Visualizing the hybridity of water system for a more sustainable urban water management

A case study in Rotterdam, The Netherlands

by

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Abstract

Water is one of the most essential resources for the sustainable development. With the tendency of urbanization and population growth, a more sustainable urban water system becomes important to create harmonized environment between human and nature, thus it is necessary to discuss integrated urban water management in a holistic manner.

In this research, starting from a water management model closed city, hybridity is identified as one character of urban water system and its contributions to improve closed city are studied by collaboration work between two disciplines, water management and urban design. A hypothesis of three components of hybridity of urban water systems is raised, which are spatial hybridity, environmental hybridity and governance hybridity. Each component consists of different elements that are involved and influence each other in urban water system.

This report presents the results of spatial hybridity and environmental hybridity in a case study area Zevenkamp in Rotterdam city, the Netherlands. Methodology to analyze and evaluate spatial and environmental hybridity is developed in the perspective of urban design and water management respectively, and then be applied to assess current situation in Zevenkamp. Based on the current analysis results, five future visions are set up according to the concept of closed city and then collaborative design between two disciplines is carried out to clarify the urban layout for each vision. Added values of hybridity in each vision is assessed by quantification, as well as their performance as a closed city. Finally, all the results are compared together and discussed.

Some main conclusions can be obtained from this research, which are given as follows:

- Hybridity concept addresses the importance of inter-disciplinary work, and it is able to provide a thinking way to promote the collaborative processes. Based on the cooperation between two disciplines in this research, it will be helpful to guide future collaboration when more expertise are involved.
- Hybridity concept gives a broader perspective on the discussion of grey and green solutions, which is not conflicting to recent debates on the importance of combination of both types of measures.
- Hybridity concept can improve the design of closed city which can enhance citizens' appreciation on urban water systems without compromising the physical performance of closed city. It will motivate locals to engage in urban water management, which can lead to the study of governance hybridity. In addition, it also inspires urban water managers for more comprehensive understandings to a more sustainable urban water management.

Contents

Abstract iii

List of Figures ix

List of Tables xi

Acronym xiii

1 Introduction 1
- 1.1 Research background . . . 1
- 1.2 Research questions . . . 3
- 1.3 Structure of the report . . . 3

2 Literature Studies 5
- 2.1 Current urban situation . . . 5
  - 2.1.1 Urbanization . . . 5
  - 2.1.2 Impacts on water security . . . 5
  - 2.1.3 Conventional urban water management approach . . . 6
- 2.2 International consensus . . . 7
  - 2.2.1 Sustainable development . . . 7
  - 2.2.2 Urban framework . . . 8
- 2.3 Transition to a more sustainable urban water management . . . 8
  - 2.3.1 Integrated urban water management . . . 8
  - 2.3.2 A glance on the Netherlands . . . 10

3 Research Methodology 13
- 3.1 Overview . . . 13
- 3.2 Data preparation . . . 14
  - 3.2.1 Spatial data . . . 14
  - 3.2.2 Environmental data . . . 14
- 3.3 Spatial hybridity . . . 14
  - 3.3.1 Definition of spatial hybridity . . . 14
  - 3.3.2 Spatial analysis . . . 15
  - 3.3.3 Spatial evaluation . . . 16
- 3.4 Environmental hybridity . . . 17
  - 3.4.1 Definition of environmental hybridity . . . 17
  - 3.4.2 Environmental analysis . . . 18
  - 3.4.3 Environmental evaluation . . . 21
- 3.5 Future visions set-up . . . 22
- 3.6 Collaborative design . . . 23
- 3.7 Performance of closed city . . . 24

4 Current situation of Zevenkamp 25
- 4.1 Study site, Zevenkamp . . . 25
- 4.2 Spatial hybridity of current Zevenkamp . . . 27
  - 4.2.1 Results of spatial analysis . . . 27
  - 4.2.2 Results of spatial evaluation . . . 28
- 4.3 Environmental hybridity of current Zevenkamp . . . 29
  - 4.3.1 Results of environmental analysis . . . 29
  - 4.3.2 Results of environmental evaluation . . . 31
- 4.4 Summary . . . 32

5 Future visions of Zevenkamp **33**
- 5.1 Future uncertainties . . . 33
  - 5.1.1 Climate change . . . 33
  - 5.1.2 Demographic change . . . 33
- 5.2 Introduction of future visions . . . 34
- 5.3 1st vision: Mechanical district . . . 35
  - 5.3.1 Selected solutions . . . 35
  - 5.3.2 Spatial hybridity of mechanical Zevenkamp . . . 35
  - 5.3.3 Environmental hybridity of mechanical Zevenkamp . . . 37
  - 5.3.4 Performance of closed city in mechanical vision . . . 39
- 5.4 2nd vision: Green district . . . 40
  - 5.4.1 Selected solutions . . . 40
  - 5.4.2 Spatial hybridity of green Zevenkamp . . . 40
  - 5.4.3 Environmental hybridity of green Zevenkamp . . . 41
  - 5.4.4 Performance of closed city in green vision . . . 44
- 5.5 3rd vision: Mixed district . . . 44
  - 5.5.1 Mixed vision 1: More mechanical . . . 44
  - 5.5.2 Mixed vision 2: Balanced . . . 48
  - 5.5.3 Mixed vision 3: More green . . . 52

