Run-of-river power plants in Alpine regions: whither optimal design?

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UNIVERSITÀ DEGLI STUDI DI PADOVA

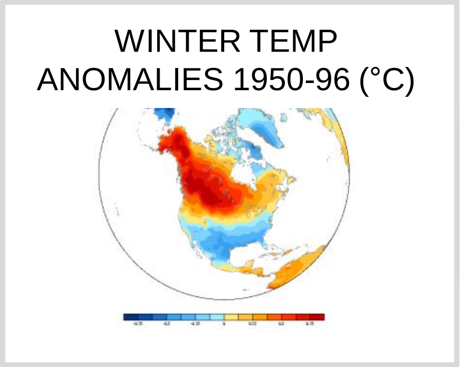
FLOW REGIME at the plant intake

- **Surface water resources** at the plant intake are the byproduct of complex processes with strong stochastic components…

INTRA-SEASONAL
(stochastic rainfall)

INTER-SEASONAL
(seasonality of climate)

INTER-ANNUAL
(long-term variations of climate/landscape)

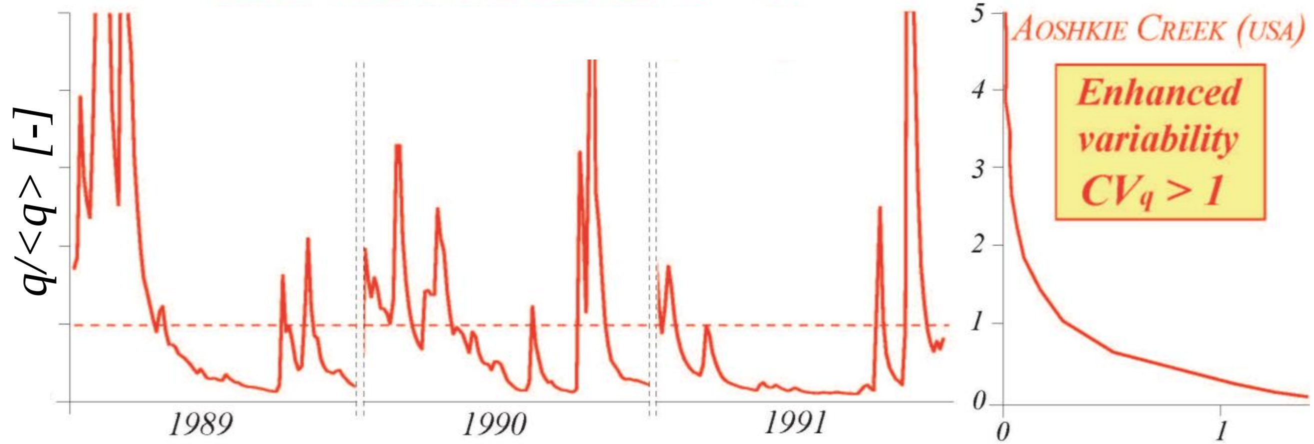


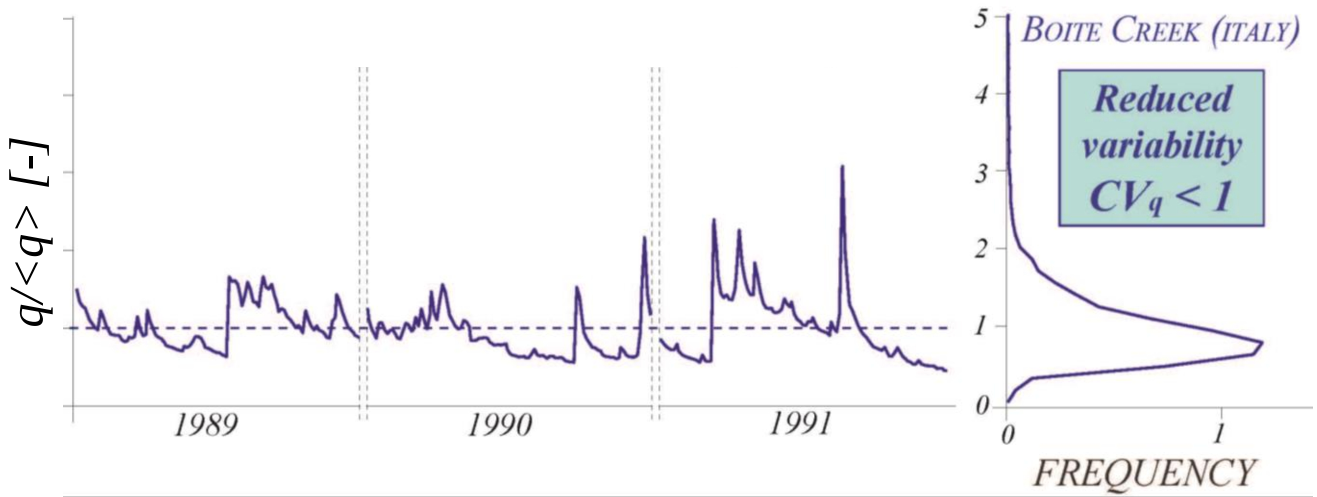
- Characterization of flow regimes in the **absence of flow data**

SEASONAL/ANNUAL FLOW REGIMES: classification

ERRATIC regimes

Monotonic streamflow pdf
Enhanced variability (CV>1)



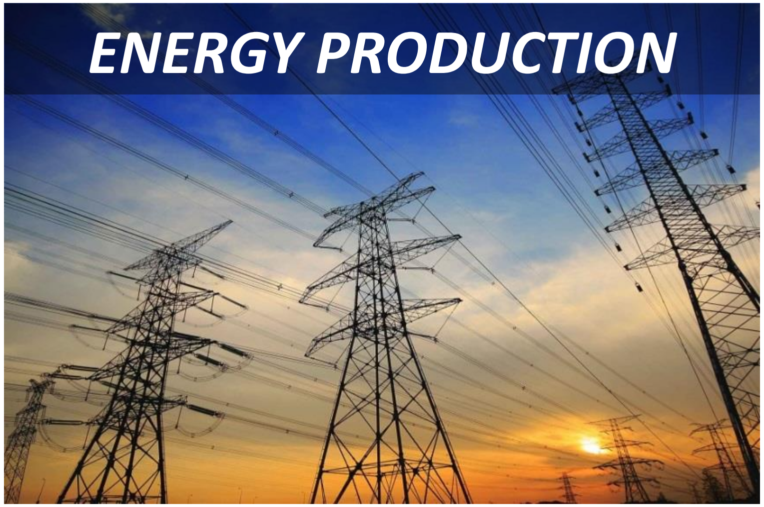


PERSISTENT regimes

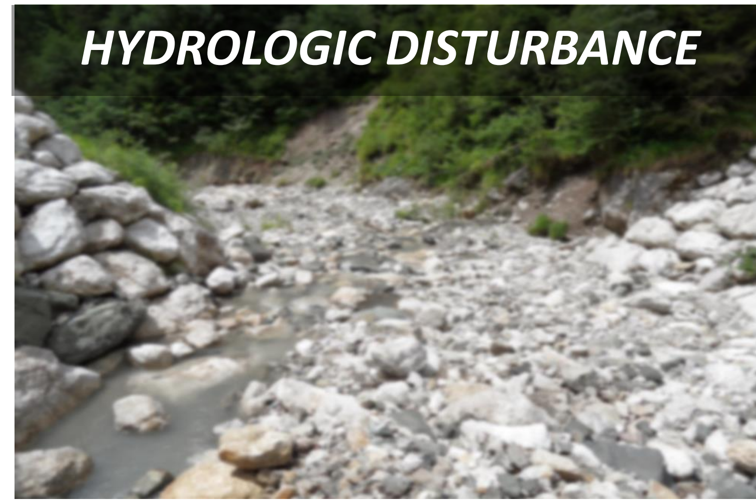
Bell-shaped streamflow pdf
Reduced variability (CV<1)

[Botter et al., PNAS 2013]

Influence of the FLOW REGIME on…



Whither OPTIMAL DESIGN?



