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# Adaptation in hindsight: Dynamics and drivers shaping urban wastewater systems

Marc B. Neumann [a, b, *], Jörg Rieckermann [c], Thomas Hug [d], Willi Gujer [e]

[a] Basque Centre for Climate Change, Alameda Urquijo, 4 - 4°, 48008 Bilbao, Spain
[b] IKERBASQUE, Basque Foundation for Science, Bilbao, Spain
[c] Eawag, Swiss Federal Institute of Aquatic Science and Technology, 8600 Dübendorf, Switzerland
[d] Hunziker Betatech AG, 8411 Winterthur, Switzerland
[e] Emeritus, ETH Zurich, Zurich, Switzerland

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ABSTRACT

Well-planned urban infrastructure should meet critical loads during its design lifetime. In order to proceed with design, engineers are forced to make numerous assumptions with very little supporting information about the development of various drivers. For the wastewater sector, these drivers include the future amount and composition of the generated wastewater, effluent requirements, technologies, prices of inputs such as energy or chemicals, and the value of outputs produced such as nutrients for fertilizer use. When planning wastewater systems, there is a lack of methods to address discrepancies between the timescales at which fundamental changes in these drivers can occur, and the long physical life expectancy of infrastructure (on the order of 25–80 years). To explore these discrepancies, we take a hindsight perspective of the long-term development of wastewater infrastructure and assess the stability of assumptions made during previous designs. Repeatedly we find that the drivers influencing wastewater loads, environmental requirements or technological innovation can change at smaller timescales than the infrastructure design lifetime, often in less than a decade. Our analysis shows that i) built infrastructure is continuously confronted with challenges it was not conceived for, ii) significant adaptation occurs during a structure's lifetime, and iii) "muddling-through" is the pre-dominant strategy for adaptive management. As a consequence, we argue, there is a need to explore robust design strategies which require the systematic use of scenario planning methods and instruments to increase operational, structural, managerial, institutional and financial flexibility. Hindsight studies, such as this one, may inform the development of robust design strategies and assist in the transition to more explicit forms of adaptive management for urban infrastructures.



## 1. Introduction

Urban infrastructure is normally developed on a project-by-project basis. It is not typical for agents to review and compare the long-term historical development of their systems and to confront assumptions and decisions from past designs with actual outcomes. Few scientific studies systematically review the long term development of urban infrastructure systems. For example, Flyvbjerg et al. (2003) uncover systematic bias between projections and actual outcomes in the transport sector. Methods exist to support the long-term planning of infrastructure, including scenario planning (Schoemaker, 1995) or more quantitative approaches such as real options (De Neufville, 2003). To better inform these approaches, we believe there is value in improving the understanding on how infrastructure systems evolve. Identifying the drivers' temporal characteristics such as smoothness, stochasticity, trend reversals, transitions, and abrupt regime shifts can critically test the assumptions underlying current planning methods. In our study we try to uncover some of these temporal characteristics for forces driving the development of wastewater infrastructure.

Socio-economic drivers of urban wastewater systems include among others population growth, urbanisation, and industrialisation. Many current design projects use forecasts based on trend analysis to predict change in these drivers (Dominguez and Gujer,

* Corresponding author. Basque Centre for Climate Change, Alameda Urquijo, 4 – 4, 48008 Bilbao, Spain.
*E-mail address:* marc.neumann@bc3research.org (M.B. Neumann).

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2006). However, political and socio-economic changes are not necessarily smooth transitions and can exhibit both abrupt shifts and trend reversals. Historically, trend extrapolation has mainly taken place within growth scenarios. A pitfall of extrapolation is that it may miss key trends. Extrapolating just prior to turning points can have highly undesired consequences. This was the case for many developed countries, where rising water use and thus wastewater generated in the 1960's and 1970's was followed by sharp declines. In a detailed example Moss (2008) showed how infrastructure expansion taking place in Eastern Germany after unification was succeeded by rapidly declining wastewater loads due to de-industrialisation, population shrinkage and a fall in per capita water consumption. He demonstrated how the resulting overcapacities did not only lead to unnecessarily high costs but also to poor performance due to sediment build-up in oversized sewers.

For natural system drivers (rainfall patterns, river dynamics) the design of wastewater systems has in most cases been based on stationarity, the assumption, that the statistical characteristics of historical data will be preserved in the future. Recent studies emphasise that due to climate change, the assumption of stationary rainfall patterns may no longer be valid as a basis for designing long-lived water infrastructure (Milly et al., 2008). Furthermore, changes within the catchment of the receiving water (e.g. land use change or river engineering measures) can change statistical characteristics of background loads and flows and impact the urban infrastructure's ability to achieve the environmental requirements.