6 Evaluation of future visions **57**
- 6.1 Spatial hybridity . . . 57
  - 6.1.1 Amount of legible area . . . 57
  - 6.1.2 Balance of scales . . . 58
  - 6.1.3 Diversity of connections . . . 58
- 6.2 Environmental hybridity . . . 59
  - 6.2.1 Involved spheres . . . 59
  - 6.2.2 Connections . . . 59
  - 6.2.3 Bi-directional connections . . . 60
  - 6.2.4 Balance of water distributed to each sphere . . . 60
- 6.3 Performance of closed city . . . 61
  - 6.3.1 Amount of water circulation . . . 61
  - 6.3.2 Number of spheres with internal circulation . . . 61
- 6.4 Summary . . . 62

7 Discussion and analysis **63**
- 7.1 Water balance model . . . 63
  - 7.1.1 Data reliability . . . 63
  - 7.1.2 Model verification . . . 63
  - 7.1.3 Sensitivity analysis . . . 64
- 7.2 Sankey diagram . . . 65
- 7.3 Results of hybridity . . . 66
  - 7.3.1 Spatial hybridity . . . 66
  - 7.3.2 Environmental hybridity . . . 66
  - 7.3.3 Linkages between two types of hybridity . . . 67
- 7.4 Hybridity and collaborative work . . . 67
- 7.5 Hybridity and grey/green solutions . . . 68
- 7.6 Hybridity for improving closed city . . . 68
- 7.7 Room for improvement . . . 68
- 7.8 Relations to the project . . . 69

8 Conclusions **71**

Bibliography **73**

A Water Balance Model **77**

B Empirical values for wastewater calculation **83**

C Collaborative design **85**

D **Water quantity involved in each sphere of future visions** **89**

List of Figures

1.1 Hybridity of urban water systems 2

2.1 Three urban layouts of closed city (Rutger 2005) 9

3.1 Research framework 13
3.2 Het Nutshuis showing different spatial elements 15
3.3 Calculating gaze concentrated region 16
3.4 Estimating Legible area of spatial connections 16
3.5 Inter-connections between human and nature systems (Hooimeijer,Maring and Van Campenhout 2016) 18
3.6 The three spheres are inter-linked and under human and nature systems 19
3.7 A detailed Sankey diagram example that visualizes water balance 20
3.8 An example of Sankey diagram for visualizing environmental hybridity 21
3.9 An example of environmental hybridity chart 21

4.1 Location of Zevenkamp District 25
4.2 Land use in Zevenkamp 26
4.3 Red and grey are connected to combined sewer system in current Zevenkamp 27
4.4 Green and blue are connected in current Zevenkamp 27
4.5 Legible area of green-blue connection in current Zevenkamp 28
4.6 Maps for spatial evaluation of current Zevenkamp 29
4.7 A detailed Sankey diagram of Zevenkamp in 2016 30
4.8 Sankey diagram of environmental hybridity of Zevenkamp in 2016 31
4.9 Environmental hybridity chart of Zevenkamp in 2016 31

5.1 Locations of all applied solutions in this research 34
5.2 Legible area of mechanical Zevenkamp 36
5.3 Legible area in three scales in mechanical vision 37
5.4 Sankey diagram of water balance in mechanical Zevenkamp 38
5.5 Sankey diagram of environmental hybridity in mechanical Zevenkamp 38
5.6 Environmental hybridity chart of mechanical Zevenkamp 39
5.7 Legible area of each connection in green vision 40
5.8 Legible area and scales in green vision 41
5.9 Sankey diagram of water balance in green Zevenkamp 42
5.10 Sankey diagram of environmental hybridity in green Zevenkamp 43
5.11 Environmental hybridity chart of green Zevenkamp 43
5.12 Legible area of each connection in mixed vision 1 45
5.13 Legible area and scales in mixed vision 1 45
5.14 Sankey diagram of water balance in mixed vision 1 46
5.15 Sankey diagram of environmental hybridity in mixed vision 1 47
5.16 Environmental hybridity chart of mixed vision 1 47
5.17 Legible area of each connection in mixed vision 2 49
5.18 Legible area and scales in mixed vision 2 49
5.19 Sankey diagram of water balance in mixed vision 2 50
5.20 Sankey diagram of environmental hybridity in mixed vision 2 51
5.21 Environmental hybridity chart of mixed vision 2 51
5.22 Legible area of each connection in mixed vision 3 53
5.23 Legible area and scales in mixed vision 3 53
5.24 Sankey diagram of water balance in mixed vision 3 54

5.25 Sankey diagram of environmental hybridity in mixed vision 3 55
5.26 Environmental hybridity chart of mixed vision 3 55

6.1 Comparisons of spatial hybridity for all visions 57
6.2 Comparisons of environmental hybridity for all visions 59
6.3 Comparisons of performance of closed city for all visions 61

