Non-linear interactions of urban and freshwater systems:

Exploring implications for sustainability and water planning and management

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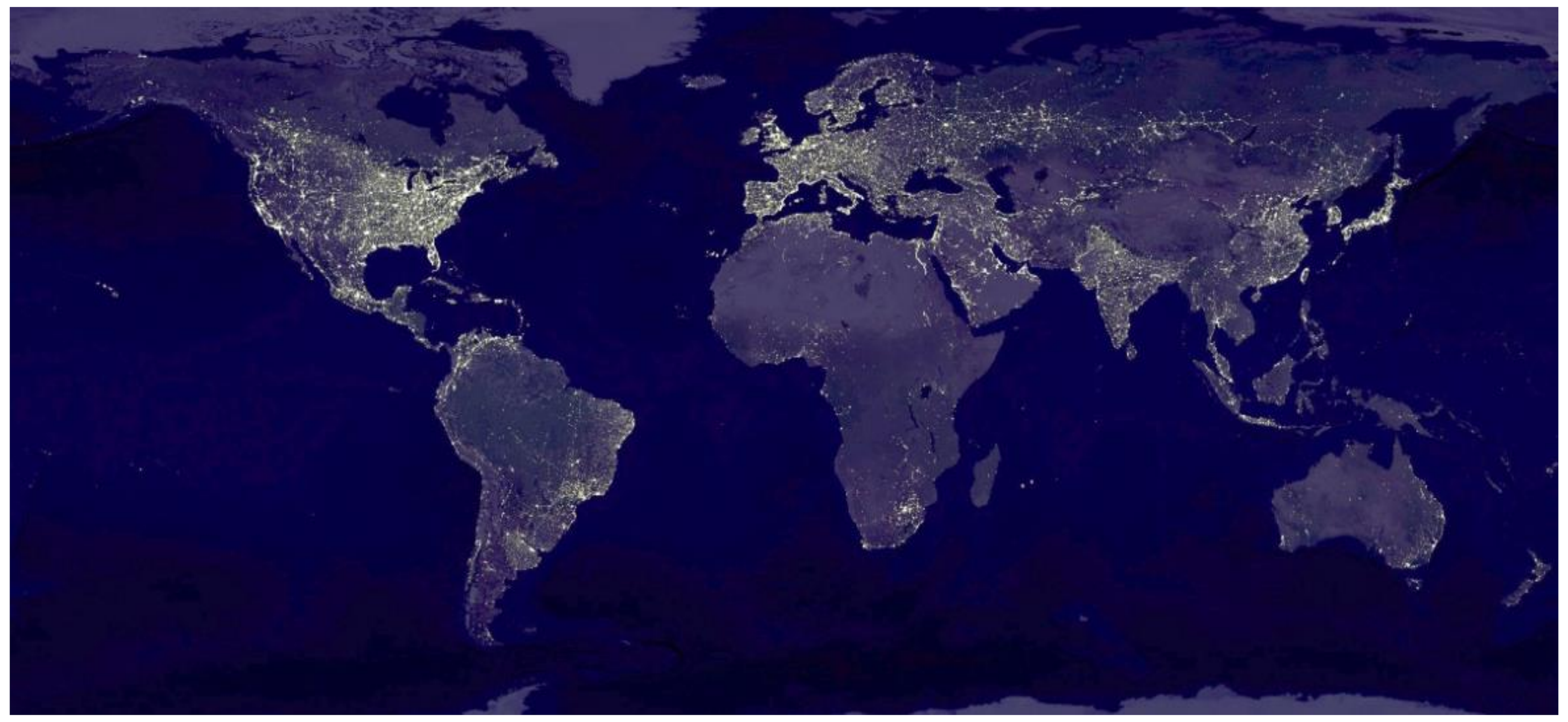
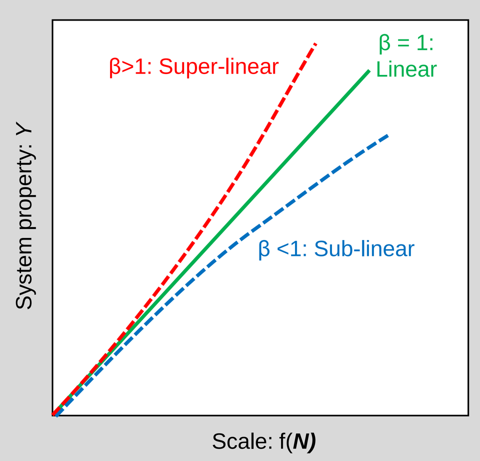
Human population is progressing into a predominantly urban configuration. Currently, 3.5 billion people – 55% of the total human population – live in urban areas, with an increase to 6.68 billion (68%) projected by 2050. In this progressively more populated world, a central issue of sustainability assessments is understanding the role of cities as entities that, despite their comparatively small physical footprint (less than 0.5% of the global area) demand resources at regional and global scales.