For the water sector Geldof (1995) described the long-term development of water management using the metaphor of multiple interlinked controllers characterising the physical and social domains and forming a complex adaptive system (Holland, 1992) with the following characteristics:

- It can be characterised as a network of agents acting in parallel.
- Multiple levels of organisation are present.
- Agents have the ability to anticipate future developments.
- The agents are perpetually confronted with novel issues.

In our study we seek to examine these features, specifically the role of the involved principal agents and their corresponding paradigms, their anticipation of future developments and their resulting actions. In the wastewater sector Geels (2006) examined the role of the principal agents in institutional regime dynamics during the hygiene revolution in the Netherlands (1840–1930) and showed how system transformation is not only due to technological substitution but is largely explained by the competition between these agents. For example, he shows how during the mid-19th century, the Dutch city councils and engineers (he uses the term “regime insiders”) initially resisted the pressures of hygienist doctors (“regime outsiders”) and how these overcame the resistance to become the new insiders. In our case study we intend to uncover how the principal agents are acting within these regimes and how the broader developments (urbanisation, industrialisation, and democratisation) alter the stage and provide resources for agents. In this, we are especially interested in the roles of the municipal engineer and the physician, the two central agents in the development of wastewater infrastructure. Whereas the former was the principal agent in enabling and shaping the growth of cities in the nineteenth century (Schultz and McShane (1978)), the latter shaped the hygiene revolution.

Dominguez and Gujer (2006) analysed the development of load and capacity of the wastewater treatment of Zurich (Switzerland) during a 14 year time period. We extend their relatively short observation window to 170 years for the same system. Where they focused on how unexpected changes in wastewater loads interacted with upgrading activities and operational adjustments at the wastewater treatment facility, we are able to capture many more phenomena. Specifically, we assess the stability of critical assumptions made by engineers in planning and design of urban wastewater systems by exploring how various drivers influence and interact upon the newly commissioned infrastructure. These drivers relate to sources of uncertainty that are dealt with in the planning stages of engineering projects and have been recognised as being more influential than sources of uncertainty that appear in more detailed design stages (Neumann (2007), Dominguez (2008), Belia et al. (2009), Neumann and Vanrolleghem (2011)). The main goal of our study is to reveal the discrepancies that arise between fast and unforeseeable dynamics in various drivers and long infrastructure design lifetime. We specifically analyse how long it takes for a new system to become inadequate and the time required to identify and to implement new solutions.

To our knowledge this is the first scientific analysis of how principal drivers shape an urban wastewater system over a period of more than a century and therefore includes a very wide range of phenomena. We analyse how the system boundaries evolve and explore the dynamics which take place both within each infrastructure generation and during the transition from one generation to the next.

The identified driver typology is expected to be transferable to other cities, although the challenges, objectives and principal agents may vary. The methodology applied in this “adaptation in hindsight” study is transferable to other urban infrastructure sectors where the infrastructure lifetime exceeds the timescales at which the principal drivers evolve.

Following a general description of components and drivers of current wastewater systems a detailed analysis is conducted on the evolution of components and drivers for Zurich's wastewater system from 1850 to 2020. The discussion then focuses on the hindsight assessment of system performance and on what we can be learnt for improving current design practice.

## 2. Materials and methods

### 2.1. Components and drivers of current wastewater systems

We start out by giving a generic characterisation of a current centralised wastewater system explaining the main components and drivers. In this way we introduce the reader unfamiliar to wastewater treatment to the main characteristics and explain our perspective of analysis.

The task of today's engineer is to provide infrastructure that is able to transform wastewater loads in a way that environmental requirements are fulfilled (rectangular shapes in Fig. 1). These components are influenced by multiple drivers (oval shapes in Fig. 1).

#### 2.1.1. Drivers of load

Wastewater loads are determined by urban catchment characteristics and rainfall patterns. Households, commerce and industry produce wastewater which is collected in sewer networks. Lifestyle- and behavioural changes, city growth or shrinkage, and changes in industrial intensity alter the wastewater patterns. Runoff entering the wastewater systems is also subject to change, e.g. due to climate change. Loads can be influenced through demand side management (e.g. increase of water price) or source control efforts that prevent substances from entering the wastewater system in the first place (e.g. disconnection of runoff from sewers).

#### 2.1.2. Drivers of infrastructure

The engineer designs using best practice tools (e.g. use of design