Site selection for small hydropower plant based on resources time footprint

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Source: Huang Xiaoxun, Kiichiro Hayashi, Minoru Fujii, Ferdinando Villa, Yuri Yamazaki, and Hiromu Okazawa. (2023). Identification of potential locations for small hydropower plant based on resources time footprint: A case study in Dan River Basin, China. *Renewable Energy*, *205*, 293–304. https://doi.org/10.1016/j.renene.2023.01.079

Resources Time Footprint (RTF) Fujii et al. (2014)

- Labor force
- Ratio between resource occupancy and allocated capacity

- Material use
- Energy consumption
- Environmental impacts
- Lifespan
- ……

Life cycle assessment (LCA) (Finnveden et al., 2009)

- Productive surface areas
- ……

Ecological Footprint (EF) (Global Footprint Network, n.d.)

- Metal stocks
- Metal flows
- ……

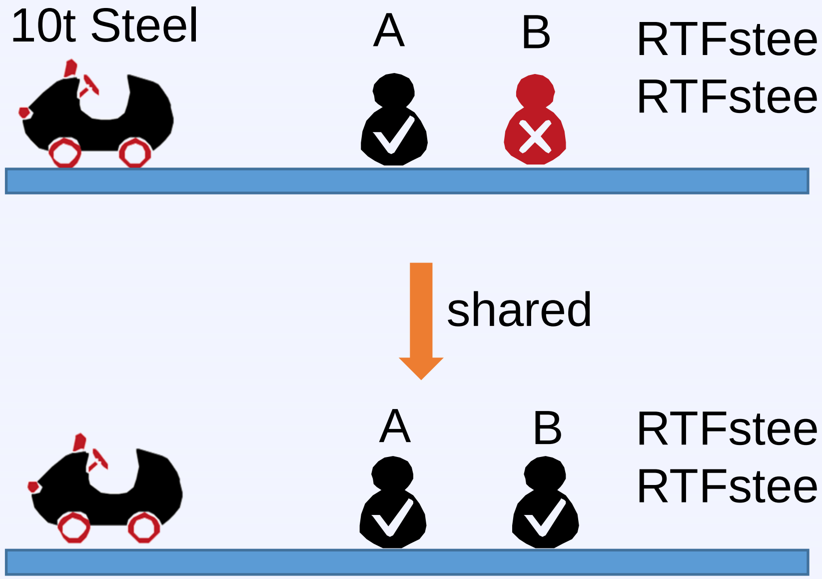
Material flow analysis (MFA) (Graedel et al., 2004)

Resources Time Footprint (RTF)

General equation:

$$RTF = \frac{OA \times OT}{TA}$$

OA: amount of resources occupied by an individual
OT: period of resource occupancy (years), usually set to be **100** years (close to the lifespan of human)
TA: total capacity of a resource (allocated amount to an individual)



