**In the absence of measured data: typical values $k_{H,i}$ or $k_{H,i} = 1$ (deviation from normalization)**

**3. TECHNICAL-ECONOMIC CHARACTERISTICS**
**(for economic assessment and scenario optimization)**

- Specific fuel consumption of the engine $SFC$ as a function of operating mode (or actual diagnostic data)
- Fuel price $C_f$ (monetary units/t)
- $CO_2$ conversion factor — $CF$ (t $CO_2$/t fuel)
- Sources: IMO recommendations, regional standards for inland waterway transport, market data

**CALCULATION OF SHIP ENERGY EFFICIENCY INDICATORS**
(in accordance with the proposed method)

**LEVEL 1. BASIC DISCRETE INDICES**
**(minimum data set)**

| $EE_{disc}$ (t fuel/tkm) | $EE_{CO_2,disc}$ (kg $CO_2$/tkm) |
|---|---|

**Required data: group 1 + $CF$**

**LEVEL 2. NORMALIZED INDICES**
**(comparision across different waterways)**

| $EE_{fuel,norm}$ (normalized) | $EE_{CO_2,norm}$ (normalized) |
|---|---|

**Required data: group 1 + 2 + $CF$**

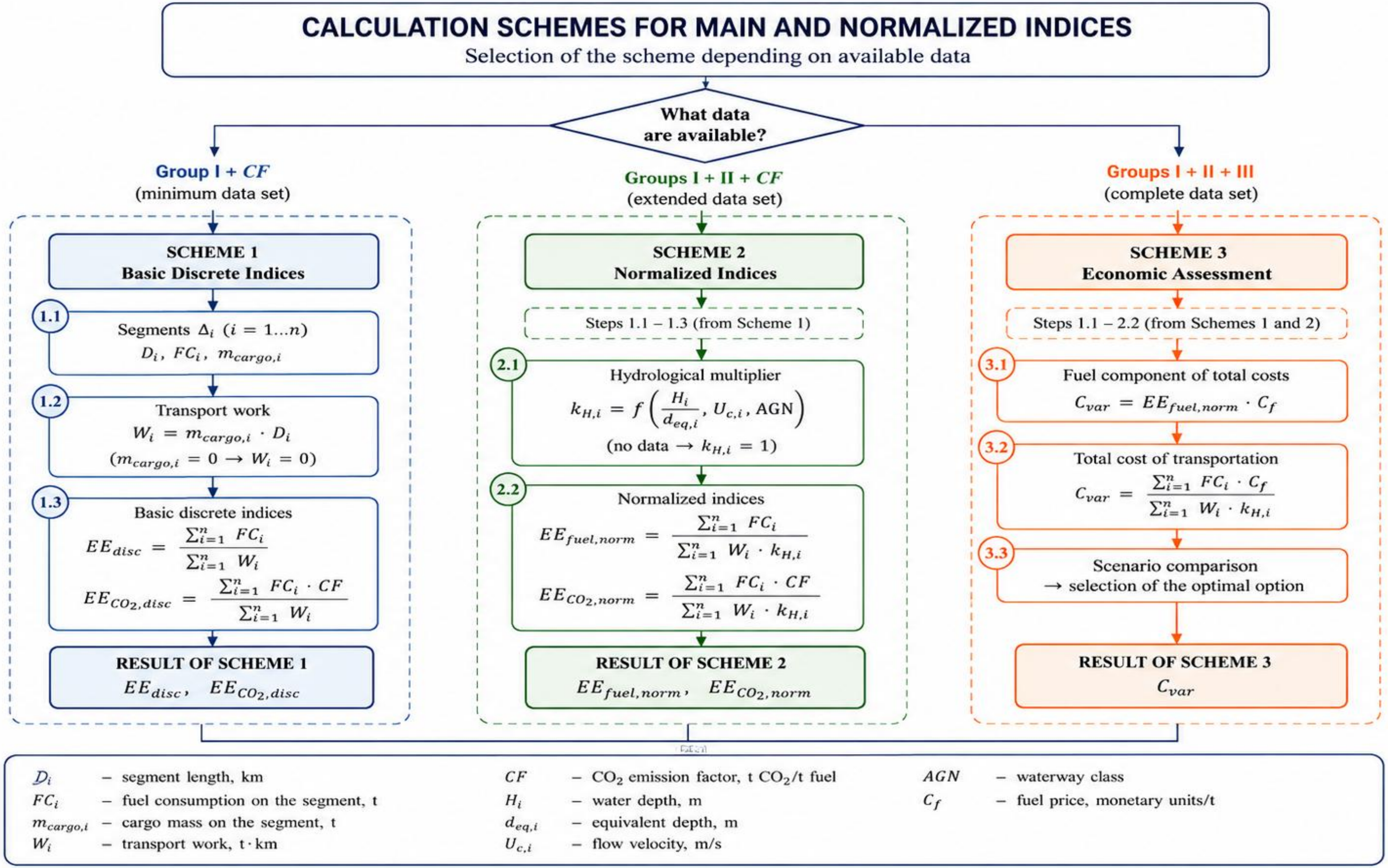
**LEVEL 3. ECONOMIC ASSESSMENT**
**(for decision-making and optimization)**