7.1 Water balance of Zevenkamp in 2016 excluding drinking water and wastewater 64
7.2 Sensitivity analysis of main parameters in water balance model 65

A.1 Water flows on different land use. In which: P (Precipitation), T (Transpiration), I (Interception), E (Evaporation), R (Run-off), WS (Water Supply), WW (Wastewater), Inf (Infiltration), Pe (Percolation), D (Drainage), and S (Seepage). 77

C.1 Initial locations for grey and green solutions 86
C.2 Regenerating historical spatial structure in Zevenkamp 87

List of Tables

3.1 Spatial hybridity methodology . . . 17
3.2 Water flows through different sectors . . . 19
3.3 Environmental hybridity methodology . . . 22
3.4 Selected solutions for future Zevenkamp . . . 23

4.1 Water Balance of Zevenkamp in 2016 (Unit: $10^6 m^3$) . . . 29
4.2 Water distribution to each sphere in current Zevenkamp . . . 32

5.1 Climate change values in 2050 of KNMI scenario (WH) . . . 33
5.2 Selected solutions for future Zevenkamp . . . 34
5.3 Selected solutions and locations in mechanical vision . . . 35
5.4 Water Balance of mechanical vision (Unit: $10^6 m^3$) . . . 37
5.5 Selected solutions and locations in green vision . . . 40
5.6 Water Balance of green vision (Unit: $10^6 m^3$) . . . 42
5.7 Selected solutions and locations in mixed vision 1 . . . 44
5.8 Water Balance of mixed vision 1 (Unit: $10^6 m^3$) . . . 46
5.9 Selected solutions and locations in mixed vision 2 . . . 48
5.10 Water Balance of mixed vision 2 (Unit: $10^6 m^3$) . . . 50
5.11 Selected solutions and locations in mixed vision 3 . . . 52
5.12 Water Balance of mixed vision 3 (Unit: $10^6 m^3$) . . . 54

6.1 Spatial hybridity of all visions . . . 62
6.2 Environmental hybridity of all visions . . . 62
6.3 Performance as closed city of all visions . . . 62

7.1 Water balance of Zevenkamp in 2016 excluding drinking water and wastewater (Unit: $10^6 m^3$) . . . 63
7.2 Main parameters used in water balance model . . . 64

D.1 Water distribution to each sphere in Mechanical Zevenkamp . . . 89
D.2 Water distribution to each sphere in Green Zevenkamp . . . 89
D.3 Water distribution to each sphere in mixed vision 1 . . . 90
D.4 Water distribution to each sphere in mixed vision 2 . . . 90
D.5 Water distribution to each sphere in mixed vision 3 . . . 91

Acronym

CSO	Combined Sewer Overflow
DEWATS	Decentralized Wastewater Treatment System
DIMI	Delft Delta, Infrastructure & Mobility Initiative
ET	Evapotranspiration
IUWM	Integrated Urban Water Management
IWRM	Integrated Water Resources Management
KNMI	Dutch acronym for Royal Netherlands Meteorological Institute
NBS	Nature Based Solution
RWH	Rainwater Harvesting
SDGs	Sustainable Development Goals
SWDS	Storm Water Drainage System
T-B-G	Techno-Bio-Geosphere
WWTP	Wastewater Treatment Plant

1

Introduction

1.1. Research background

This master thesis lies within an inter-disciplinary project named "Hybridity for Closed City: A study about the impact of applying hybridity concept for designing urban water management model Closed City". Researchers and students from track Water Management of Faculty Civil Engineering and track Urbanism of Faculty Architecture in TU Delft are jointly working on this project. The project is sponsored by Delft Deltas, Infrastructures & Mobility Initiative (DIMI).

Since the famous Brundtland Commission in 1987 [1], sustainability has been addressed all over the world. Governments are working together through many discussions to find out the way to achieve sustainable development. In 2015, the international consensus on 17 sustainable development goals (SDGs) of the 2030 Agenda were adopted during the UN General Assembly and came into force in 2016 [2]. Among all the 17 Goals, water-related issues are acknowledged specifically in SDG 6, which calls for integrated water resources management (IWRM) approaches to achieve 'universal and equitable access to water and sanitation for all'. Water, one of the most essential natural resources, is considered as a driver of sustainable development for both human and nature [3].

By the end of 2016, almost 54.5 % of global population are living in cities [4]. Urban sectors are asking for a considerable amount of water to support all the activities. On the other hand, the rapid urbanization has changed original land cover and thus altered natural hydrologic process, which causes environmental issues and threatens water security. In response to the sustainable development, more and more cities are now experiencing a transition to more integrated urban water management (IUWM) approaches. Therefore, a sustainable urban water system can make great contributions to sustainability.