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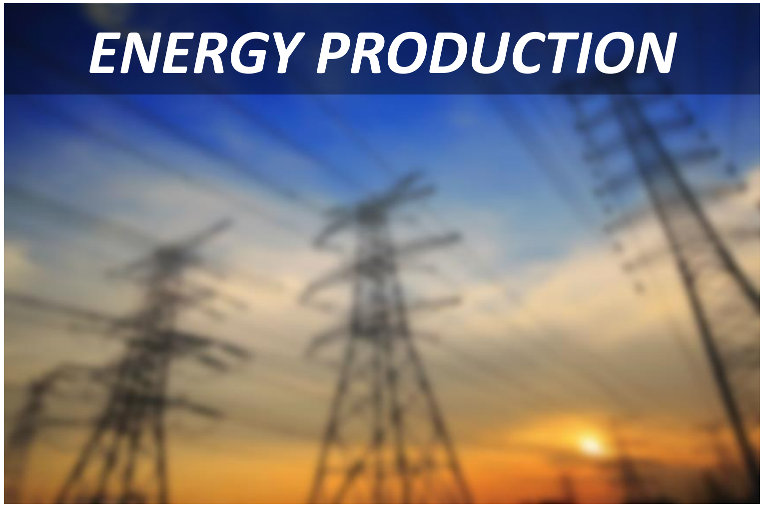

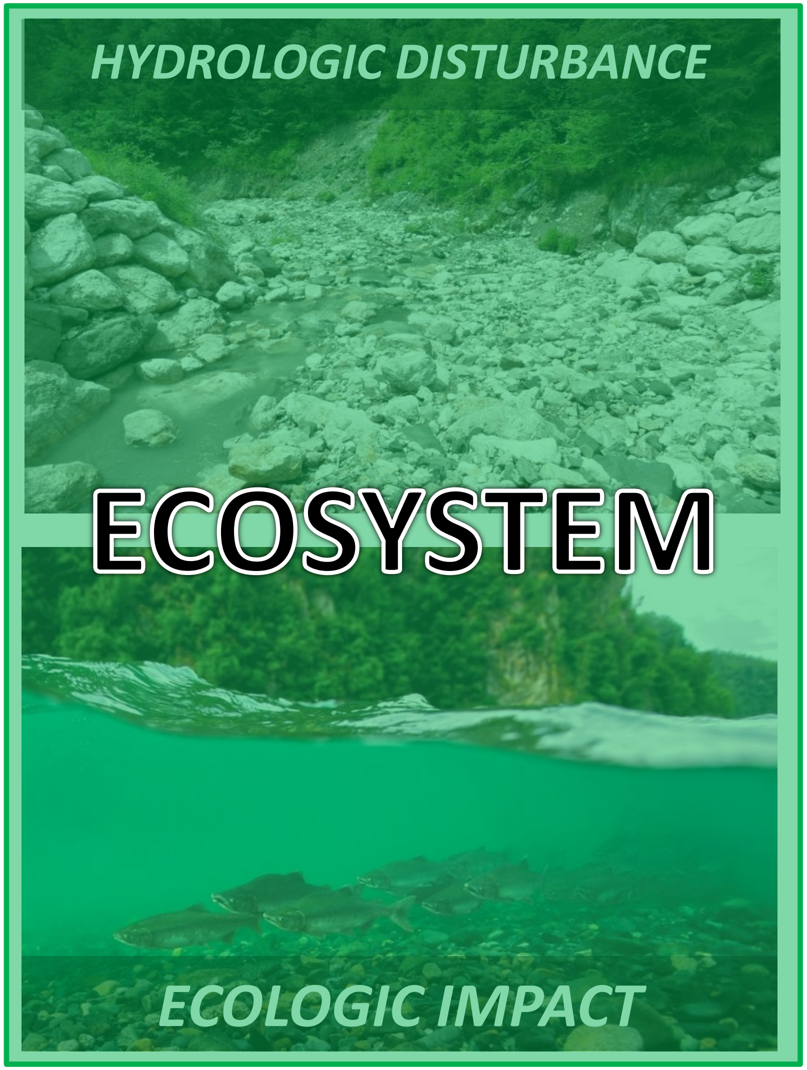

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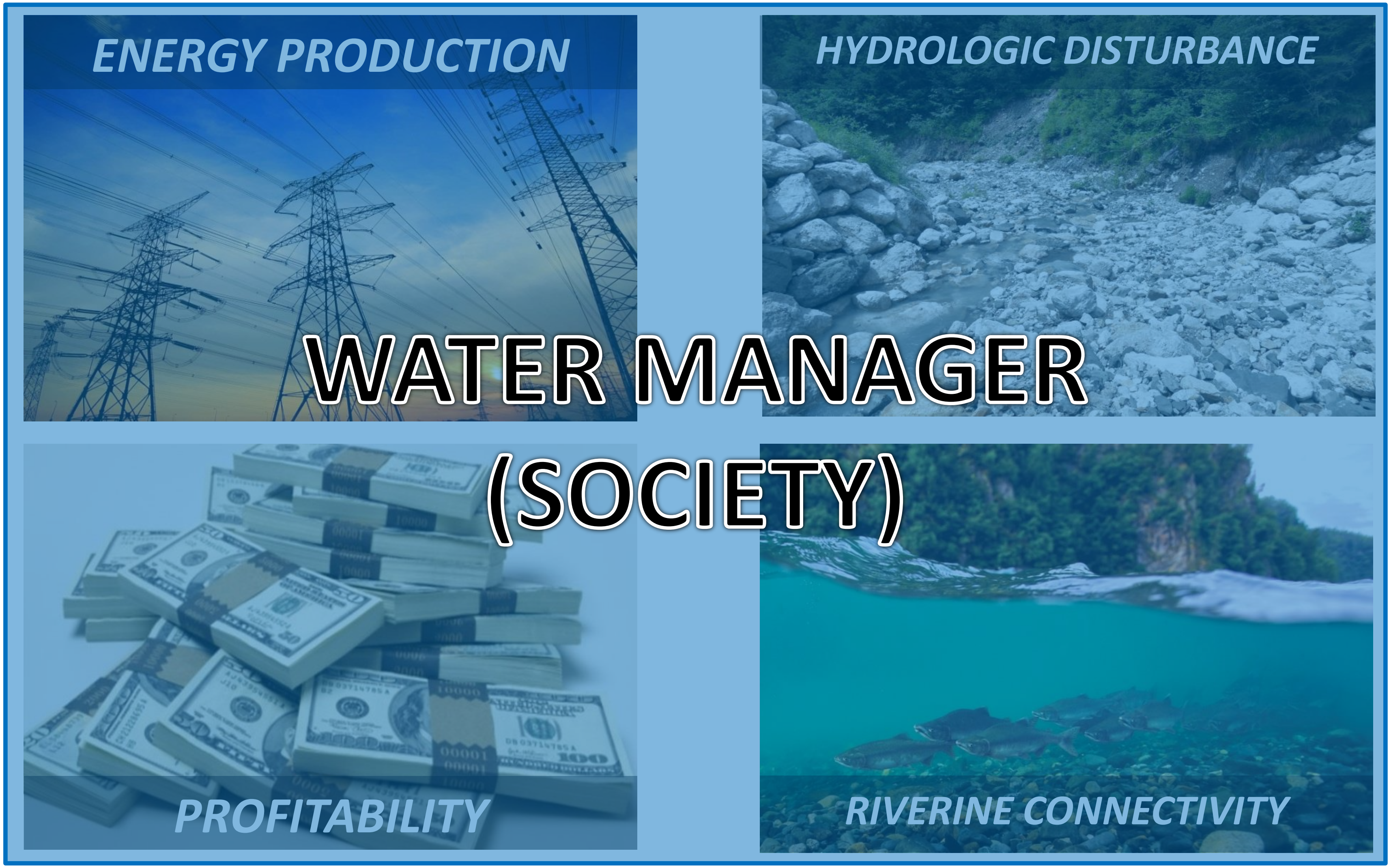