| $C_{var}$ (variable fuel costs) | Cost per 1 tkm (monetary units/tkm) | Scenario comparison |
|---|---|---|

**Required data: group 1 + 2 + 3**

**Legend:** → mandatory data flow ⇢ optional (if available) ⇢ optional (for economic assessment)

**Minimum required data set: data group 1 + value of $CF$ → basic discrete indices.**
**Extended data set (groups 1+2+3) → full application of the method, comparative analysis *and* substantiated economic decisions.**



# CALCULATION SCHEMES FOR MAIN AND NORMALIZED INDICES

Selection of the scheme depending on available data

**What data are available?**

**Group I + *CF***
(minimum data set)

**SCHEME 1**
**Basic Discrete Indices**

1.1 Segments $\Delta_i$ $(i = 1 \ldots n)$

$D_i$, $FC_i$, $m_{cargo,i}$

1.2 Transport work

$W_i = m_{cargo,i} \cdot D_i$

$(m_{cargo,i} = 0 \rightarrow W_i = 0)$

1.3 Basic discrete indices

$$EE_{disc} = \frac{\sum_{i=1}^{n} FC_i}{\sum_{i=1}^{n} W_i}$$

$$EE_{CO_2,disc} = \frac{\sum_{i=1}^{n} FC_i \cdot CF}{\sum_{i=1}^{n} W_i}$$

**RESULT OF SCHEME 1**
$EE_{disc}$, $EE_{CO_2,disc}$

**Groups I + II + *CF***
(extended data set)

**SCHEME 2**
**Normalized Indices**

Steps 1.1 – 1.3 (from Scheme 1)

2.1 Hydrological multiplier

$$k_{H,i} = f\left(\frac{H_i}{d_{eq,i}}, U_{c,i}, \text{AGN}\right)$$

(no data $\rightarrow k_{H,i} = 1$)

2.2 Normalized indices

$$EE_{fuel,norm} = \frac{\sum_{i=1}^{n} FC_i}{\sum_{i=1}^{n} W_i \cdot k_{H,i}}$$

$$EE_{CO_2,norm} = \frac{\sum_{i=1}^{n} FC_i \cdot CF}{\sum_{i=1}^{n} W_i \cdot k_{H,i}}$$

**RESULT OF SCHEME 2**
$EE_{fuel,norm}$, $EE_{CO_2,norm}$

**Groups I + II + III**
(complete data set)

**SCHEME 3**
**Economic Assessment**

Steps 1.1 – 2.2 (from Schemes 1 and 2)