RTFsteel of A: 200
RTFsteel of B: 0

RTFsteel of A: 100
RTFsteel of B: 100

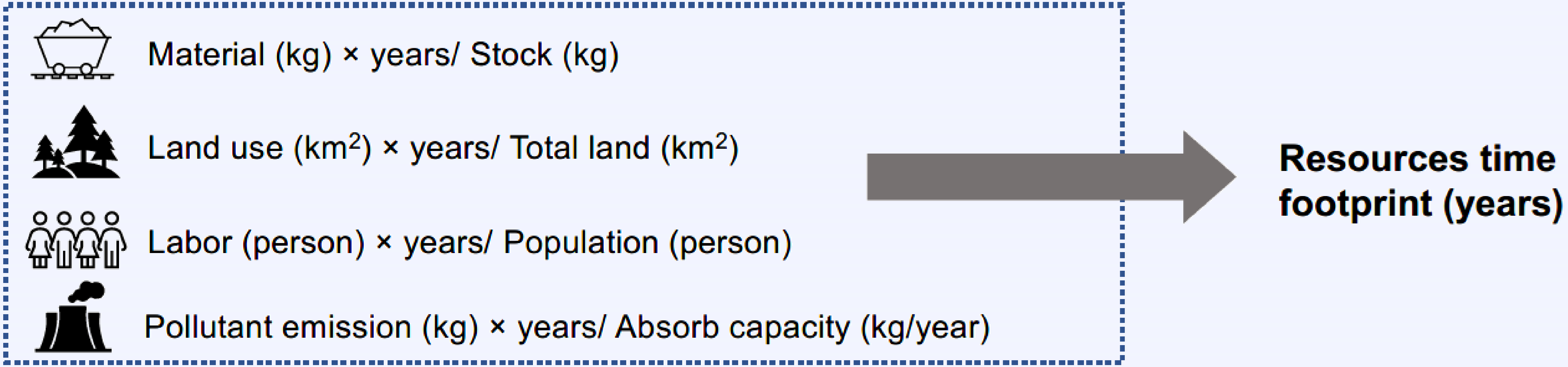
OA: diamond **<** steel

TA: steel **>>** diamond

RTF: diamond **>** steel

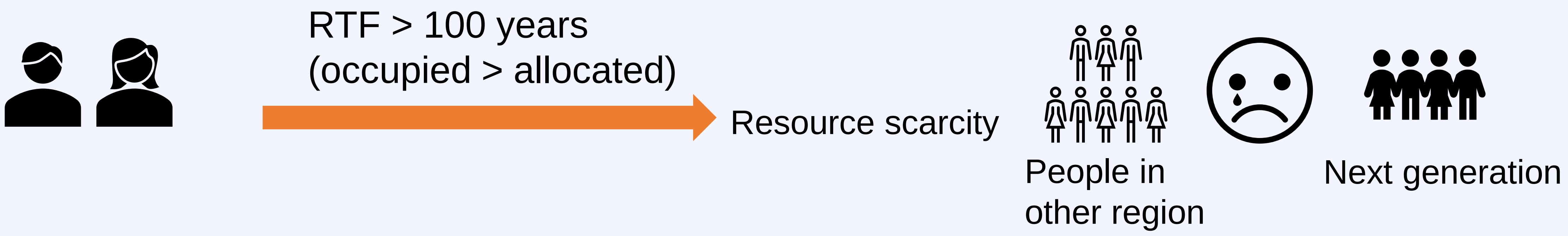
Scarcity of material can be described

Resources Time Footprint (RTF)



- Whether the usage of each resource **exceed** its **capacity**
- When RTF is **smaller**, fewer resources are used or less pollution is emitted, the process is more **sustainable**.

Resources Time Footprint (RTF)



- ➢ Considers not only consumption but also the **resource availability** on Earth
- ➢ Resource **equality** among individuals and generations
- ➢ Mostly utilized to compare production processes, and different practices of forest management.
- ➢ Our study is the first to apply it to a site selection as a **spatial assessment.**

Background

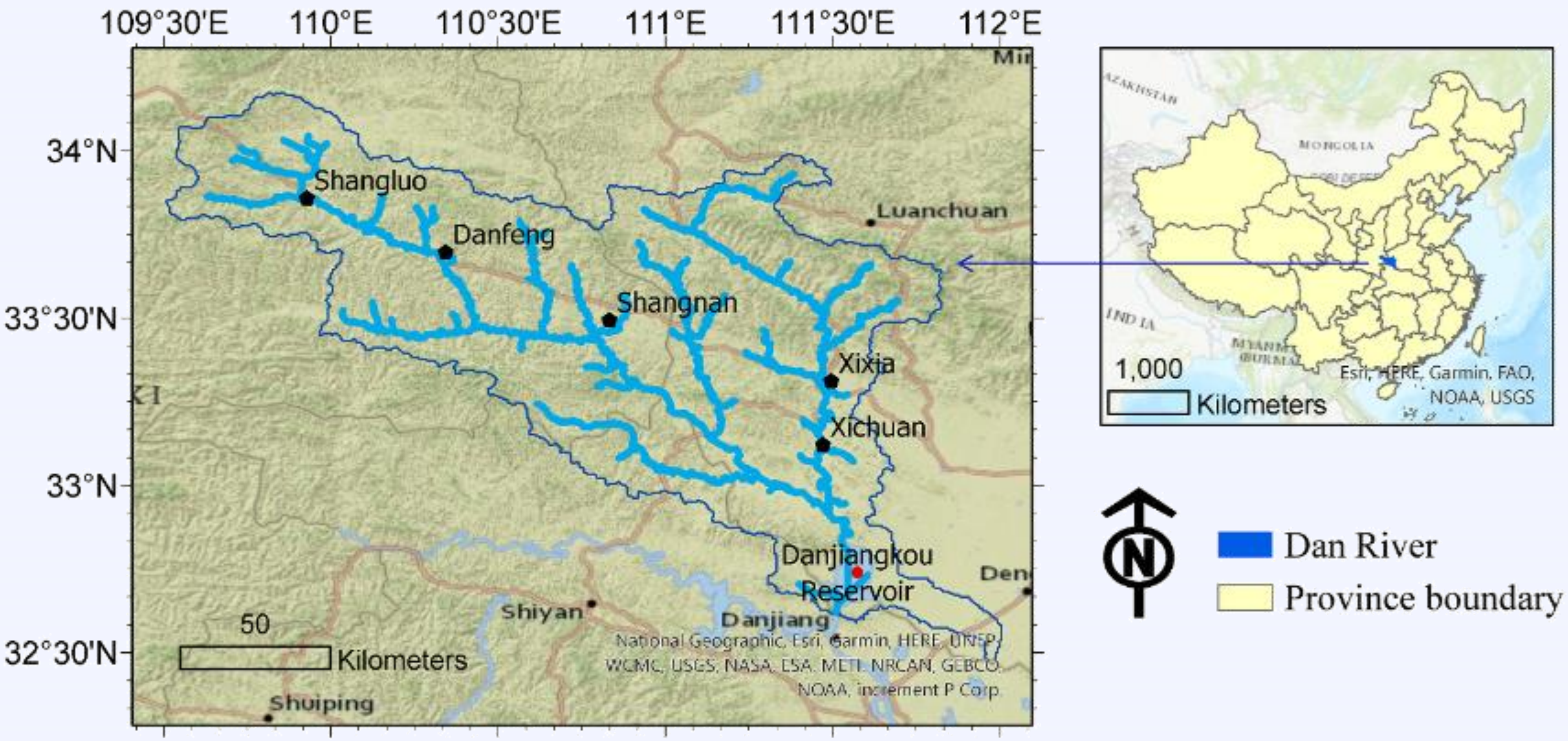
- Many countries are exploring renewable energy sources
- Global potential of hydropower is 9.49 PW h per year, of which 39% is located in the Asia Pacific region (Gernaat et al., 2017)
- People are skeptical about building new large dams
- **Small hydropower (SHP):** clean, mature, and cost-effective conversion technology with little or no storage facility
- Preferred energy source in rural and mountainous areas
- Capacity: not exceeding **10** MW