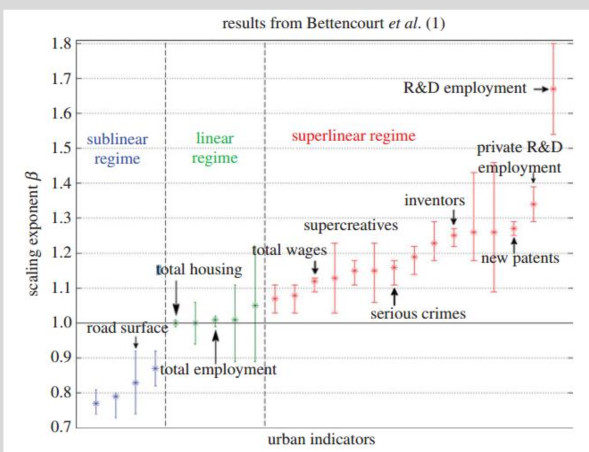
Many of the resources that sustain cities directly depend on the freshwater system: from direct fluxes from/to the immediate environment for water supply or waste elimination, to water-dependent activities like biomass (food, biofuels, fibers) and energy production. Urban and freshwater system interactions are subject to multiple sources of non-linearity.



Background: Scale-dependency and long-term urban system dynamics

$$Y = Yo * N^{\beta}$$

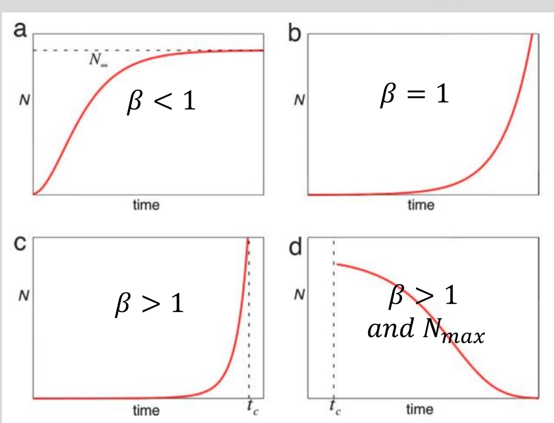




(Fig. 1 from Arcaute et al., 2015)

As defined by Bettencourt et al. (2007), "The exponent, β, reflects general dynamic rules at play across the urban system" over a wide range of scales.

$$Y(t) = RN + E(N)\frac{dN}{dt}$$



(Fig. 3 from Bettencourt et al., 2007)

Although debate remains with respect to the universality of scaling laws to predict some city's attributes (i.e. Arcaute et al., 2015), understanding the scaling of resource dependency and environmental impacts is a promising element in assessing pathways for long-term sustainability of the population.