3.1 Fuel component of total costs

$C_{var} = EE_{fuel,norm} \cdot C_f$

3.2 Total cost of transportation

$$C_{var} = \frac{\sum_{i=1}^{n} FC_i \cdot C_f}{\sum_{i=1}^{n} W_i \cdot k_{H,i}}$$

3.3 Scenario comparison
→ selection of the optimal option

**RESULT OF SCHEME 3**
$C_{var}$

$D_i$ – segment length, km
$FC_i$ – fuel consumption on the segment, t
$m_{cargo,i}$ – cargo mass on the segment, t
$W_i$ – transport work, t · km
$CF$ – $CO_2$ emission factor, t $CO_2$/t fuel
$H_i$ – water depth, m
$d_{eq,i}$ – equivalent depth, m
$U_{c,i}$ – flow velocity, m/s
$AGN$ – waterway class
$C_f$ – fuel price, monetary units/t

# Probabilistic and forecasting extension

MC

### Monte Carlo simulation

Random sampling of input parameters from empirical distributions. Output: distribution of EE, confidence intervals, exceedance probability.

AR

### AR(1) forecasting model

Autoregressive model of daily water levels calibrated on Danube Commission yearbooks. Provides conditional forecasts up to operational horizon.

ρ

### Spatial correlation clusters

Three correlation clusters along the river (upper, middle, lower Danube). Information from upstream posts improves downstream forecasts via cross-correlation.

**Integration:** *AR(1) → conditional depth distributions → Monte Carlo → narrowed EE confidence interval*

# Hydrological foundation: 16-year Danube Commission database

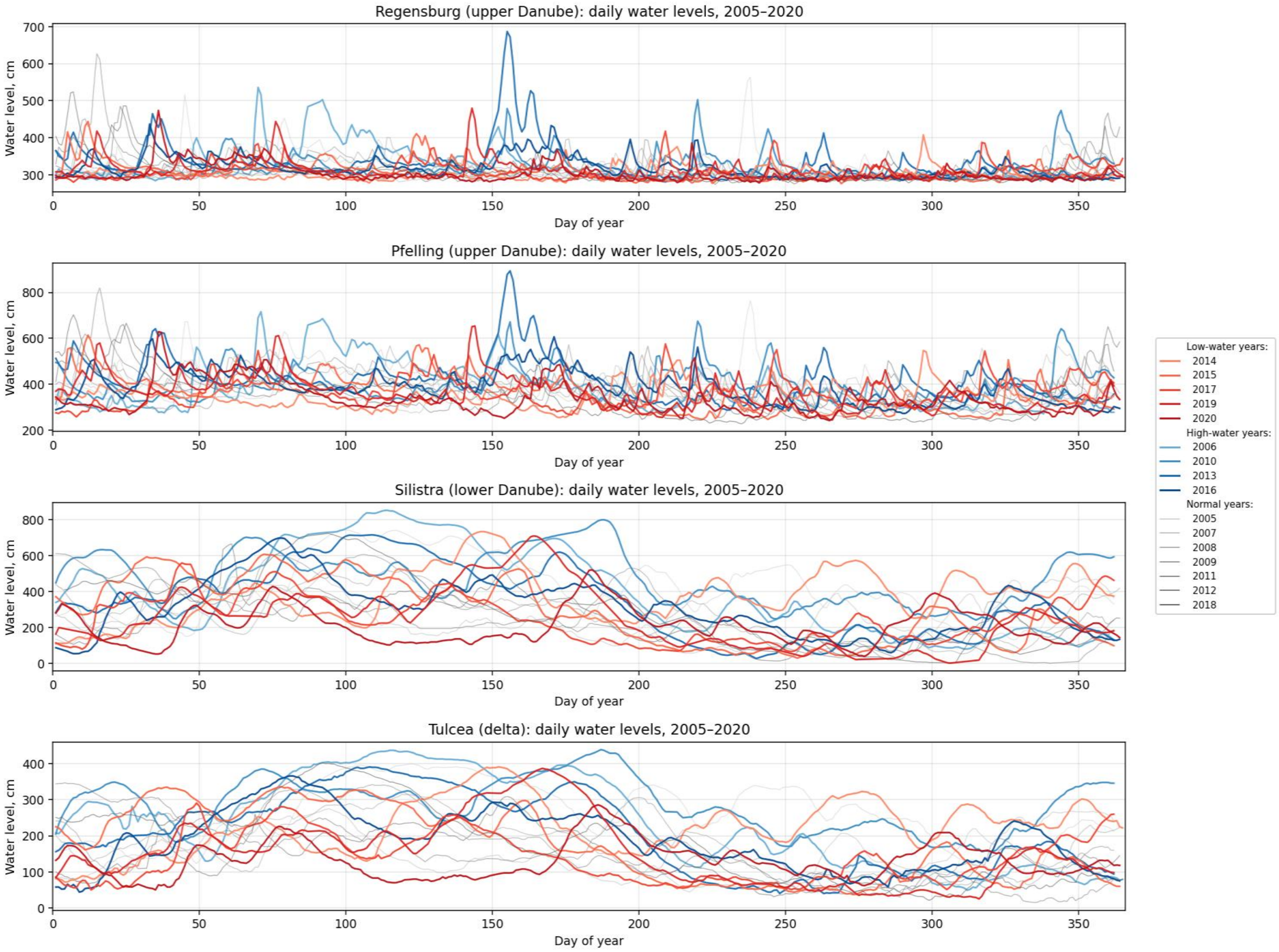
**16** years (2005–2020)