Background

- No fossil fuel cost during regular operation
- **Initial investment** is required: construction materials, electricity generation equipment, and transportation costs
- Systematic assessment is required
- **Construction** stage is the largest contributor to environmental impact
- LCA studies primarily focus on flows of material and energy, rarely consider resource stock.

Objective

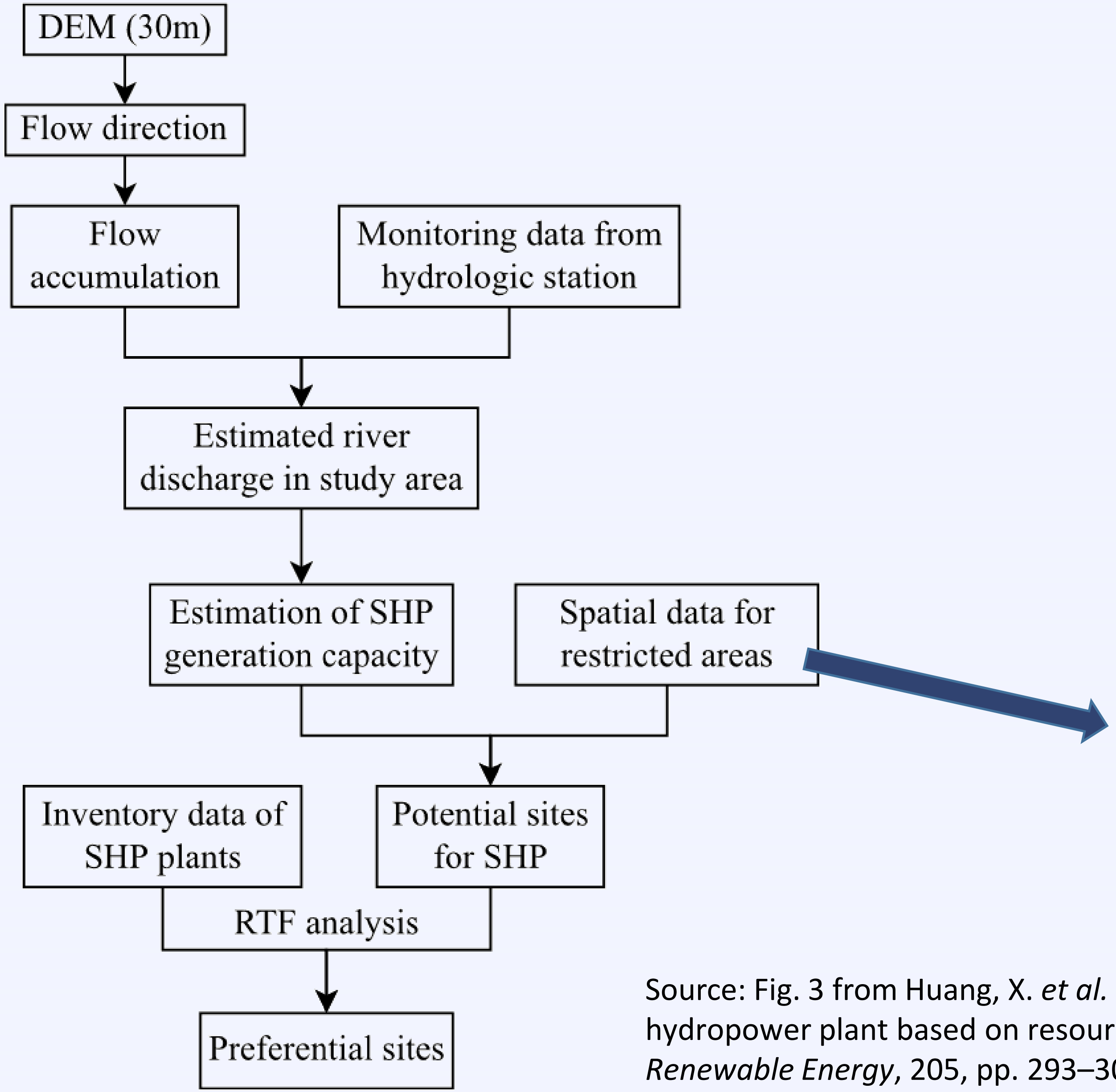
➢ Evaluate spatial variation of **environmental impact** of potential SHP plants through **RTF**, and to develop a framework for the **site selection** of future plants.