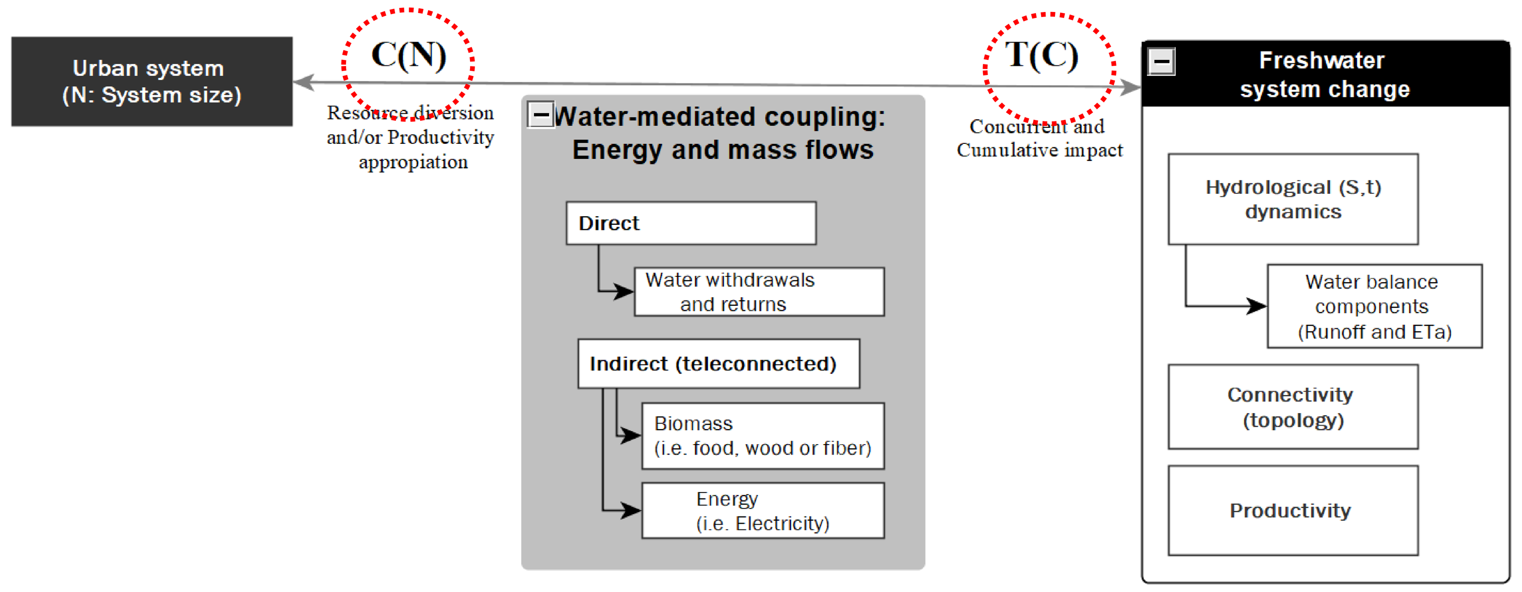
A framework to quantify regional interactions between urban and hydrologic systems

We propose a framework to explore how non-linear factors like:

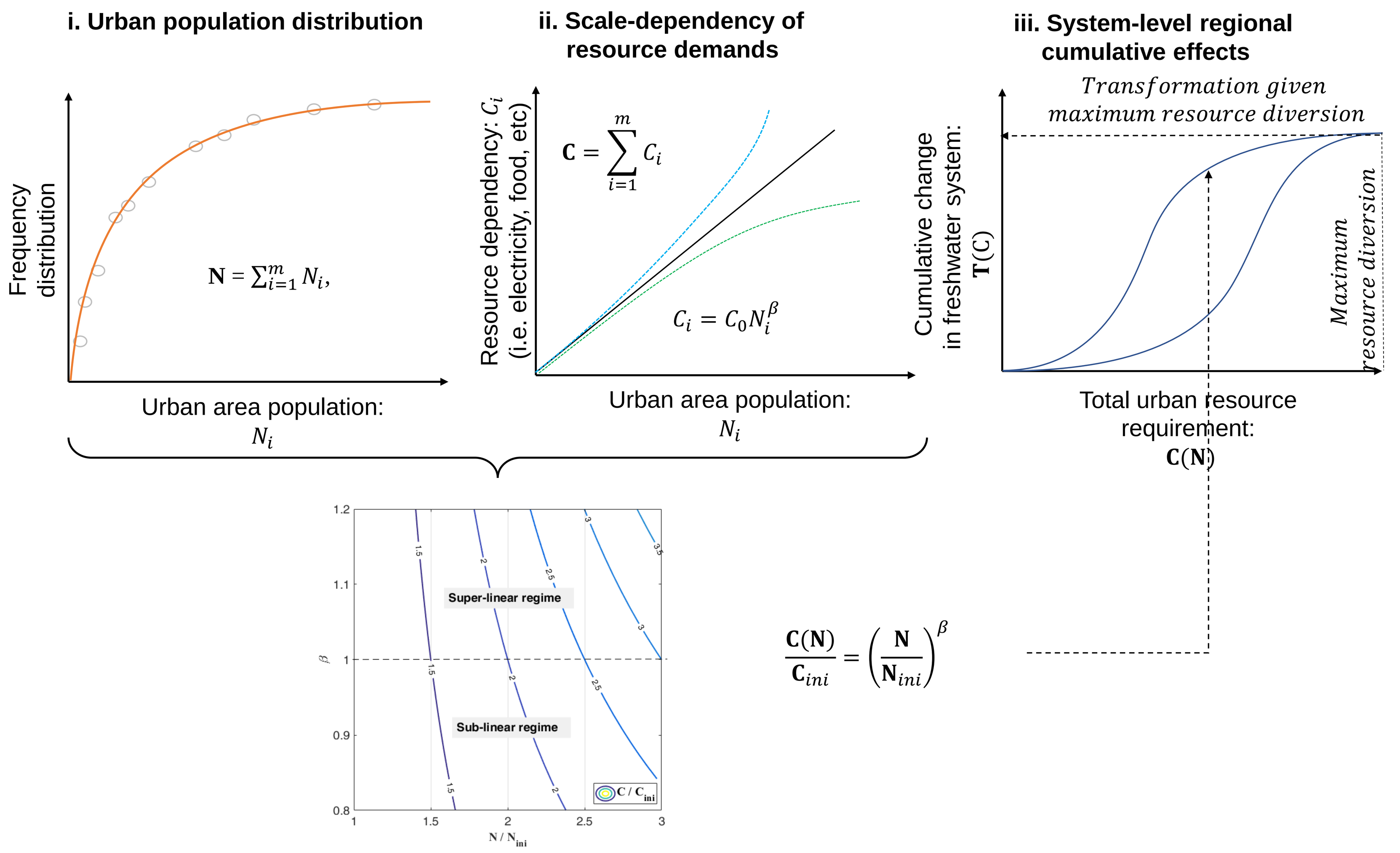
- Patterns of size or distribution and interconnection of groups of cities
- Nested and hierarchical character of freshwater systems
- Management strategies