**71** water-level posts

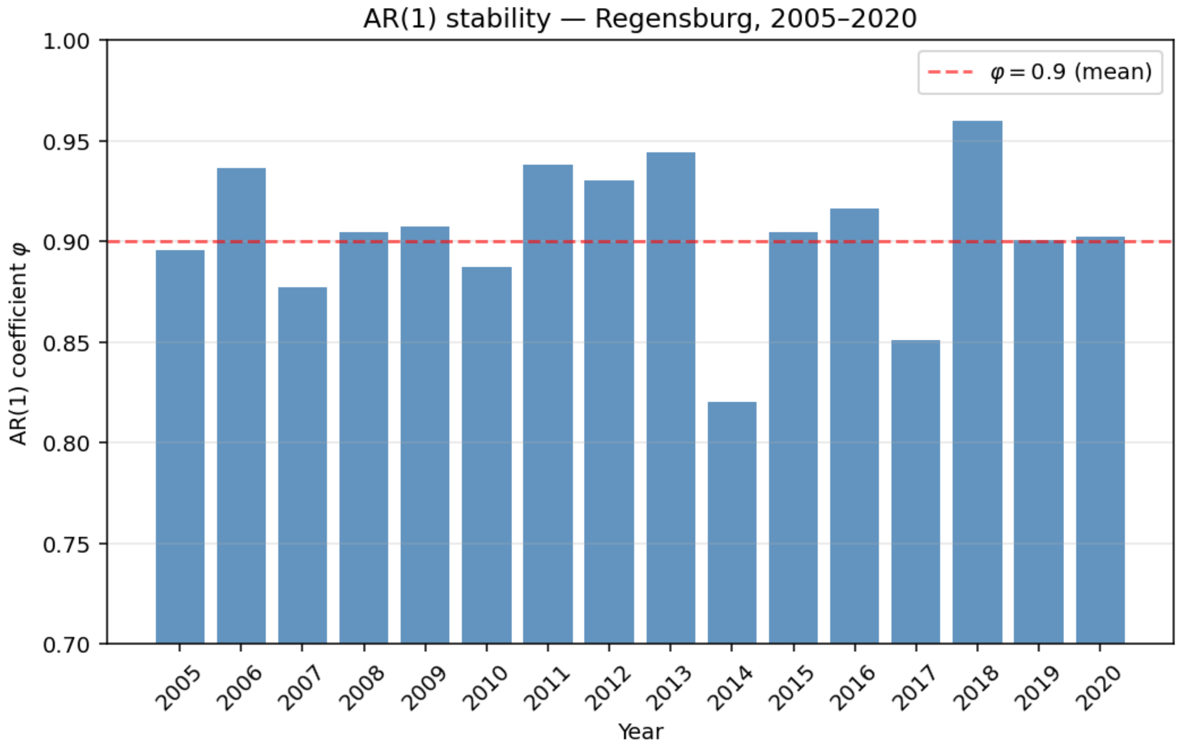
**265 798** validated daily records

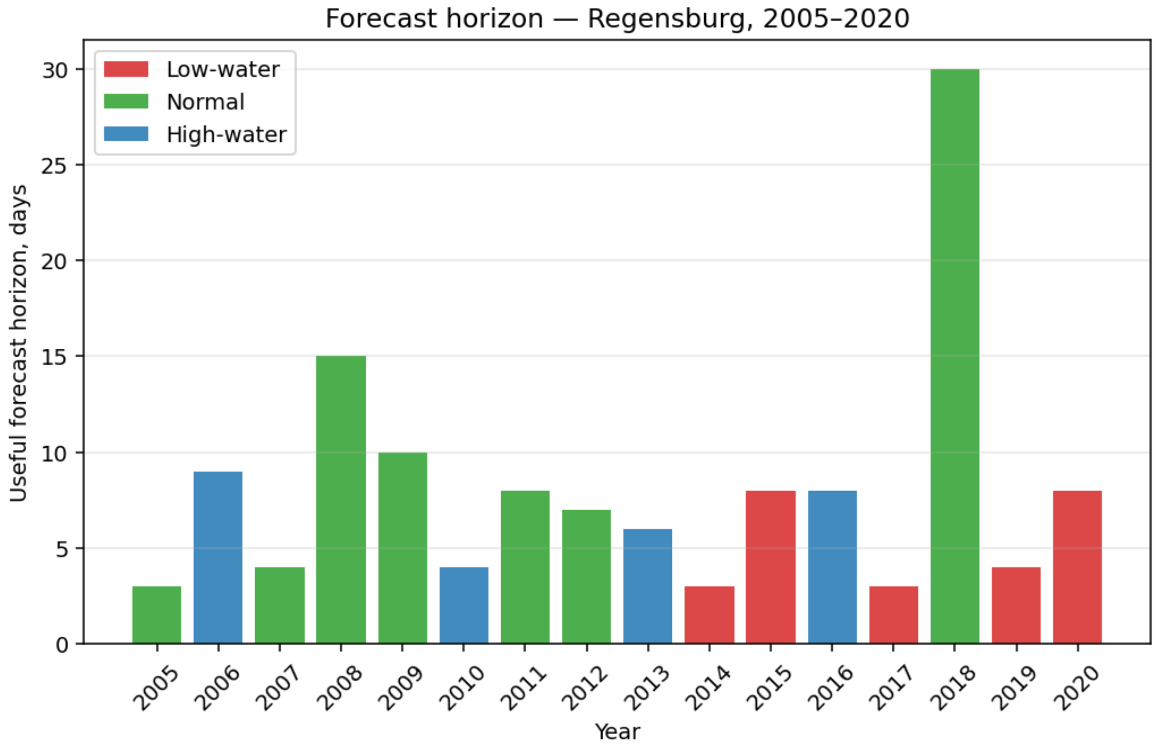
*Source: Danube Commission Annual Hydrological Yearbooks*

**Trend:** 5 of 7 years post-2014 classified as low-water



# AR(1) model stability across 16 years


AR(1) stability — Regensburg, 2005–2020


Forecast horizon — Regensburg, 2005–2020

**ϕ = 0.90 → 0.99**

AR(1) coefficient grows along the river (upper → lower Danube)