- Drainage area: 16,812 km^2
- Length: 287 km
- Hilly and have dense vegetation

Source: Fig. 2 from Huang, X. *et al.* (2023) 'Identification of potential locations for small hydropower plant based on resources time footprint: A case study in Dan River Basin, China', *Renewable Energy*, 205, pp. 293–304. https://doi.org/10.1016/j.renene.2023.01.079

Research flow of RTF analysis of potential SHP plants



$$IC_i = 9.8 \times Q_i \times H_e \times \eta$$

IC_i: SHP generation capacity (kW)

Q_i: flowrate (m^3/s),

H_e: the effective head (m), set to 5 m

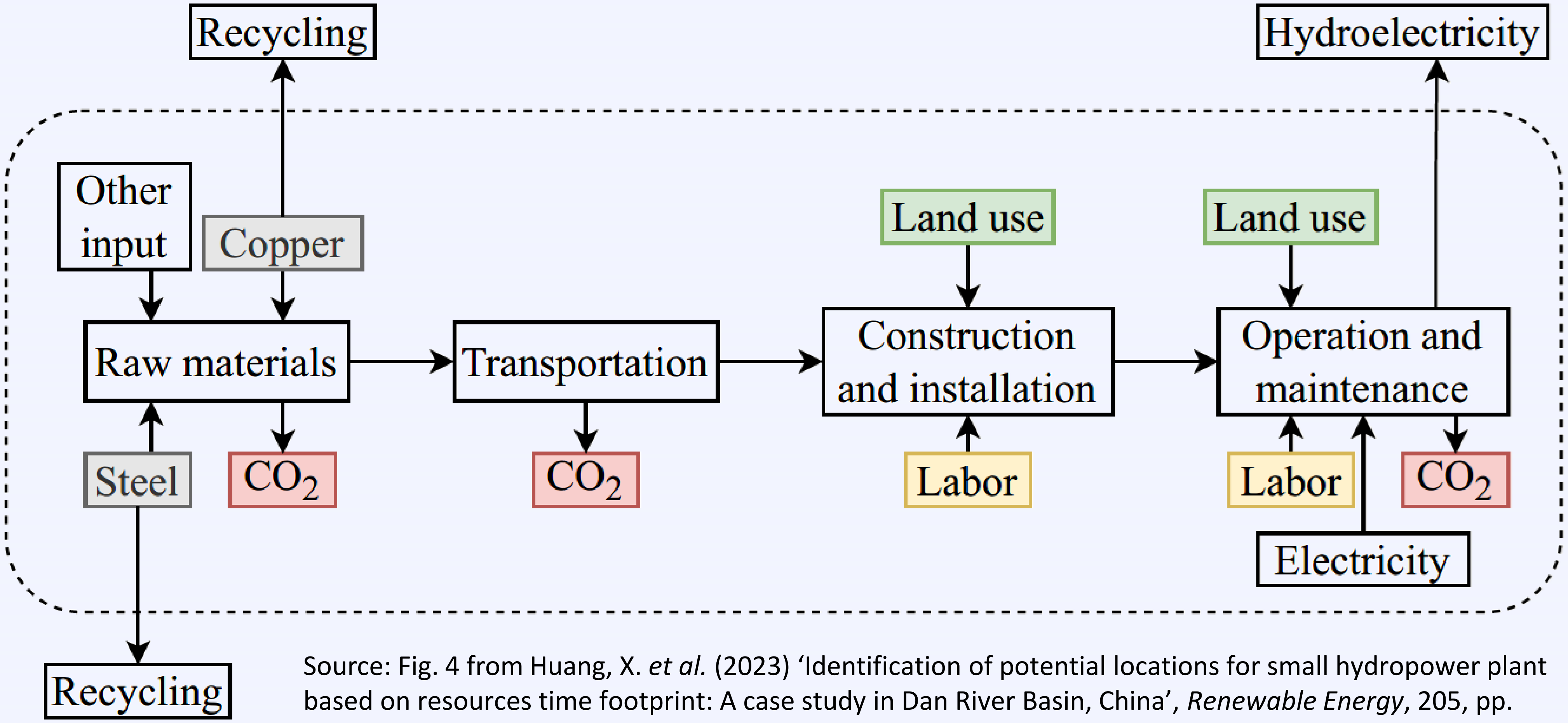
η: total efficiency, set to 0.8

Soil-erodible areas, landslide susceptible areas, protected areas, and key biodiversity areas

Source: Fig. 3 from Huang, X. *et al.* (2023) 'Identification of potential locations for small hydropower plant based on resources time footprint: A case study in Dan River Basin, China', *Renewable Energy*, 205, pp. 293–304. https://doi.org/10.1016/j.renene.2023.01.079

System boundary for RTF analysis on the power generation by the operation of SHP plant for 100 years

- The RTF value calculated in the case study was ΔRTF
- If RTF = **0** is current resource utilization (**BAU** scenario), ΔRTF<0 means positive effect on the environment