Can influence

- The amount of resources required to sustain and grow urban population
- The cumulative pressure exerted on the freshwater system



Population size and distribution: **N**
Total urban resource requirement: **C**
Cumulative change in freshwater system: **T**



We explore the non-linear character of those interactions, to:

i. identify water management options to avoid, minimize or offset regional impacts of growing urban populations, and
ii. explore long-term implications of such non-linearities for the resource base of urban areas.

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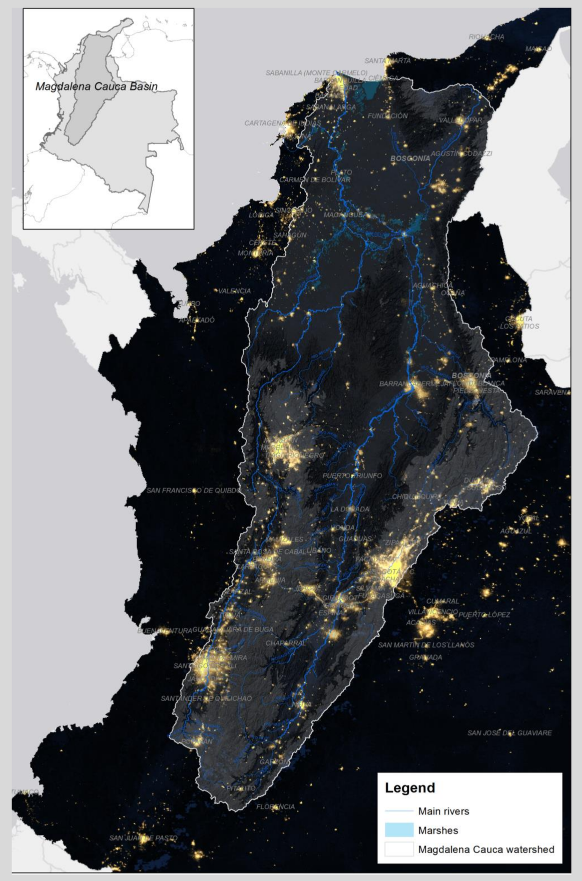
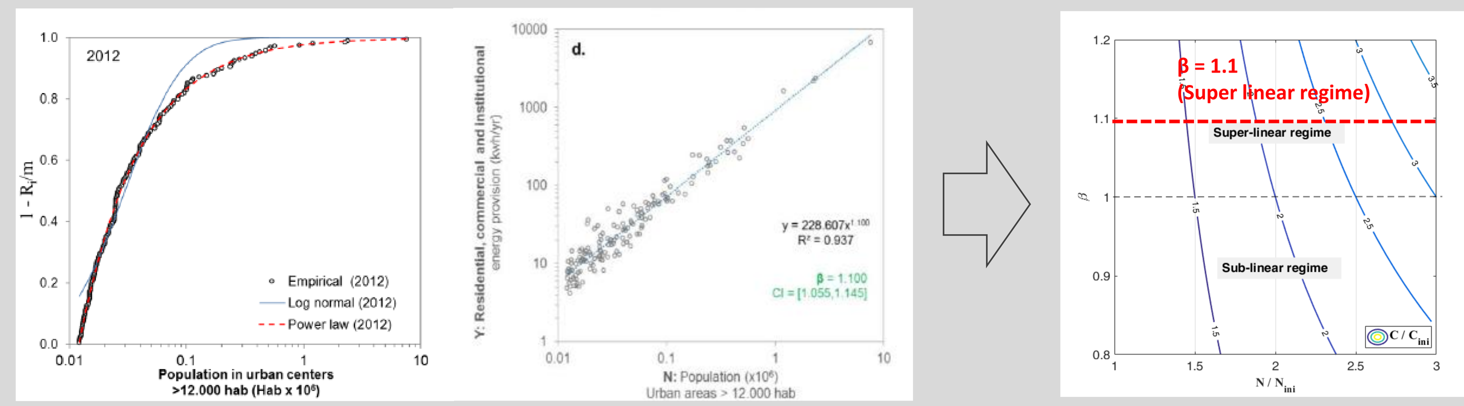
A case study



An example of this approach is presented in a case study in the Magdalena River Basin - MRB (Colombia):

- covers one quarter of Colombia's national territory
- provides sustenance to 36 million people
- three quarters of basin inhabitants live in urban settlements of 12 000 or more inhabitants
- 50% of population concentrated in the 15 largest cities

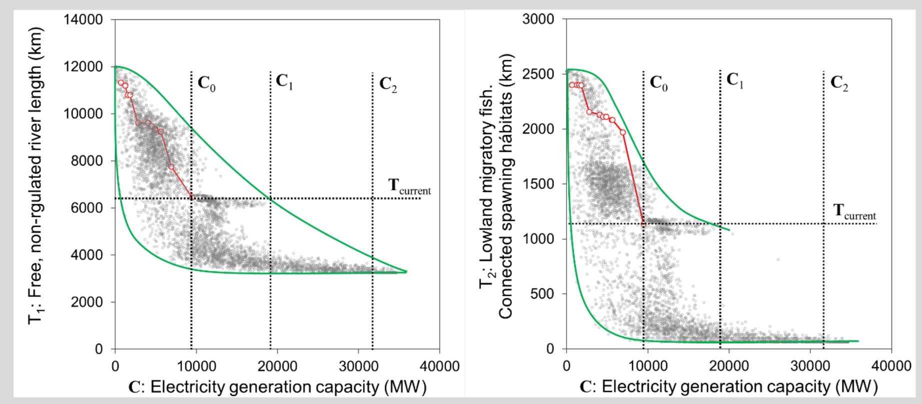
URBAN SYSTEM: Electricity demands



FRESHWATER SYSTEM CHANGE

$N_{ini} = 3.5e7$ (2012)
$N_1 = 5e7$ (2050)
$N_2 = 1e8$ (2100)

$$\frac{C}{C_{ini}} = \left(\frac{N}{N_{ini}}\right)^{\beta = 1.1}$$



(Scenario data from Angarita et al., 2018)

The case study results indicate that freshwater-mediated resource dependencies of urban population are described by a linear or super-linear regime that indicates a lack of scale economies. However, freshwater systems' capacity to assimilate those resource demands is characterized by a sublinear regime. Current practices and technological approaches to couple freshwater and urban systems will not be able to withstand the resource demands of mid-term future population scenarios.

Our approach allows quantification of the projected gaps to achieve a sustained resource base for urban systems in the MRB

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