Among many researches on discussing IUWM approaches, the concept of Closed City is proposed for transitions to more sustainable urban water management [5]. A closed city is defined as 'a city that does not have adverse effects on its surroundings, such as water depletion or emission of pollution'. According to the concept, local water resources such as rainwater and treated wastewater can be used to reduce water stress by either centralized or decentralized solutions. Three possible urban layouts are discussed to achieve closed city. However, if we want to realize closed city, there may be some questions remaining, such as what solutions are going to be selected, and where are they located. In this case, cooperation between urban water managers and urban planners becomes necessary.

For this reason, hybridity is proposed in this project for designing future urban water systems. Hybridity here is defined as an integration of formerly separated components within a system to achieve a common goal so that human and nature can be more intertwined and have more dynamic interconnections. From the perspectives of water management and urban design, the research team raises the hypothesis that hybridity of urban water systems consists of three aspects, which are spatial, environmental and governance. Each aspect has hybridity as well because they can be sub-divided into different elements. These elements influence each other and can finally affect the performance of water systems.

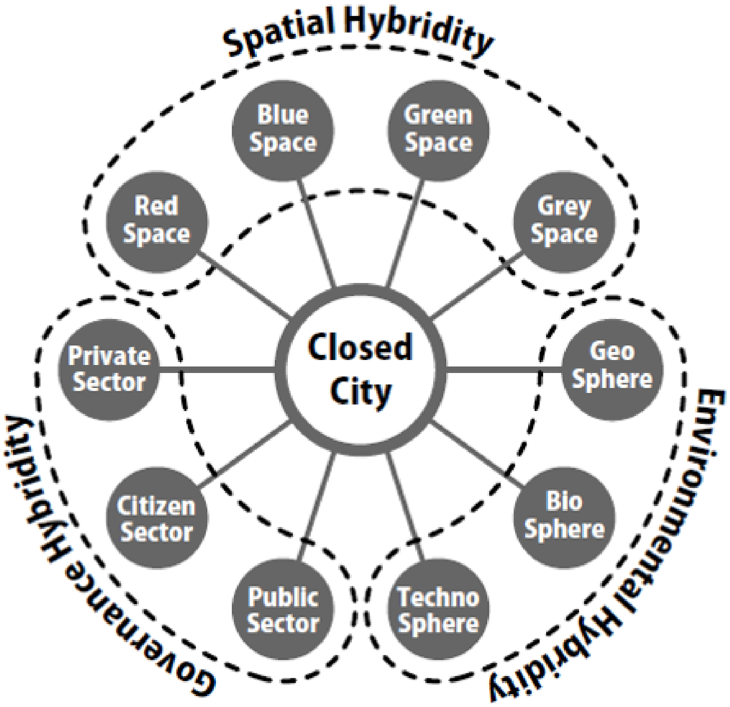


Figure 1.1: Hybridity of urban water systems

- **Spatial Hybridity** refers to the relations between different land use, including red (buildings), grey (streets), blue (water) and green (vegetation);
- **Environmental Hybridity** is composed by three spheres, which are Geosphere, Biosphere and Technosphere;
- **Governance Hybridity** includes groups of stakeholder from private sector, citizen sector and public sector.

Unfortunately, there are no studies yet on the applications of closed city to existing urban areas. Hence, the project team then focuses on Dutch urban concept because they have a long history of living with water. Finally, two districts in Prins Alexanderpolder of Rotterdam are selected as study area for this project, as Rotterdam is aiming at a water-resilient city and many projects are undergoing. In addition, the Prins Alexanderpolder is one of the lowest areas in the Netherlands, so if Closed City can be applied here, it will be much easier to upscale nationwide.

Ommoord and Zevenkamp are the names of the two selected districts, which are developed in the 1950s and the 1970s respectively. Ommoord was designed shortly after World War II, when the car-oriented practice mainstreamed the urban vision. Many waterways were land filled for transportation, which caused violent controversy and people started to ask for more public space. So in the 1970s, Woonerf, a Dutch word describing an improved urban design principle was applied. Zevenkamp was developed exactly during this period. Public space was reserved based on existing waterfront, which would be further connected to a planned surface water network.

By comparing the two districts, water is becoming more and more identified in urban design principles, and it can be expected that water (system) will play a key role in future cities. Therefore, with this project, we are trying to find out how hybridity can be applied to contribute to sustainable urban water systems, and how the two disciplines (i.e water management and urban design) can work together to harmonize both nature and human that can improve the quality of future cities.

1.2. Research questions

This master thesis will focus on the 1970s district Zevenkamp, to study how environmental hybridity can change by applying different technologies and how it is connected to the analysis of spatial hybridity. Therefore, the main research question is, how can hybridity concept contribute to sustainable urban water management? Sub-questions are formulated as follows:

- How to assess spatial and environmental hybridity respectively, and what are the correlations between them?
- How will decentralized and circular water management solutions perform and function, and how can they, including both grey and green measures, contribute to the hybridity of urban water systems?
- What can hybridity concept bring for closed city model, and how will hybridity change in closed cities with different solutions?

1.3. Structure of the report

To answer the research questions formulated in the previous section, the report first starts with a literature review in Chapter 2. It will introduce current urban development and its effects on urban water management approach, as well as the tendency to a more integrated approach. Through this chapter, readers can get more insights about the background knowledge of this project.