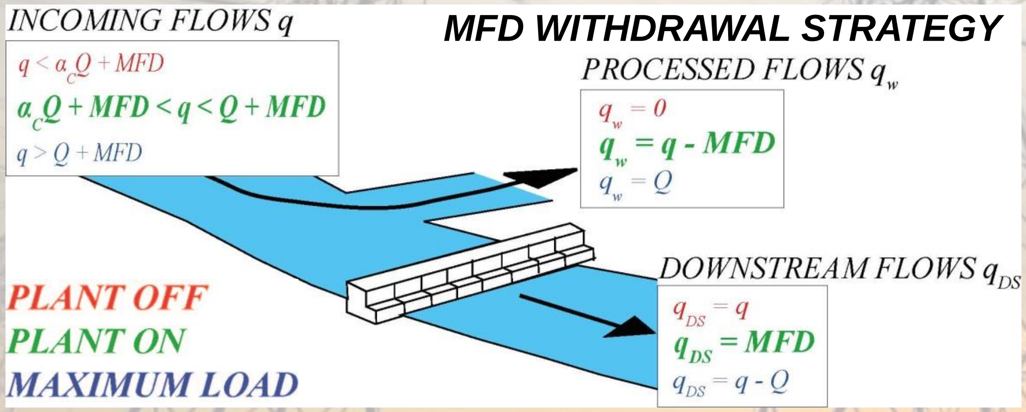
INVESTOR: ENERGY PRODUCTION

ENERGY PRODUCTION (E) *and PROFITABILITY (NPV) of run-of-river plants depend on the* ***pdf of available streamflows****:*

$$E(Q) = \Delta T \; H \; \rho g \int_0^\infty \eta \left(\frac{q_w}{Q} \right) \; p_w(q_w) \, q_w \, dq_w$$

[Basso and Botter, WRR 2012]

ρ = water density
g = gravitational acceleration
η = turbine efficiency
H = hydraulic head
ΔT = plant lifetime
q_w = worked flow



Explicit analytical link among:
Q -> plant capacity
E -> energy production
$p_w(q_w)$ -> pdf of flows worked by the plant

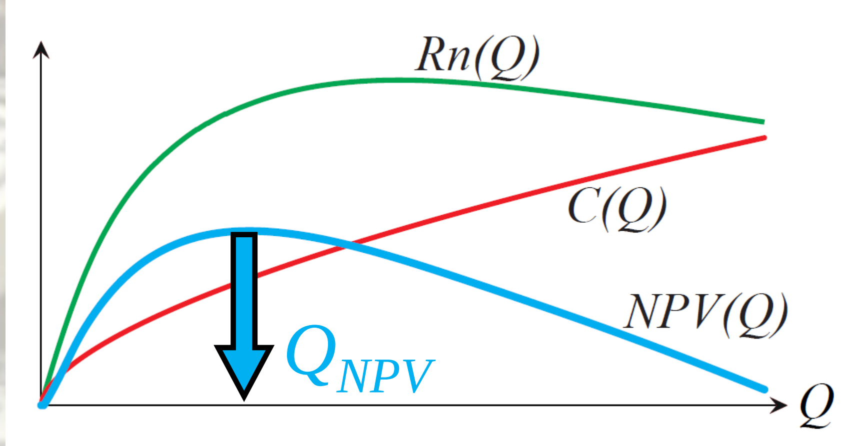
INVESTOR: PROFITABILITY

*ENERGY PRODUCTION (E) and **PROFITABILITY (NPV)** of run-of-river plants depend on the **pdf of available streamflows**:*

$$Rn = e_P \cdot E$$

Rn = revenues
e_P = energy price
E = energy produced depends on:

- *plant capacity (Q)*
- *pdf of available streamflows*



$$NPV(Q) = Rn(Q) - C(Q)$$

[Basso and Botter, WRR 2012]

*The **Net Present Value (NPV)** is the **sum of every cash flow** discounted back to its present value*

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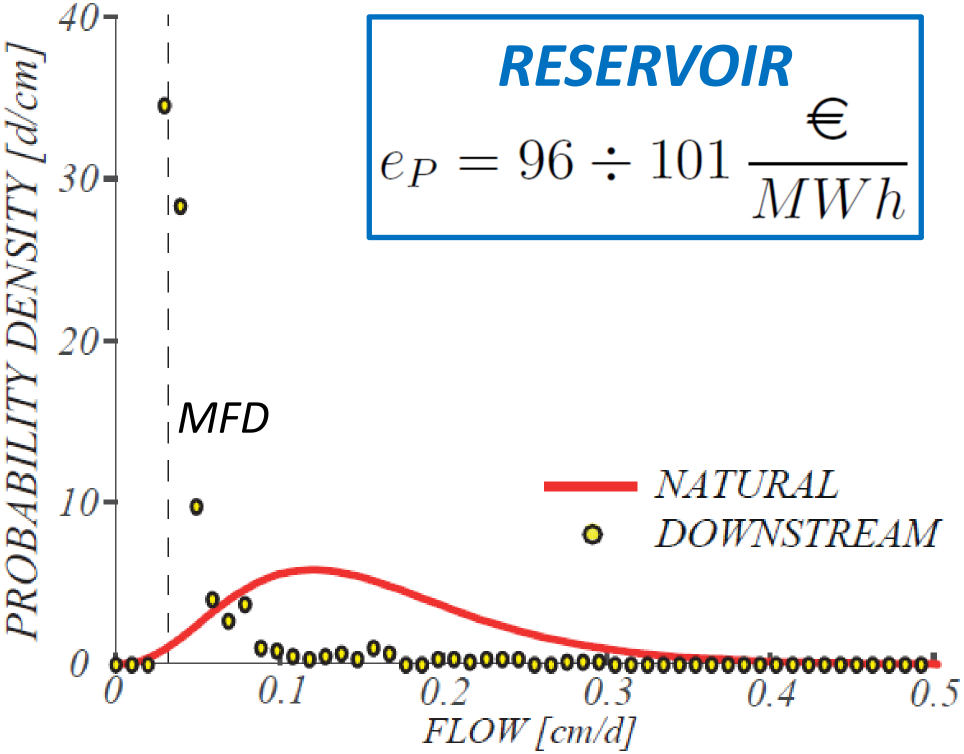
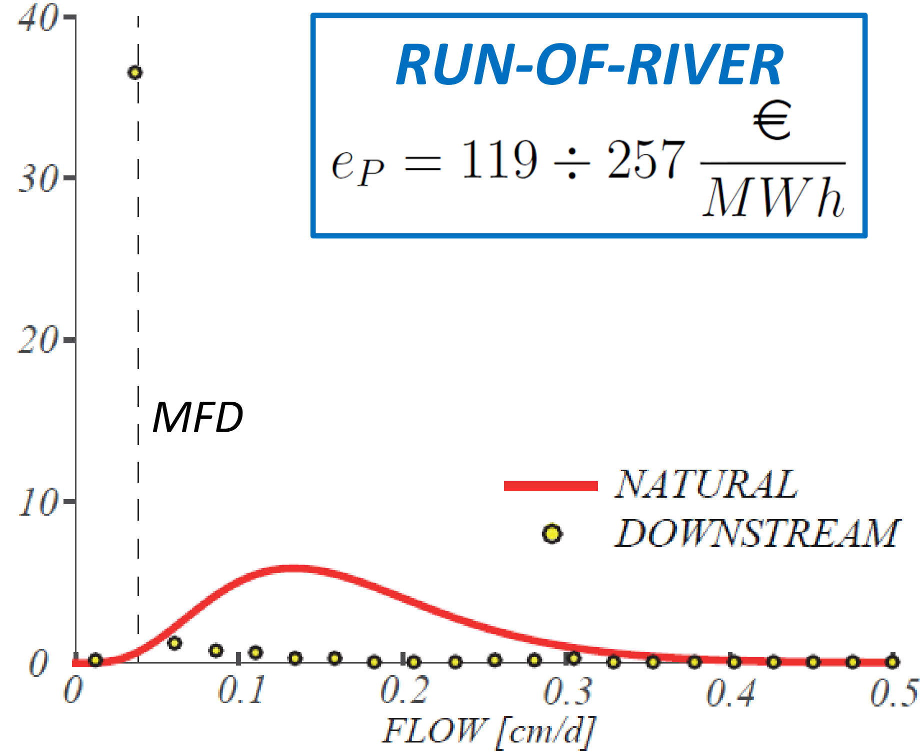
ECOSYSTEM