Source: Fig. 4 from Huang, X. *et al.* (2023) 'Identification of potential locations for small hydropower plant based on resources time footprint: A case study in Dan River Basin, China', *Renewable Energy*, 205, pp. 293–304. https://doi.org/10.1016/j.renene.2023.01.079

RTF calculation

- Calculated on a **per-capita** basis
- **Beneficiary**: number of people who can utilize the electricity generated by the SHP plant to meet the annual electricity demand.

$$P_i = IC_i \times \frac{APH}{EC}$$

P_i: Population of beneficiary
IC_i :installed capacity of the *i*th potential SHP plant
APH: annual operating hours of the SHP plant, 3491 h
EC: annual electricity consumption in China

$$\mathrm{RTF_{steel}} = \frac{(S_{c,i} + S_{e,i}) \times T/P_i}{SR_w + SD_w/P_w}$$

$(S_{c,i} + S_{e,i}) \times T/P_i$ → occupancy of steel per capita during 100 years

$SR_w + SD_w/P_w$ → present capacity of steel allocated per person

$$\mathrm{RTF_{copper}} = \frac{CO_i \times T/P_i}{CR_w + CD_w/P_w}$$

$CO_i \times T/P_i$ → occupancy of copper per capita during 100 years

$CR_w + CD_w/P_w$ → present capacity of copper allocated per person

RTF of CO_2

Emissions from production of raw materials

Emissions from transportation

$$RTF_{CO_2} = \frac{\left[S_{c,i} \times CI_s + \left(S_{e,i} \times CI_s + CO_i \times CI_{co}\right) \times 4 + CE_i \times CI_{ce} + CET_i + \left(CI_{hp} - CI_{tp}\right) \times APH \times IC_i \times T\right] / P_i}{CU / P_w}$$

Nature's capacity to absorb CO_2

Reduced emissions compared to coal power plant

- During the 100 years, materials for hydro-equipment would be replaced 3 times.
- Replacement steel and copper were made from secondary (recycled) metals, and those for new installations were from primary sources.

RTF of labor

Labor force for plant and road construction

Labor force for operation

$$\mathrm{RTF}_{\mathrm{labor}} = \frac{\frac{WH_r \times ARC_i + WH_p \times VC_i}{2000} + WO_i \times T}{PWP_c \times P_i}$$

Working-age population among beneficiaries

- Annual working hours in China: 2000

RTF of land

$$RTF_{land} = \frac{\left[AT_i \times \frac{1+0.4}{2} \times 40 + LRE_i + (ARC_i + AP) \times 1 \times T\right] / P_i}{\sum_{x=1}^{5} \frac{y \times TA_x}{P_d}}$$

Timber use (AT_i)

Takes 40 years for the land to transform back to artificial forest ($\frac{1+0.4}{2} \times 40$)

Prevented area of land for solar power and biomass to generate the same amount of electricity (LRE_i)

Occupied area by road and plant for 100 years ($(ARC_i + AP) \times 1 \times T$)

Naturalness and occupancy level of each land cover type in the provinces of Shaanxi, Henan, and Hubei in China.