Next in Chapter 3, the research framework and methodology will be explained in details. The methods used to analyze and evaluate spatial hybridity and environmental hybridity will be clarified, as well as the evaluation of the performance of closed city.

Results of the hybridity and performance as a closed city are present in the following Chapter 4 and 5. Then all the visions are compared and evaluated together in terms of spatial hybridity, environmental hybridity and the performance of closed city, which is in Chapter 6.

Based on the results and comparisons, Chapter 7 will have a deep discussion on the indications, and finally the conclusions are given in Chapter 8.

2

Literature Studies

2.1. Current urban situation

2.1.1. Urbanization

The world's population is growing rapidly over the last few decades, especially in the urban areas. By the end of 2016, almost 54.5 % of global population are living in cities [4]. Increasing urban residents demand more living space to settle down, which leads to continuous urban expansion. This urbanization tendency becomes phenomenal which can be found throughout the world: cities began to spring up in most developing countries from Asia and Africa. While European cities emerge slower, given their already developed status. It is reported that by the year of 2030, urban residents will be doubled in developing countries and urbanized coverage will be three times of current ratio [6].

Despite the factor of natural population growth, waves of migrants from countryside come to cities for job opportunities. Within urban contexts, business activities are more concentrated and thus attract more settlers. A study shows that top 600 cities around the world contribute to 60 % of global GDP, and economic influence increases as the city grows [7]. In some developing countries, however, certain basic services (e.g. water supply, sewer systems) cannot keep pace with this population surge, leading to a rise of informal settlements. In European cities, on the other hand, the influx of refugees and asylum seekers in recent years also cause problems. Cities are struggling with providing accommodations and dealing with unemployment and poverty issues [8].

Expansion of urban areas is consuming more resources, including land, water and energy. The original natural processes are altered considerably due to land cover change, which results in urban heat island effects and change of local hydrologic regimes [9]. Gas emissions from modern traffics and industrial production processes are to blame for more than 70 % of global carbon dioxide release [10], consequently exacerbating climate change. As a matter of fact, the current urban situation is facing a lot of challenges. Cities may not develop towards sustainability if these issues are not addressed properly. Therefore, there is a need to transform cities for future, where different kinds of resources can be reasonably used within the capacity of both nature and society [11].

2.1.2. Impacts on water security

Among all the required resources for urban development, water, is the most essential one. Different activities are competing for the limited water resources to meet their demands, such as domestic use, industrial production and irrigation. Without water, cities cannot survive. However, urbanization and human development have already had influence on water quantity and quality, and have rung the alarm on water security.

Growing population are asking more water with irresponsible use behavior, putting much pressure on water supply systems. If this trend continues, almost all cities will get into water shortage in the coming three decades, with nearly 47 % of global population being affected [12][13]. Although big achievement of Millennium Development Goals (MDGs) to halve the percentage of people without access to safe drinking water was reached in 2010, there are still 663 million people living under water-deficit situation, mostly in regions from Africa and Asia [14]. Furthermore, more people means more food demands, which again points to water supply. If sufficient irrigation water cannot be ensured, issues to secure food supply will rise too.

Water pollution and sanitary problems are noteworthy in the mean time. Annually, a great amount of wastewater is generated in urban areas. This amount of wastewater needs to be treated in treatment plant before being discharged back to nature. However, according to 2017 World Water Development Report [15], more than 80 % of wastewater is discharged directly to receiving waters in developing countries. Globally, 2.4 billion people are still lacking adequate access to sanitation systems [14]. Compared to the efforts made to extend water supply coverage, improved sanitation coverage receives less attention, and the percentage varies from country to country. In developed countries, water supply and sanitation coverage reach both nearly 100 %, while in many developing countries, water distribution system can cover almost the whole nation, with a relatively lower sanitation coverage. Due to inadequate sanitation systems, pure freshwater resources are contaminated by untreated or simply treated wastewater, which in turn, aggravates water scarcity. Serious water pollution has also threatened human health, approximately four fifths of diseases are water-borne that caused by poor water quality [16]. In addition, pesticide residues in the water may result in eutrophication, which might cause irreversible biodiversity loss of aquatic ecosystems [17].

Climate change is also becoming a prevalent environmental issue. Both global warming induced by greenhouse gas emission and urban micro-climate such as urban heat island [18] could imperils water security. The occurrence of extreme weather events, including heat, drought and rainfall, is observed to be more frequent, as well as the magnitude is predicted to be increasing. Heat waves and droughts would potentially raise water and energy consumption, such as household cooling and crops irrigation, influencing the water-food-energy nexus. While the intensified precipitation makes impervious urban areas much easier to be inundated since the generated run off has extended the capacity of drainage systems. In a word, the current urban water systems are facing a great challenge.

2.1.3. Conventional urban water management approach

The principle of existing urban water management model can be traced back to the 19th century, when the population number was not large, water stress was subtle and environment was in a good health condition [19]. Developed countries started their practices at an early stage. Water-related institutions have been established by sufficient financial and human resources. While for developing countries, limited financing capacity make them fall behind to build a well-functional urban water system, and weak institutional efficiency drives situation even worse.