RUN-OF-RIVER *power plants induce an* ***impact on flow regimes*** *which is* ***similar*** *to that produced by* ***DAMS***



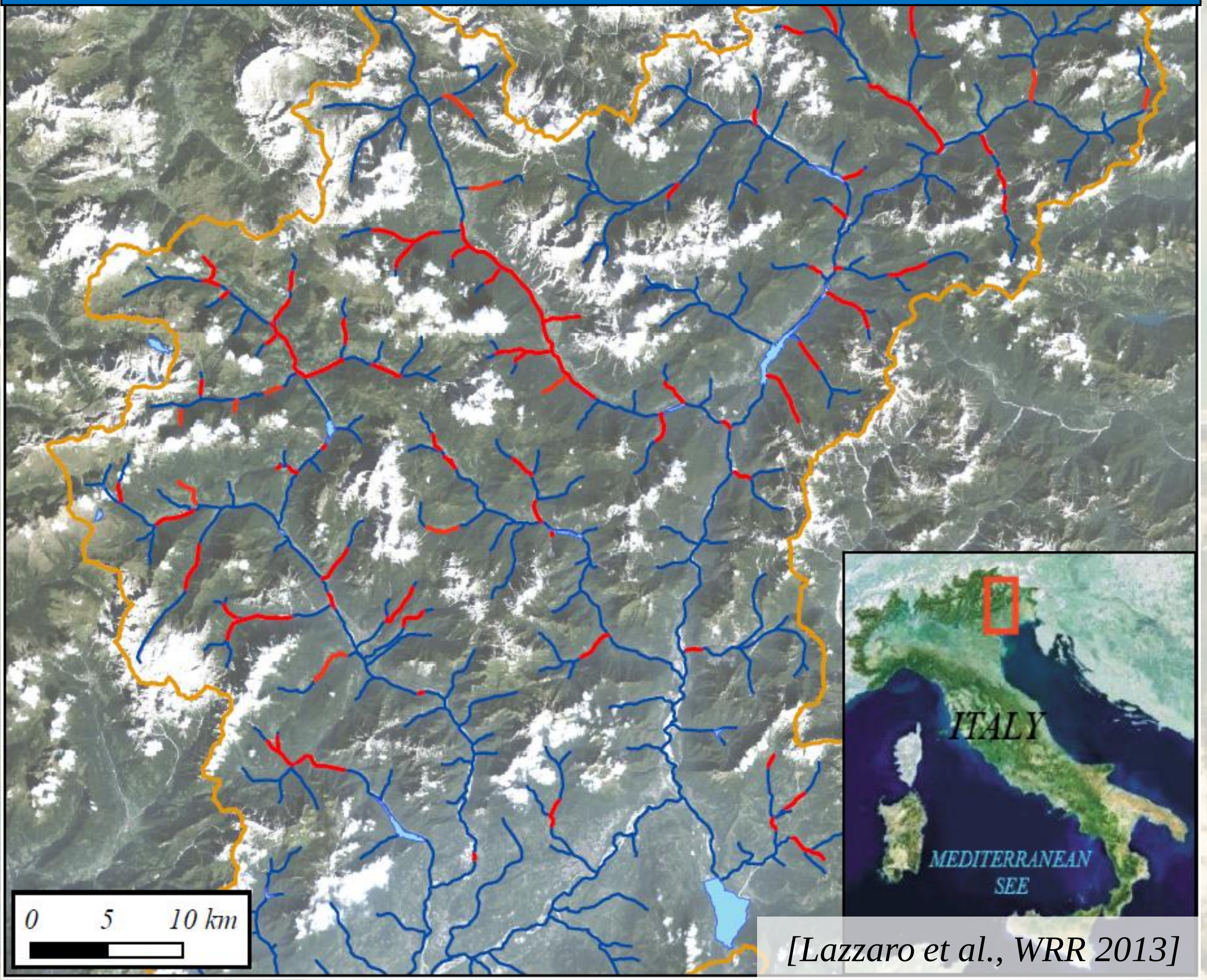


Cordevole River
(700 km^2, regulated by ***3 reservoirs****)*

Valfredda Creek
(5 km^2, run-of-river power plant)

ECOSYSTEM

Overall **150 km** of river network impacted by run-of-river plants (**Piave river** basin, Italy)



[Lazzaro et al., WRR 2013]

Small run-of-river power plants built **in cascade** along the same river result in **NEGATIVE CUMULATIVE EFFECTS**

Loss of **connectivity**

Mean length of **impacted reaches** : **2 km**

ECOSYSTEM

Run-of-river impact *has been evaluated through the* ***upstream/downstream changes*** *of a set of* ***hydrologic indexes:***

HYDROLOGIC INDEX	→	***ECOLOGIC IMPLICATIONS***
MEAN DISCHARGE (μ)	Available water resources	**Ecosystem Size, Carrying Capacity**
COEFFICIENT OF VARIATION (CV)	Intra-seasonal flow variability	**Bed Revitalization, Interactions with Riparian Areas, Habitat Heterogeneity**
CORRELATION SCALE (I)	Short-term rate of change	**Short-term Adaptation Strategies (Behavioral)**
REGIME INSTABILITY (RI)	Inter-annual flow variability	**Long-term Adaptation Strategies (Life-history and Morphological)**

ECOSYSTEM

*The **HYDROLOGIC DISTURBANCE (D_H)** is the sum of the upstream/downstream relative variation of hydrologic indexes*

$$D_H(Q) = \frac{|\mu_{up} - \mu_{ds}(Q)|}{\mu_{up}} + \frac{|CV_{up} - CV_{ds}(Q)|}{CV_{up}} + \frac{|I_{up} - I_{ds}(Q)|}{I_{up}} + \frac{|RI_{up} - RI_{ds}(Q)|}{RI_{up}}$$