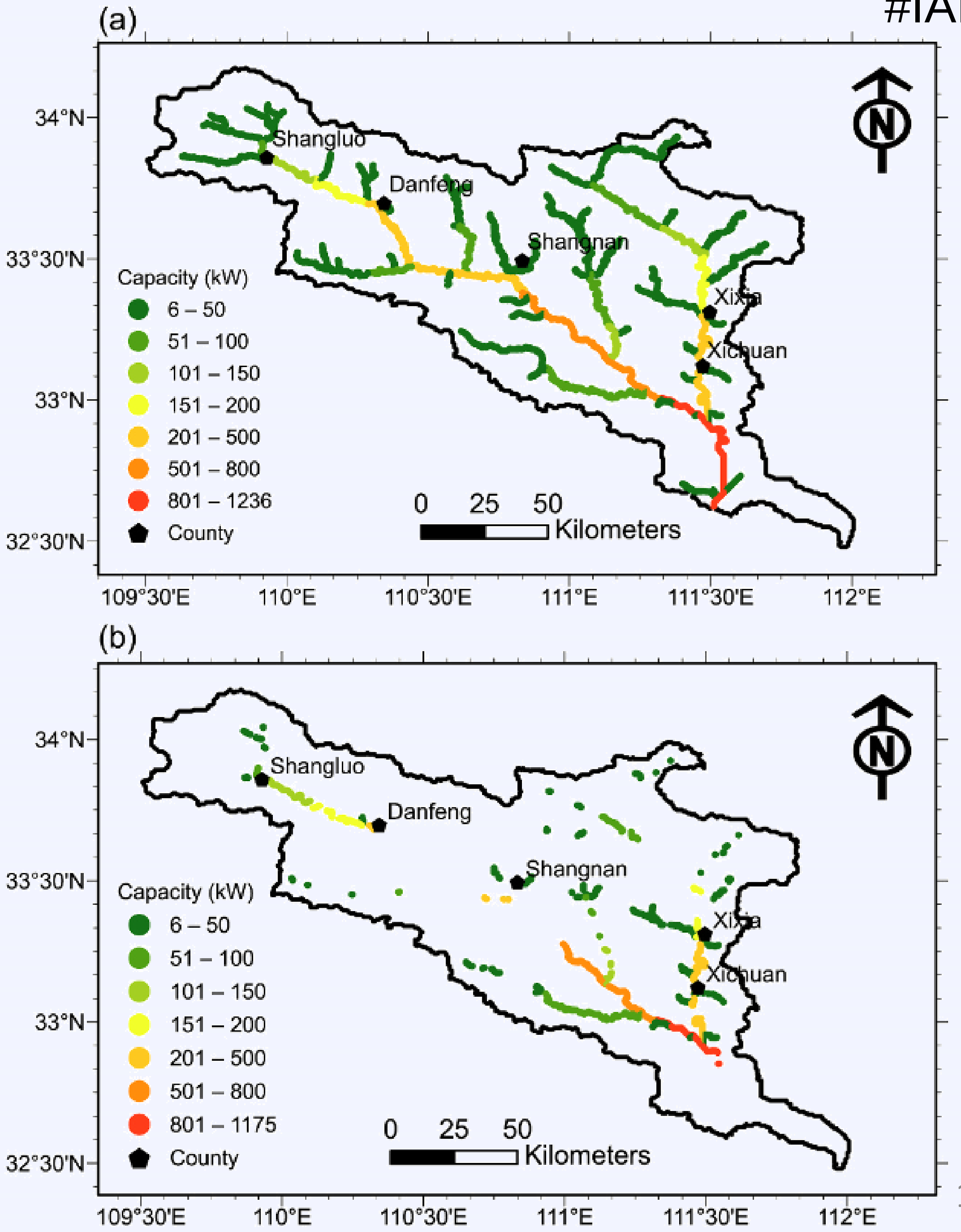
Land Cover Type	Naturalness[a]	Occupancy level[a]	Total Area (km^2)[b]
Natural Forest	9	0	140,389
Natural grassland	10	0	6812
Artificial forest, shrub	6	0.4	96,838
Artificial grassland	5	0.5	61,714
Cultivated and managed vegetation/agriculture (cropland)	2	0.6	205,344
Urban/built up	1	1.0	32,342

[a]: values were cited from N. Kawaguchi, K. Hayashi, M. Fujii, Assessing the sustainability of urban forest management using the resources time footprint analysis, J. Human Environ. Symb. 36 (1) (2020) 53–64

Results

(a) Potential capacity from the waterway in the Dan River Basin (unit: kW)

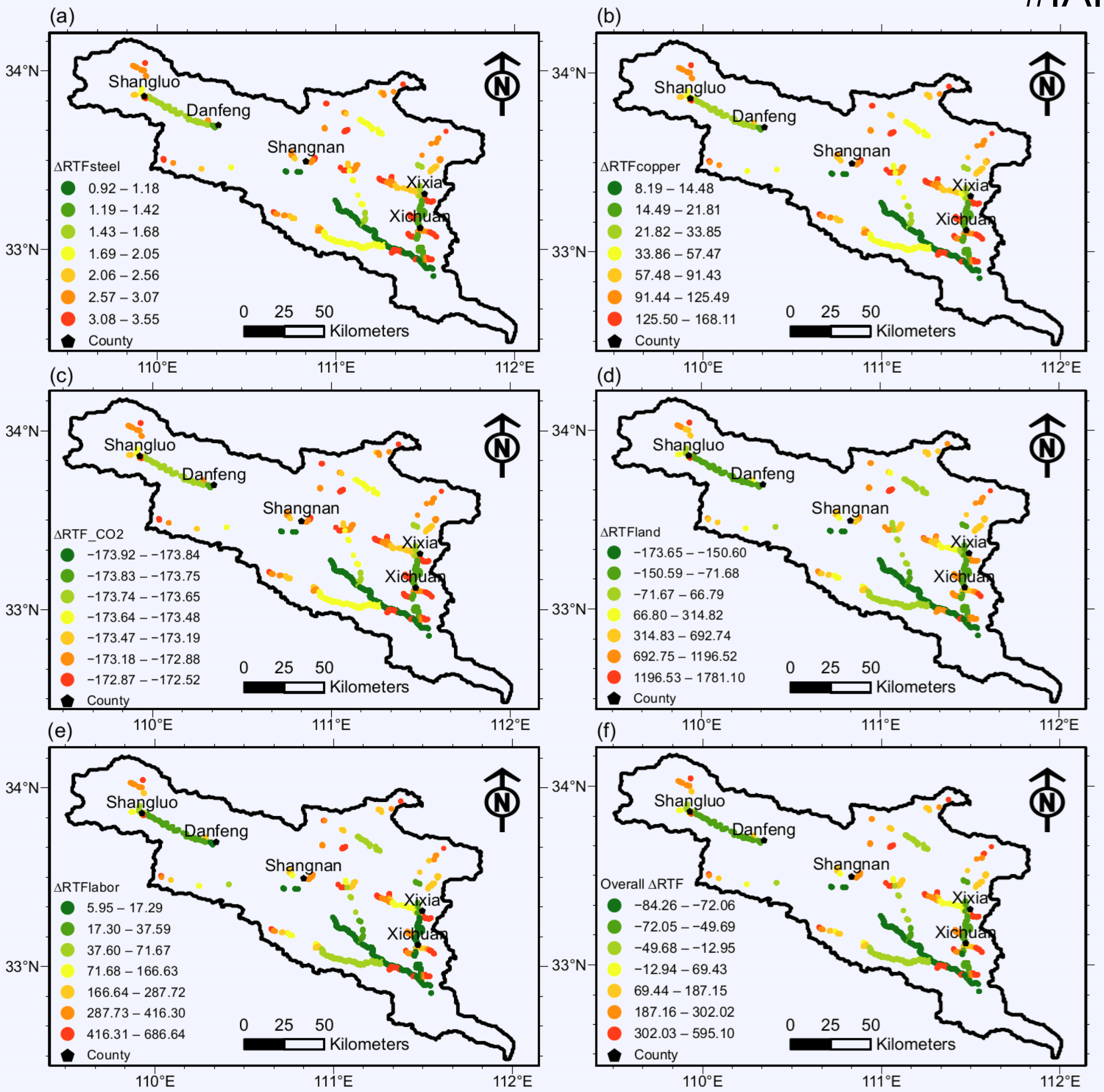
(b) Potential installed capacity of possible sites of SHP plants in the Dan River Basin after excluding **protected areas, key biodiversity areas, landslide-susceptible areas**, and **soil-erodible areas** (unit: kW).