Normally, urban water management involves water supply, sanitation and storm water management. Conventional approach is following a simple take-use-dispose chain. Freshwater is abstracted from water sources and then distributed to different sectors. After that, generated wastewater is transported to wastewater treatment plants (WWTP) and finally be discharged back to natural water bodies after treatment. Notably, high-quality drinking water is delivered to different users indiscriminately, without making a water quality portfolio for different activities [20]. In addition, storm water is also collected and transported to WWTPs along with wastewater via combined sewer systems. The relatively clean rainwater dilutes wastewater flows and puts extra pressure on WWTPs. As climate change effects and population growth continue, increasing inflows of wastewater and rainwater might exceed the capacity of existing urban water system, then urban flooding will occur. Along this traditional one-way path of urban water management, each water component is considered separately. Instead, if water chain can be treated as a whole, for instance, rainwater and treated wastewater could be recycled for non-potable use to partially release growing water supply stress, it would be promising to enhance inner-city water circulation.

At the city scale, conventional urban water management approach usually invests a huge amount of money into centralized systems. These systems are too large to have flexibility [21]. In the face of future changes, existing centralized systems may lack ability to serve as a long-term solution. Besides, urban water plans often neglect the relations between upstream and downstream, and linkage to a broader basin-scale water management. On the other hand, urban water plans are also separated from urban spatial plans [22], which will potentially hinder sustainable urban development.

Fragmented institutions are considered to be the barrier to an overall approach [21]. In conventional urban water management, different water authorities are responsible for different water components under the guidance of distinct policies and regulations. Within water authorities, they are further divided into sub-sectors hierarchically. This way of distributing responsibilities and tasks leads to a complex situation, in which communications and coordination among sectors are difficult to be arranged. Without proper information exchange in the traditional system, interactions among water components are usually ignored, which would blind water managers to discover potential solutions to water-related issues. Hence, for a more comprehensive understanding of urban water management, integration of all related sectors, at different levels and scales, is of great importance [22].

2.2. International consensus

International consensus has been growing to address water security. Governments and experts from different disciplines are working together, seeking out a sustainable way to manage water resources.

2.2.1. Sustainable development

Ever since the Brundtland commission in 1987, the term sustainability has been addressed all over the world. The central principle of sustainability is identified as to improve human welfare for both current and future generations, without making irreversible damages to nature [1]. Human development is dependent on natural resources, which may be depleted in a few generations if we still keep the business-as-usual mode. Water, as one of the most indispensable resources for life, is the key to sustainable development [23].

Sustainable Development Goals

Although the 8 Millennium Development Goals (MDGs) have gained historical progress, the role that water plays to make contributions are only implicitly stated. Hence during 2015 UN Summit, the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development was adopted as successor of MDGs and launched in 2016.

The framework of SDGs proposes 'effective, accountable and inclusive institutions at all levels' (SDG 16) to serve as a strong base, by 'strengthening the means of implementation and revitalizing the global partnership' (SDG 17), to meet the other SDGs that will benefit the prosperity of people and planet. Among all the 17 SDGs, water-related issues are explicitly stated in SDG 6, which calls for integrated water resources management (IWRM) approaches to achieve 'universal and equitable access to water and sanitation for all' [2]. As water can be regarded as a bonding between human and environment, sustainable water management could be an entry point to promote other SDGs based on the foundation of SDG 16 and SDG 17 [3].

Circular Economy

Circular Economy (CE) usually comes up along with sustainability. This concept started to be noticed in the 1970s [24]. While CE receives many discussions and researches, there are bunch of definitions offered by different authors and organizations [25][26][27][28], and the relations between CE and sustainability remains unclear. However, the core of CE could be summarized as reducing the input of finite resources by reusing/recycling 'generated wastes' as new resources during different phases of a loop business model, which may ideally lead to zero-waste discharge.

The application of CE concept has been much discussed within water management. As water shortage is becoming increasingly prominent, the traditional take-use-dispose water chain could be replaced by a closed water loop. Surface water, groundwater, storm water and even treated wastewater can be treasured as potential water sources. In other words, every drop is valuable. Different flows can be diversified, which would increase water availability for different purposes. In addition, the application of CE in water sector will open the opportunity for economy, society and environment, the three pillars of sustainability, which will move SDGs agenda forward.

2.2.2. Urban framework

As urbanization trend continues, it is foreseeable that in the emerging future, cities will be the main location where human socio-economic activities take place, and sufficient water resources in urban areas can make sure everything works smoothly [4]. Therefore, to get along well with sustainable development, it is essential to consider urban water systems when we plan and design sustainable settlements , so that in this man-made environment (i.e. cities), human and nature can live in harmony.

Since current urban water systems are facing a lot of challenges, transformations are needed to change the status quo. As a result, realizing sustainable urban water management would be strongly supportive for sustainable urban development, which would finally contribute to the prosperity of both people and planet. So designing future cites and reinventing existing ones are inseparable from designing urban water systems, and thus collaborations between nations and disciplines are necessary.