HYDROLOGIC INDEX		*ECOLOGIC IMPLICATIONS*
CORRELATION SCALE (I)	Short-term rate of change	Short-term Adaptation Strategies (Behavioral)
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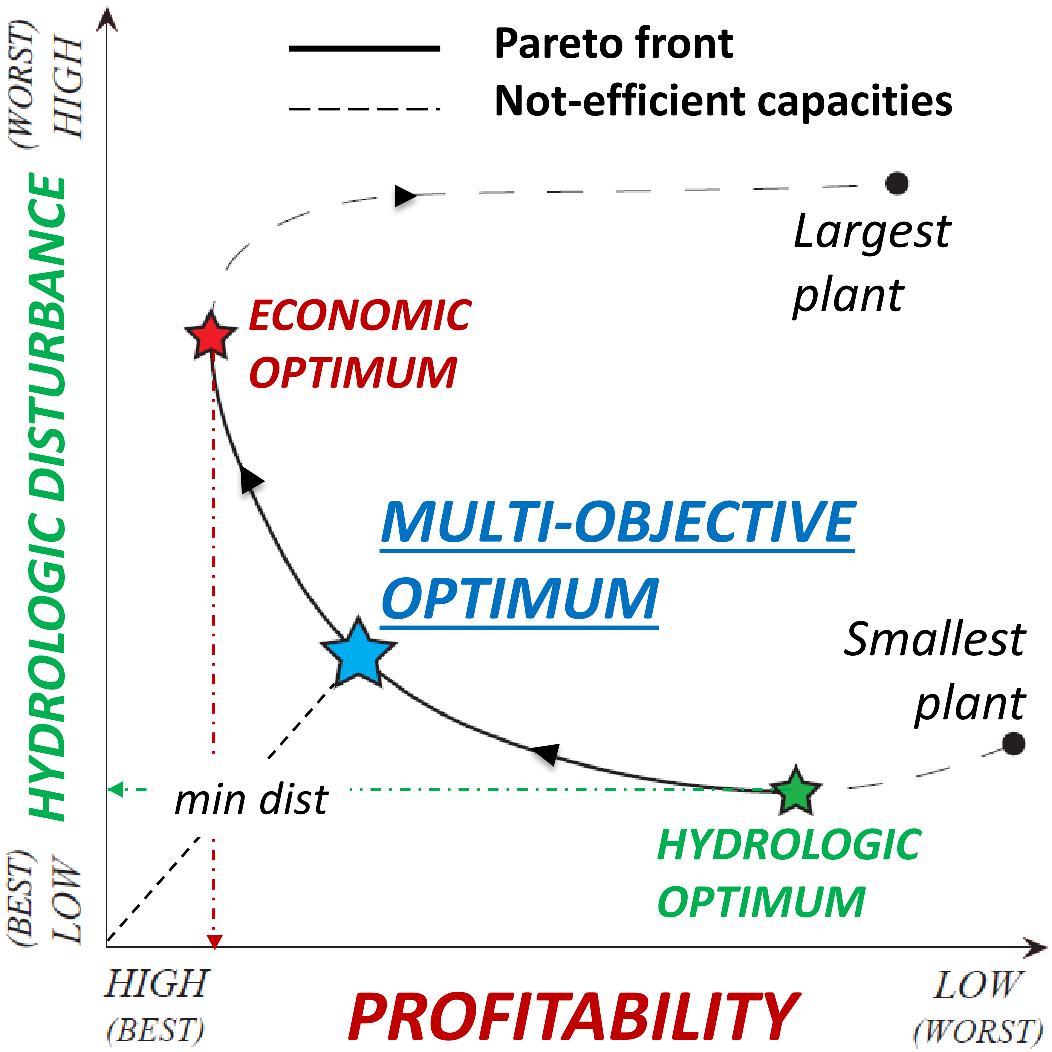
WATER MANAGER - SOCIETY



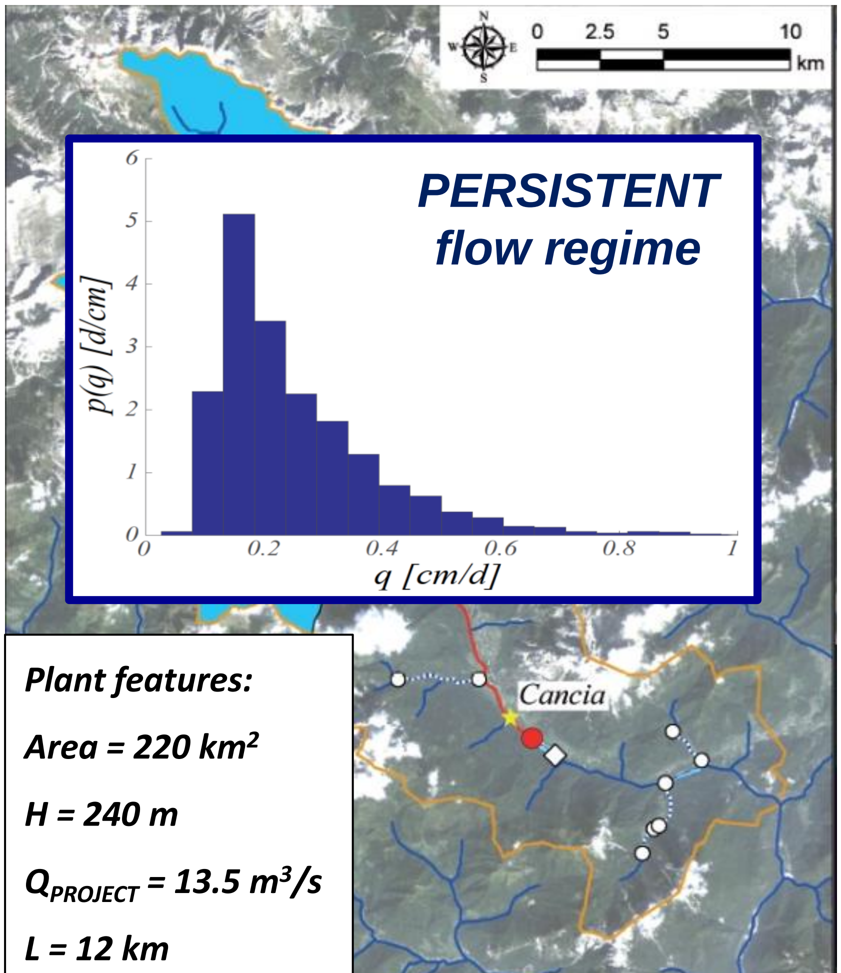
The **PARETO FRONT** *identifies a set of* ***efficient solutions*** *trading between:*

- ***MAX profitability (investor)***

- ***MIN hydrologic disturbance (ecosystem)***

CASE STUDIES

BOITE RIVER



Plant features:

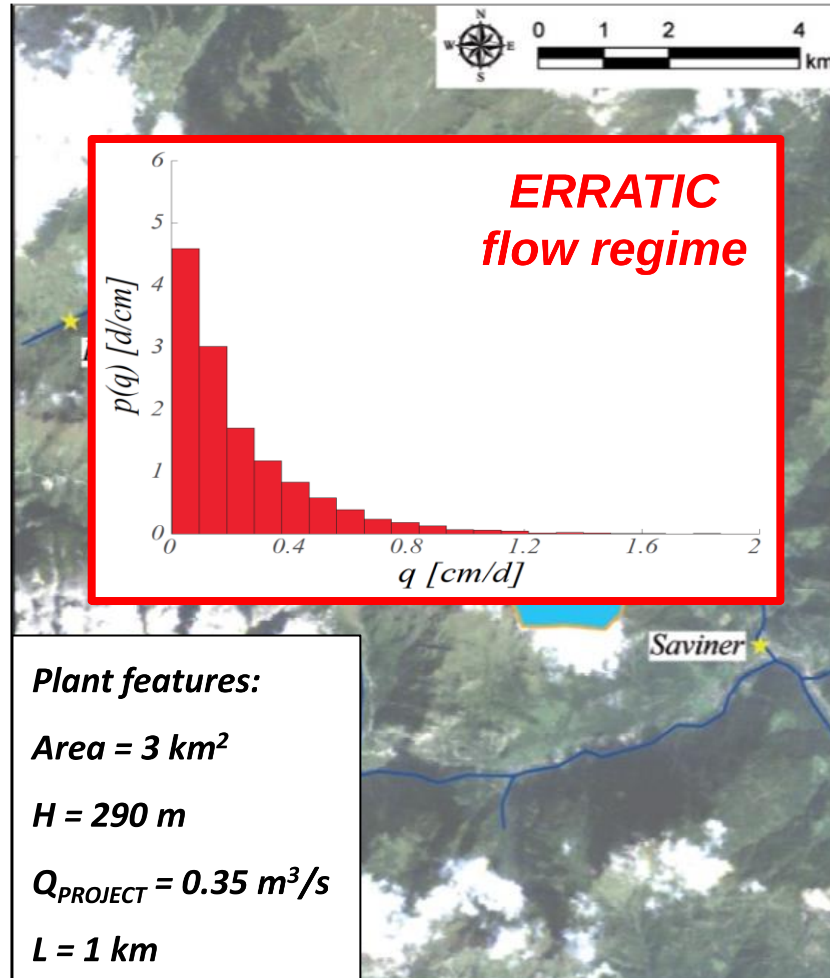
Area = 220 km²

H = 240 m

$Q_{PROJECT}$ = 13.5 m³/s

L = 12 km

RU DELLE ROSSE CREEK



Plant features:

Area = 3 km²

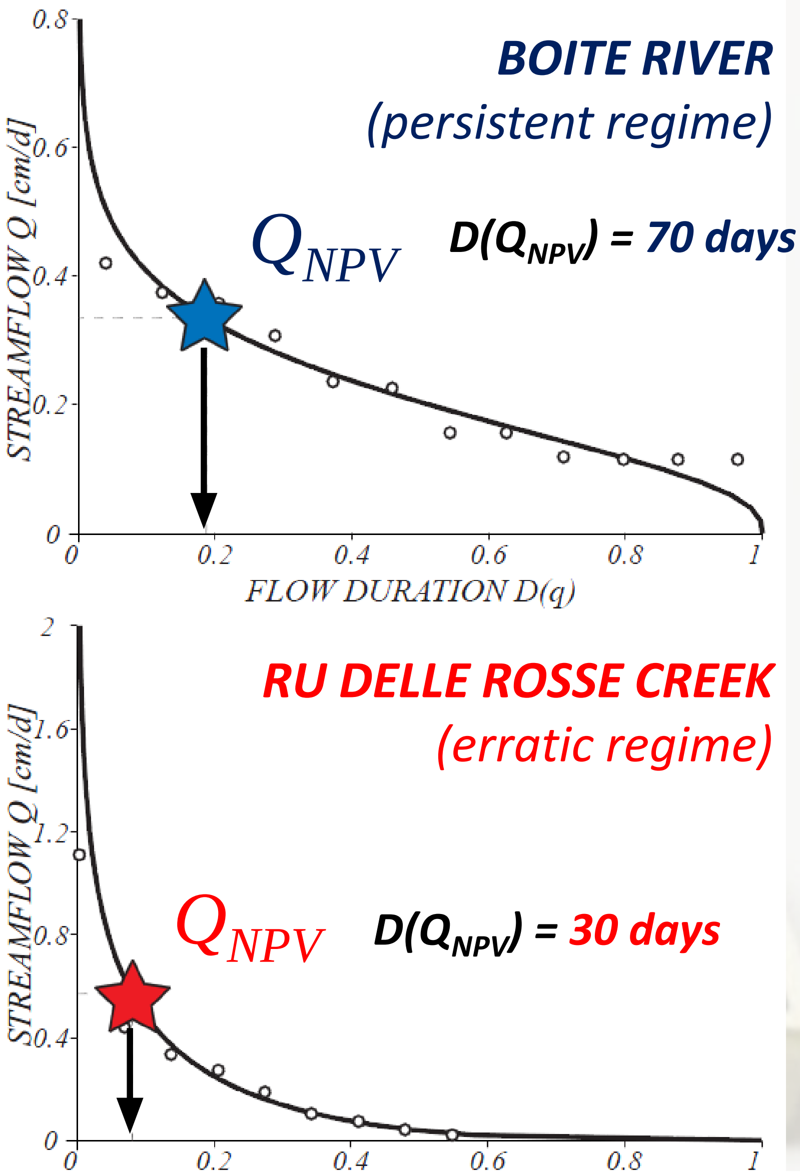
H = 290 m

$Q_{PROJECT}$ = 0.35 m³/s

L = 1 km

INVESTOR: PROFITABILITY

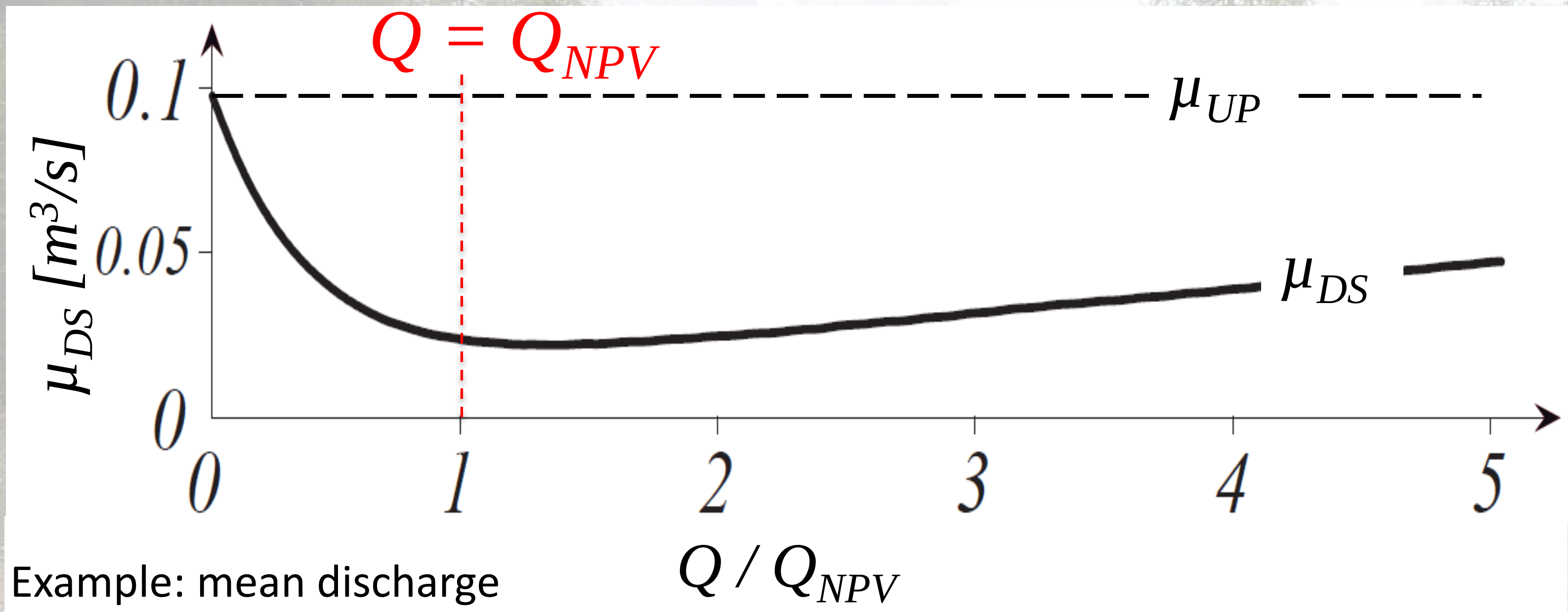
The **duration** of **economic optimal plant capacities Q_{NPV}** depends on the **flow regime**