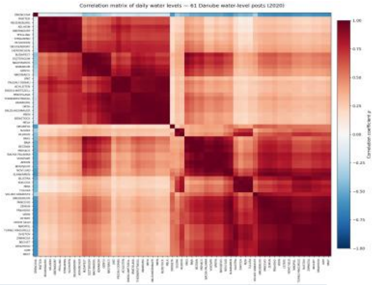
**6–8 days**

Useful forecast horizon in normal years (matches typical trip duration)

**< 4%**

Relative variation of ϕ over 16 years confirms quasi-stationarity

# Spatial correlation structure of water-level posts



## Three correlation clusters

**Upper Danube** ρ̄ = 0.84
*Kelheim – Gönyű*

**Middle Danube** ρ̄ = 0.81
*Gönyű – Iron Gates*

**Lower Danube** ρ̄ = 0.83
*Iron Gates – delta*

**Between upper & lower:**
*ρ̄ = 0.29 — different hydrological regimes (Alpine snowmelt vs Carpathian-Balkan inflow)*

| Danube Part | Season | Average $H/d$ | $k_H$ | |
|---|---|---|---|---|
| | | | Parameterization A | Parameterization B |
| **Upper Danube** | Winter-Spring | 1,32 ± 0,27 | 1,21 ± 0,05 | 1,35 ± 0,07 |
| **Upper Danube** | Summer-Autumn | 1,28 ± 0,30 | 1,21 ± 0,05 | 1,36 ± 0,07 |
| **Middle Danube** | Winter-Spring | 1,35 ± 0,30 | 1,20 ± 0,06 | 1,34 ± 0,08 |
| **Middle Danube** | Summer-Autumn | 1,26 ± 0,32 | 1,22 ± 0,06 | 1,36 ± 0,08 |
| **Lower Danube** | Winter-Spring | 1,47 ± 0,35 | 1,18 ± 0,06 | 1,31 ± 0,09 |
| **Lower Danube** | Summer-Autumn | 1,23 ± 0,32 | 1,22 ± 0,06 | 1,37 ± 0,08 |

**Values are given as mean ± standard deviation.**

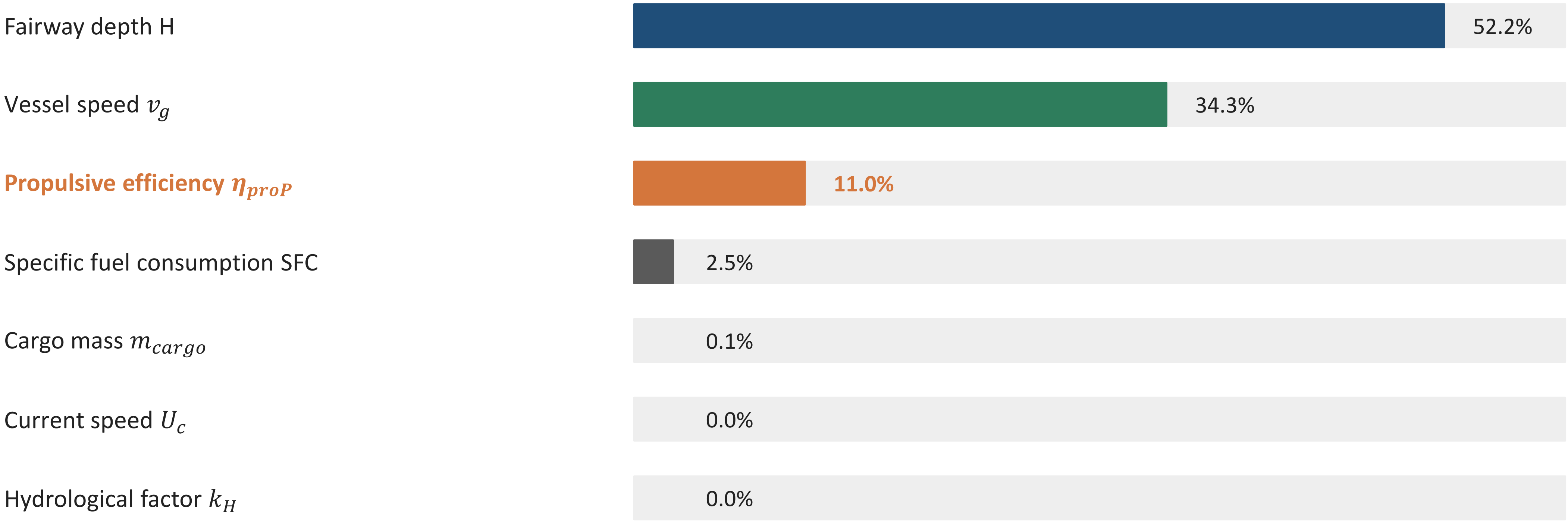
**Parameterization A and B for $k_H\left(\frac{H}{d}\right)$ function:**