New Urban Agenda

One year after the proposal of SDGs, the New Urban Agenda (NUA) was adopted in 2016, which represents a shared vision of 167 nations for how to plan, manage and live in future cities [29]. The NUA is closely linked to SDGs agenda, especially with SDG 11 of 'sustainable cities and communities', and other SDGs can also be reflected in the principles and commitments outlined in the NUA. These two agendas are so well-connected that the NUA can be regarded as the carrier for SDGs. Cities will be the key to solve the major challenges that are threatening the world now.

NUA emphasized the importance of 'universal access to safe and affordable drinking water and sanitation', which shares the goal with SDG 6. The water vision of NUA is that water resources in urban areas, as well as its relations to land, can be protected and conserved to support social, economic and ecological functions of city. In order to achieve the vision, all the nations involved committed to promote integrated management of water, land and other related resources, and to strengthen interdisciplinary communication for improved human habitat. This reveals the desire that subjects involved in urban development need to work together, especially for the main two, urban water management and urban design.

2.3. Transition to a more sustainable urban water management

Urban water situation will be more dynamic in the future, which could go beyond the capability of existing urban water management approach. As the relations between water, urban design and sustainable development have been discussed above, a paradigm shift is now acknowledged for a more holistic and integrated water system and water management approach.

2.3.1. Integrated urban water management

Integrated urban water management (IUWM) approach is now becoming widely-accepted to push forward the paradigm shift, providing the potential to satisfy the water demand of cities at the lowest costs while minimizing adverse environmental and social impacts [22]. IUWM is nested within the framework of integrated water resources management (IWRM), which gives an outlook for consideration over the entire water cycle, thus the idea of IUWM is to treat urban water system in a holistic manner [30], aiming at improved availability of and access to water facilities, and minimized negative impacts on water.

Based on the understandings of Global Water Partnership (GWP), an international organization that advocates IWRM as the main guideline of its operation, the intentions of IUWM can be translated into five principles [22][31][32], which are:

- **Involving all key players:** Since the fragmentation of institutions is considered to be the main barrier, IUWM proposes to identify all the key stakeholders and involve them through planning, decision-making, implementation and monitoring processes continuously. The role and responsibility of each stakeholder should be clear.
- **Considering the entire urban water system holistically:** Conventional water chain should be replaced by a circular way, in which each water component is part of a plan instead of isolated

activity. The improved approach also has the potential to be contextualized into a broader basin-scale water management framework.

- **Assessing a portfolio of water resources:** To form a circular water loop, different water resources within urban catchment can be considered as potential sources, and they should be connected. By diversifying different water flows, IUWM recommends to take water quality into account so that different water quality can match different purposes.
- **Maximizing benefits from waste:** Now that wastewater could be potential resource, reusing at local scale may be the most suitable way considering the transportation costs. In this case, decentralized systems would be promising for productive use.
- **Designing adaptive systems:** There are still uncertainties in the future, such as climate change and demographic change. When developing IUWM strategies, the resilience of cities needs to be reserved to confront these uncertainties. Hence, urban water systems should not only be robust enough to solve existing problems, but also be flexible to cope with changing conditions in the future.

IUWM approach provides water managers and experts with a mindset to rethink the management of urban water systems. It should be well noted that IUWM is a way of thinking, rather than a methodology per se. There is no one-fits-all IUWM model, cities have their own IUWM strategies with a combination of solutions which are best appropriate for their own issues.

Closed city

Among many researches on discussing IUWM approaches, the concept of Closed City is proposed for transitions to more sustainable urban water management within Dutch urban contexts [5]. A closed city refers to 'a city that does not have adverse effects on its surroundings, such as water depletion or emission of pollution'. In the closed city, the value of local water resources are treasured, such as storm water and treated wastewater. These water flows can be recycled through either centralized or decentralized solutions. Based on the selected solutions, three possible urban layouts are consequently discussed, which is presented in Figure 2.1.

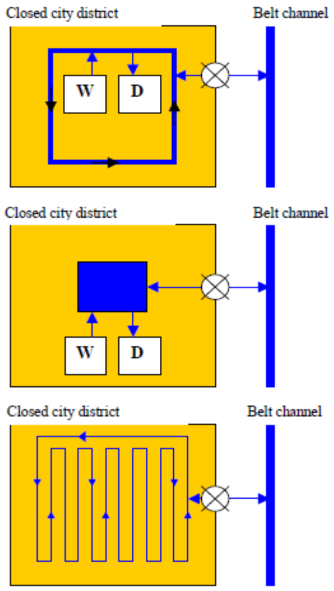


Figure 2.1: Three urban layouts of closed city (Rutger 2005)

- **Ring type:** A ring canal is structured for a circulated system. Centralized WWTP is located at the upstream, discharging treated wastewater into the canal, while the drinking water treatment plant stands at the downstream of the flow. This system involves the natural purifying function of surface water by adding the pumping station at the end of the canal so that adverse impacts on surrounding areas are reduced.