[Lazzaro et al., WRR 2013]

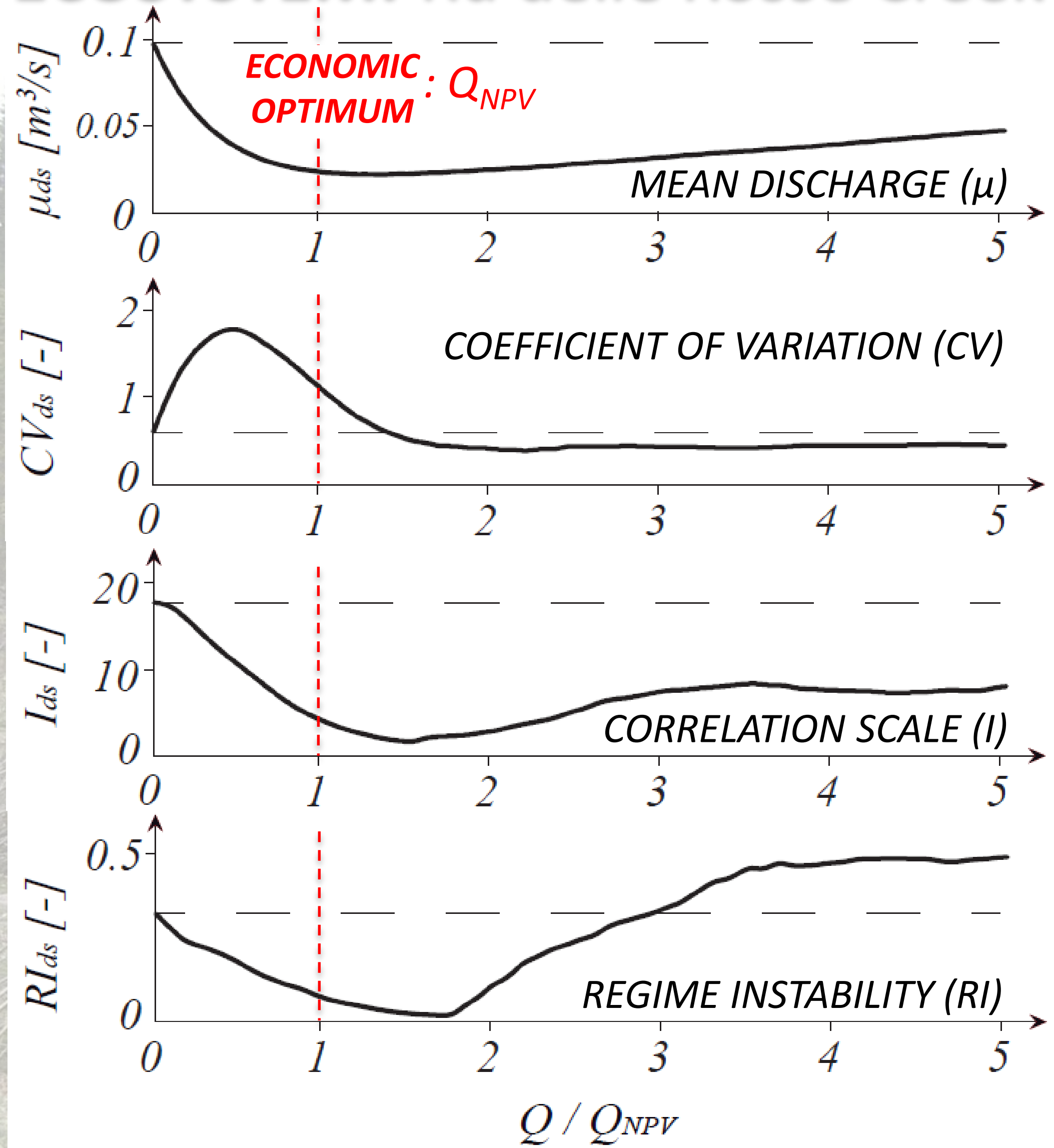
ECOSYSTEM

*The **HYDROLOGIC DISTURBANCE (D_H)** is the sum of the upstream/downstream relative variation of hydrologic indexes*



*For **large capacities** the **plant is switched off** more frequently*

ECOSYSTEM: Ru delle Rosse Creek (erratic regime)



*For **large capacities** the **plant is switched off** more frequently*

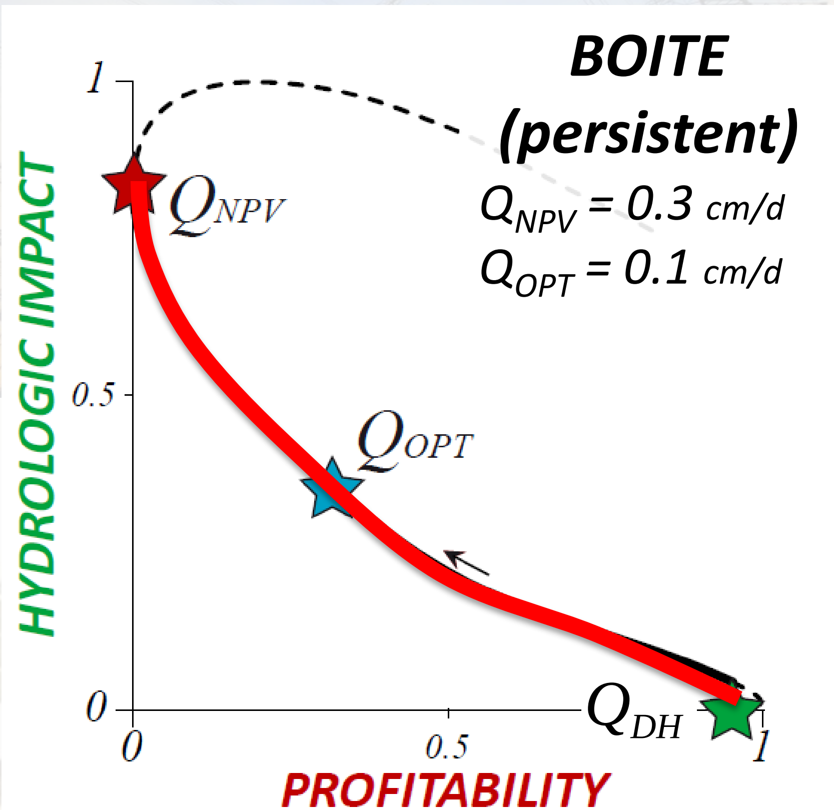
***Reduced contribution of floods** to the downstream variability when $Q>Q_{NPV}$*