Parameterization A (Zeng et al., 2019) in power form. Recommended for Danube pushed convoys of flat bottom shape.

Parameterization B (Tabaczek, 2007) is more conservative—it yields higher values of $k_H$, consistent with studies with full-form barges.

# Sensitivity analysis: which factors drive EE variance

## Variance decomposition of $EE_{CO2}$



**Key finding:** propulsive efficiency $\eta_{proP}$ emerges as the third most influential factor **(11.0%)**, justifying its separate stochastic treatment and the role of parametric diagnostics in calibrating the model.

# Method validation across three experimental campaigns

*Real Danube voyages on three vessels — each campaign reveals a distinct dimension of operational efficiency*

CAMPAIGN A

## Range of EE values

*4 caravan configurations × 5 speeds, single vessel (52 measurements)*

**3.8×**

range of trip EE on the same vessel
(1.79 → 6.81 g/(t·km))

EE varies more by **operator choice** (speed × caravan shape) than by any external factor.

→ A single number cannot characterise a vessel — methodology must report the index *per voyage*.

CAMPAIGN B

## Engine condition matters

*In-cylinder diagnostics, 2 × 8-cylinder main engines (16 cylinders)*

**11/16**

cylinders with detected defects
(injection timing, valve seating, plunger wear)

Each defect causes **elevated specific fuel consumption** invisible in fleet-level statistics.

→ Parametric diagnostics is a *necessary input* to the EE assessment, not an optional add-on.

CAMPAIGN C

## Hidden operational regimes

*Flood-period voyage with continuous fuel-flow and indicator measurements (7 segments)*

**119% / 72%**

engine load on different segments of the same voyage
(overload from current vs underload)

Within a single voyage, the engines passed through **two opposite stress regimes** — neither visible in trip-averaged figures.

→ Methodology must operate at *segment level*, not trip level, to capture real operational diversity.

**Convergent message:** the proposed three-tier methodology is **necessary and sufficient** to capture the operational diversity revealed by independent experimental data on different Danube vessels.

*Sources:* Tarasenko et al., J. Phys. Conf. Ser. 1297 (2019) · Varbanets et al., Двигуни внутрішнього згоряння 2(2021) · Varbanets et al., Polish Maritime Research, 31(3) (2024)

# Summary and outlook for cooperation

## Methodological contributions

- Integrated EE assessment for self-propelled vessels with caravans
- Three-level index system with graceful data degradation
- Probabilistic extension via Monte Carlo simulation
- Forecasting block based on AR(1) and spatial correlations
- Empirical calibration on 16-year DC database (265,798 records)

## Cooperation perspective

This methodology is offered to the Working Group as a contribution to the common toolkit for Danube navigation efficiency assessment.

We welcome dialogue with member-state delegations on:

- Adapting the framework to specific national fleet configurations;
- Joint validation on rich, multi-operator datasets;
- Alignment with the Roadmap and Attachment 5 of the Danube Commission.

# Thank you for your attention

*Дякую за увагу*

**Open for questions and discussion**

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