Source: Fig. 5 from Huang, X. *et al.* (2023) 'Identification of potential locations for small hydropower plant based on resources time footprint: A case study in Dan River Basin, China', *Renewable Energy*, 205, pp. 293–304. https://doi.org/10.1016/j.renene.2023.01.079

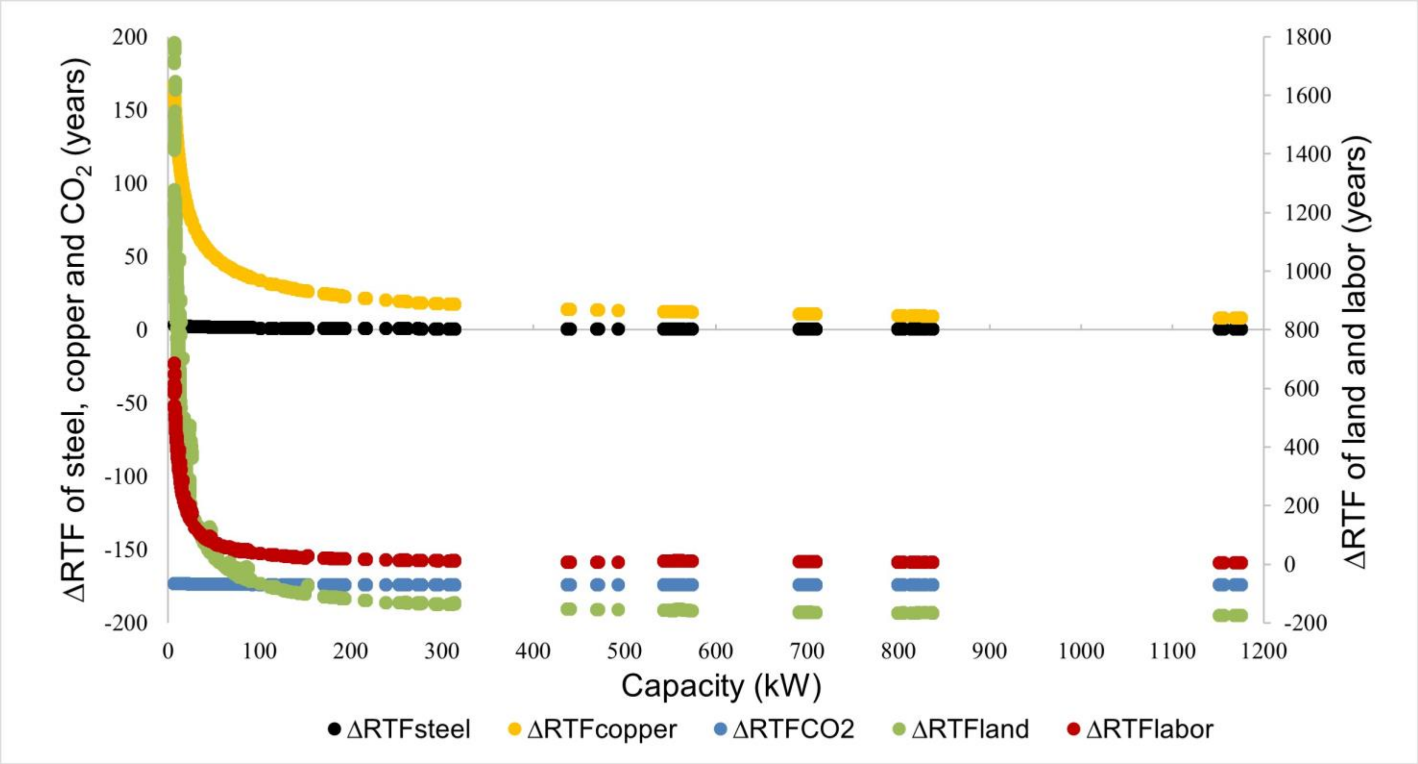
Spatial variation of RTF

- When **installed capacity** is **larger**, the ΔRTF of material is **smaller**.
- ΔRTF of CO_2 emissions is **negative**
- For 60% of sites, the potential to reduce prospective land use could compensate for land occupancy
- ΔRTF of labor is much larger when installed capacity is small, due to the small number of beneficiaries.
- Overall ΔRTF is calculated as the **average** of four aspects.