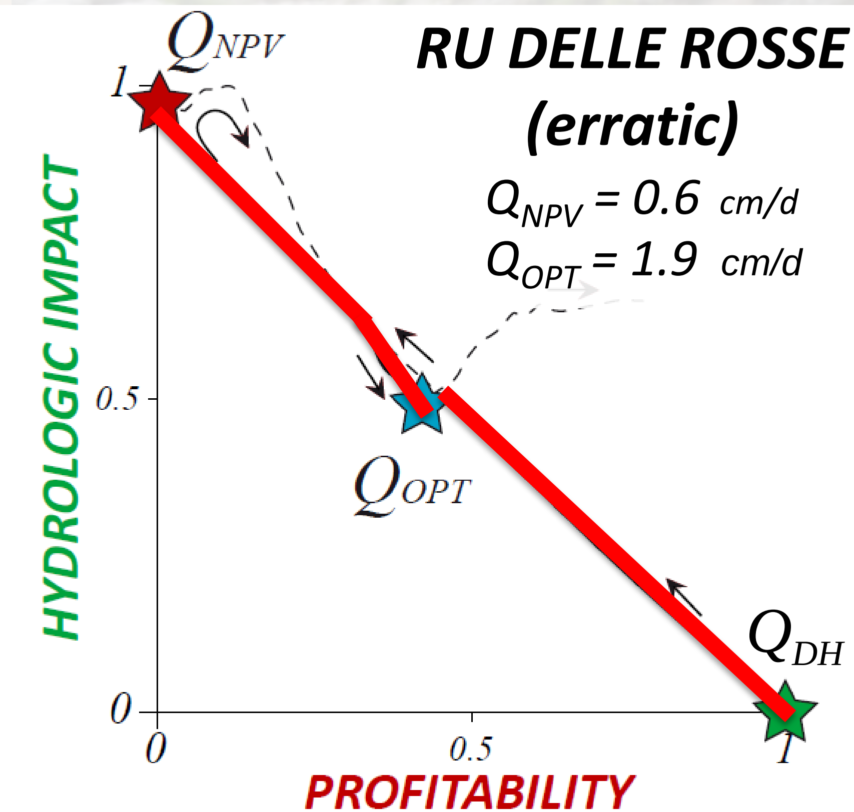
***Less correlated** downstream streamflows during each season/year*

*Inter-annual variability **unaltered for $Q = 3\ Q_{NPV}$***

WATER MANAGER - SOCIETY

Pareto Front *obtained accounting for* ***profitability*** *and* ***hydrologic impact***





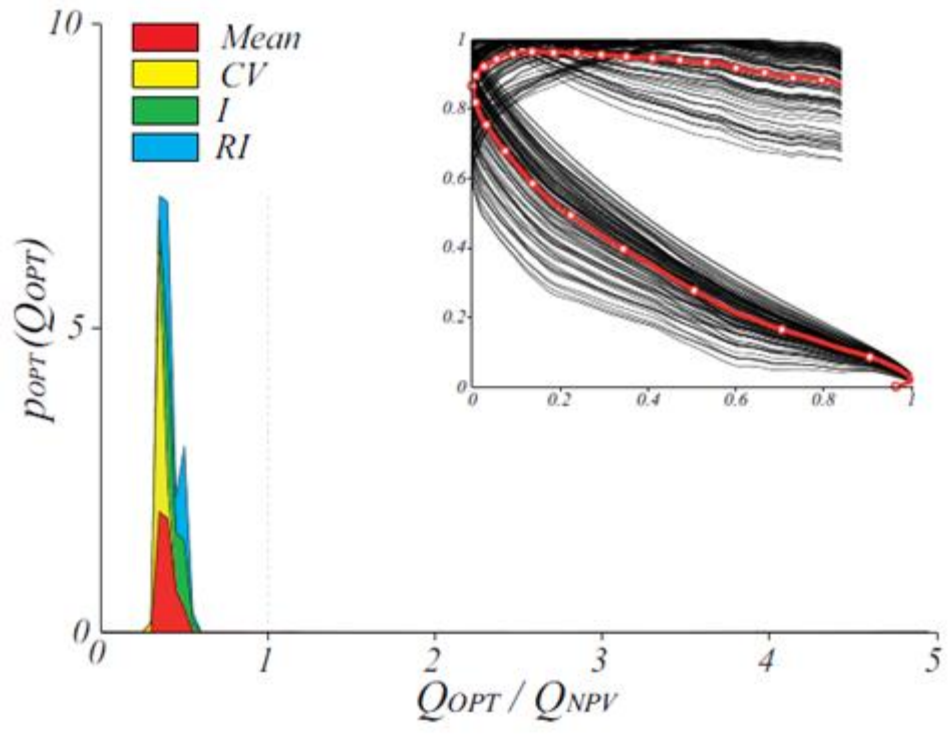
Efficient capacities *lower than* Q_{NPV}

Three disconnected ranges
efficient capacities

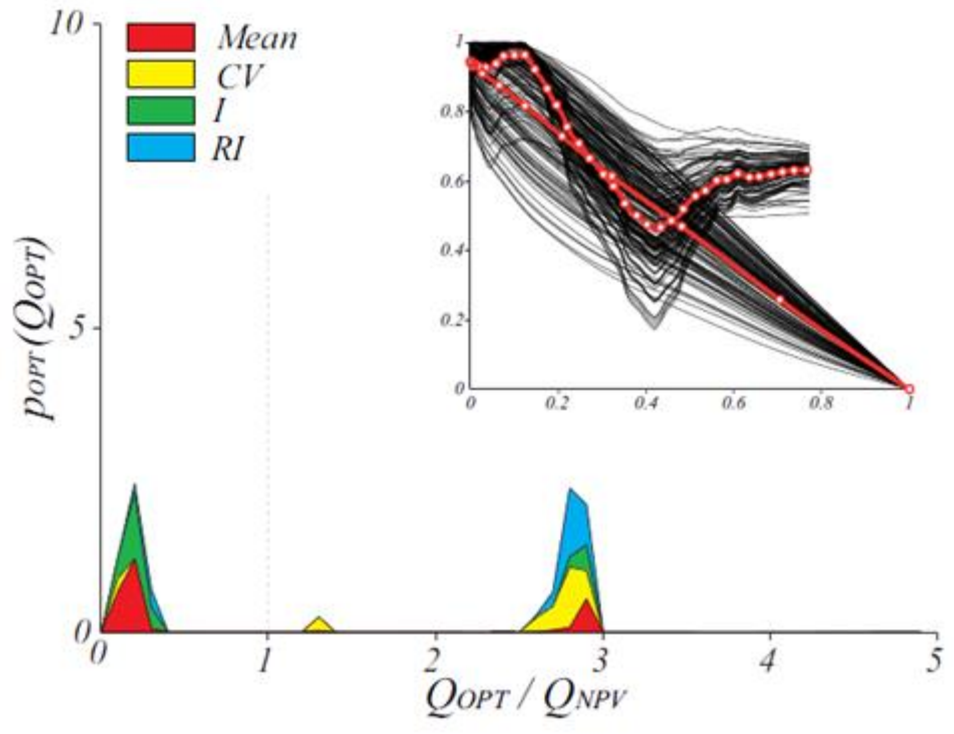
WATER MANAGER - SOCIETY

***Randomly weighting** the contribution of each statistic…*

BOITE (persistent)



RU DELLE ROSSE (erratic)



*The **Pareto-optimal plant capacity***
Q_{OPT}** is **smaller than Q_{NPV}

*The flow **variability (CV and RI) is less impacted** with a capacity **$Q_{OPT} = 3Q_{NPV}$***

CONCLUSIONS

*Run-of-river power plants imply a **strong disturbance on flow regimes and river connectivity***

Multi-criteria analysis** can be useful to **trade** between **profitability and hydrologic impact

***Flow regimes** at the intake strongly **affect optimal design features** of run-of-river power plants*

FUTURE IMPLICATIONS

Basin-scale** multi-objectives analysis: overall **profitability** (or **produced energy**) VS **riverine connectivity

THANKS FOR YOUR ATTENTION

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