Source: Fig. 6 from Huang, X. *et al.* (2023) 'Identification of potential locations for small hydropower plant based on resources time footprint: A case study in Dan River Basin, China', *Renewable Energy*, 205, pp. 293–304. https://doi.org/10.1016/j.renene.2023.01.079

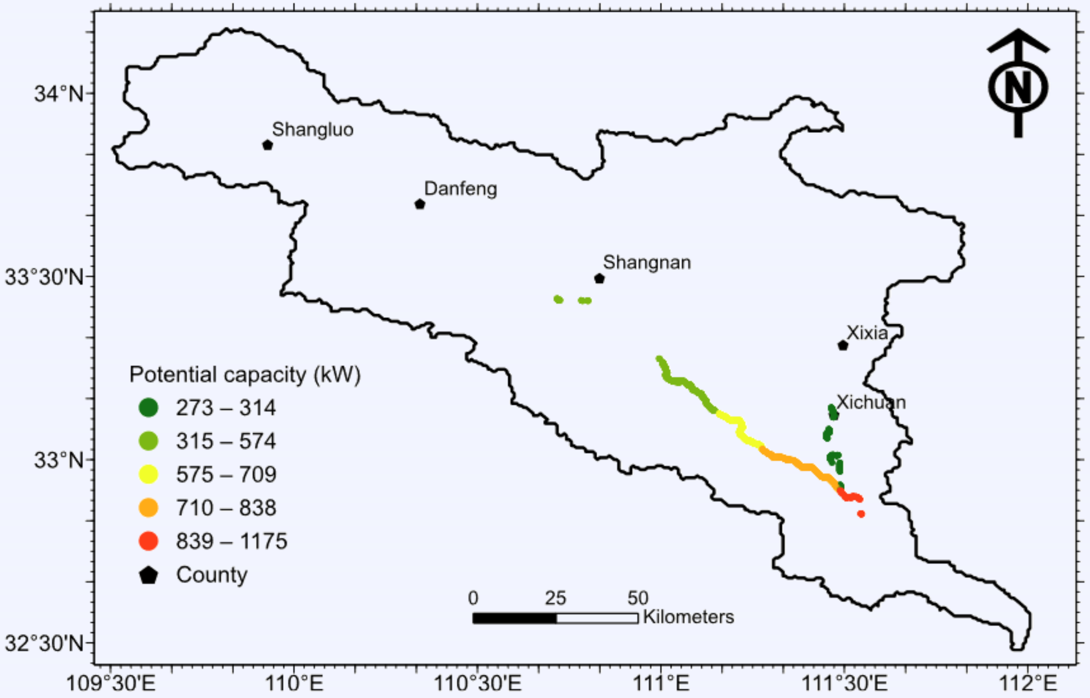
Relationship between RTF and installed capacity



Source: Fig. 7 from Huang, X. *et al.* (2023) 'Identification of potential locations for small hydropower plant based on resources time footprint: A case study in Dan River Basin, China', *Renewable Energy*, 205, pp. 293–304. https://doi.org/10.1016/j.renene.2023.01.079

- The capacity of SHP plants to reduce CO_2 emissions and prevent future land use is overwhelming compared to the material and labor inputs.
- Although some site-specific factors are included in the analysis, the trend of ΔRTF is determined by **installed capacity**.
- When installed capacity **increased**, overall ΔRTF is **smaller**.

Preferential sites of SHP plants



Source: Fig. 8 from Huang, X. *et al.* (2023) 'Identification of potential locations for small hydropower plant based on resources time footprint: A case study in Dan River Basin, China', *Renewable Energy*, 205, pp. 293–304. https://doi.org/10.1016/j.renene.2023.01.079

- The top 25% of the 11,086 potential SHP plants in the Dan River as sorted by ascending overall ΔRTF values.
- Contribute to sustainability the most among all potential sites

Discussion

- Only considers CO_2 as a pollutant, but the RTF can also be used to assess other pollutants.
- Not consider the impact on aquatic habitat because run-of-river SHP scheme is more eco-friendly than the diversion weir and the pondage hydropower plants.
- Verified the capability of RTF to rank potential locations for SHP plants.
- **Preferential areas** can be identified intuitively on the map by **smaller RTF**
- **Multidimensional** aspects can be weighted based on priority
- Site selection of other renewable energies can be analyzed using RTF to find optimal energy mix.

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