- **Lake type:** A central lake is created in the district, which is the main source of local water supply. Centralized WWTP and drinking water treatment plant are constructed, while the surplus water will be pumped outside. Besides the expected function to reduce water stress, the central lake is assumed to offer extra recreational values for local residents.
- **Channel type:** Longer canals are constructed for a circulated system. The use of longer canals is to connect all households to the surface water because decentralized wastewater treatment and water supply systems are applied, which is different from the other two types. Decentralized solutions could be either grey infrastructures (e.g. settling basin) or green infrastructures (e.g. reed bed filter).

From the perspective of water management, the proposal of closed city and its possible layouts could considerably decrease the vulnerability of cities to face climate change [33]. However, there may be some questions remaining to realize this conceptual design. Since land use change is included in the three possible plans, and which solutions are going to be selected and where to locate them may go beyond the capability of water managers, in this case, cooperation with urban planners becomes necessary.

Nature-Based Solutions

The application of either grey or green solutions in the proposal of closed city refers to one extensively-discussed issue in recent years, which is the trade-off between grey and green infrastructures. According to the 2018 UN World Water Development Report [34], green infrastructures are the application of nature-based solution (NBS), of which the feature is 'proactively manage natural processes to achieve a water-related objective'. Plants and vegetation are indeed water recyclers instead of water consumers [35], so that NBS are able to secure water availability, improve water quality and reduce water-related risks. Applications of NBS will support circular economy and yield significant benefits for human and nature.

NBS also calls for a more integrated water resources management, and two tools are appreciated to be normally employed, which are integrated land use planning and IWRM [34]. Therefore, in this report, the performance of grey and green infrastructures in urban water systems will also be discussed, to examine how they can contribute to sustainable water systems.

2.3.2. A glance on the Netherlands

Water management in the Netherlands

Dutch people have been learning to live with water for many years. Their low-lying country is famous for the polders, which are the results of land reclamation. To defence river flooding and for some military and economic reasons [36], the combination of dug canals and natural rives creates the unique landscape of the Netherlands.

Water management in the Netherlands may originate in the 13th century, when the first water boards were formed. Today, systematic water institutions are well established, from the state government to each province and finally to municipalities. Central government supervises through the Ministry of Transport, Public Works and Waterways to coordinate inter-provincial rivers and lakes, while the provinces are responsible for groundwater and recreational water. At local scale, water boards take care of flood control and surface water, while municipalities are in charge of sewer systems. Water supply is provided by drinking water companies, who are responsible for different regions of the country.

The government realized the importance of a more integrate water management since the 1980s [36], and several water-related legislations have been introduced. The National Water Plan (NWP) is the official water policy plan that is reviewed every six years. The core of NWP is 'sustainable water management' [37], which also includes the relations between water and spatial development. In 2009, the Water Act merged eight existing water acts and came into force. The Act emphasizes the role of water systems that mediate the relationship between water, spatial planning and water users [38]. Therefore, for a better future to live with nature, Dutch cities are taking the lead in the transition to a sustainable water management approach.

Rotterdam's pathway towards a resilient city

Rotterdam is one of the most outstanding Dutch cities to realize a water-proof future. Located at the delta of River Rhine and River Meuse, Rotterdam is influenced by four types of water flows, which are the sea tides, river discharge, precipitation and high groundwater table. Because of some districts being 6 meters below sea level, flood control is always on the top of Rotterdam's agenda. Although sufficient dikes have been constructed, much of Rotterdam now lies in outer-dike area due to urban expansion. Meanwhile, the municipal drainage system is under burden and not sufficient enough to deal with climate change. Many people have thus left because they cannot find preferred living environment, which causes a stagnation of population in Rotterdam [39]. Therefore, to offer attractive living quality and adapt to climate change, Rotterdam determined to reinvent itself as a water city of the future.

The municipality of Rotterdam and its water board drafted Rotterdam Waterplan 2 in 2007 to promote IUWM approach that focuses on water shortage, water quality and flood control. Rainwater is recognized as an alternative water source to collect, and innovative ideas are applied for water storage, such as water plaza and multi-functional garage. Citizens are also encouraged to participate in the implementation of the Plan, for instance, through a campaign called 'Paving out. Plants in.', private house owners who are willing to replace impermeable surfaces in their yards and install green roofs are granted.

By learning from nature, Rotterdam keeps focus on how the city can function as an ecosystem to not only solve water-related issues, but also provide a smart living way for residents. Several projects have been implemented, but many of the districts are under planning, especially urban districts located in Prins Alexanderpolder of north Rotterdam are less involved. In addition, the Prins Alexanderpolder is one of the lowest areas in the Netherlands. Therefore, these areas are appropriate for this research project, as the case study here would inspire other Dutch cities, even for urban areas that are outside of the Netherlands.

3

Research Methodology

3.1. Overview

This chapter provides the research processes and explains the methods that are applied for analyzing and evaluating spatial and environmental hybridity respectively. Figure 3.1 below gives the general framework of this research.

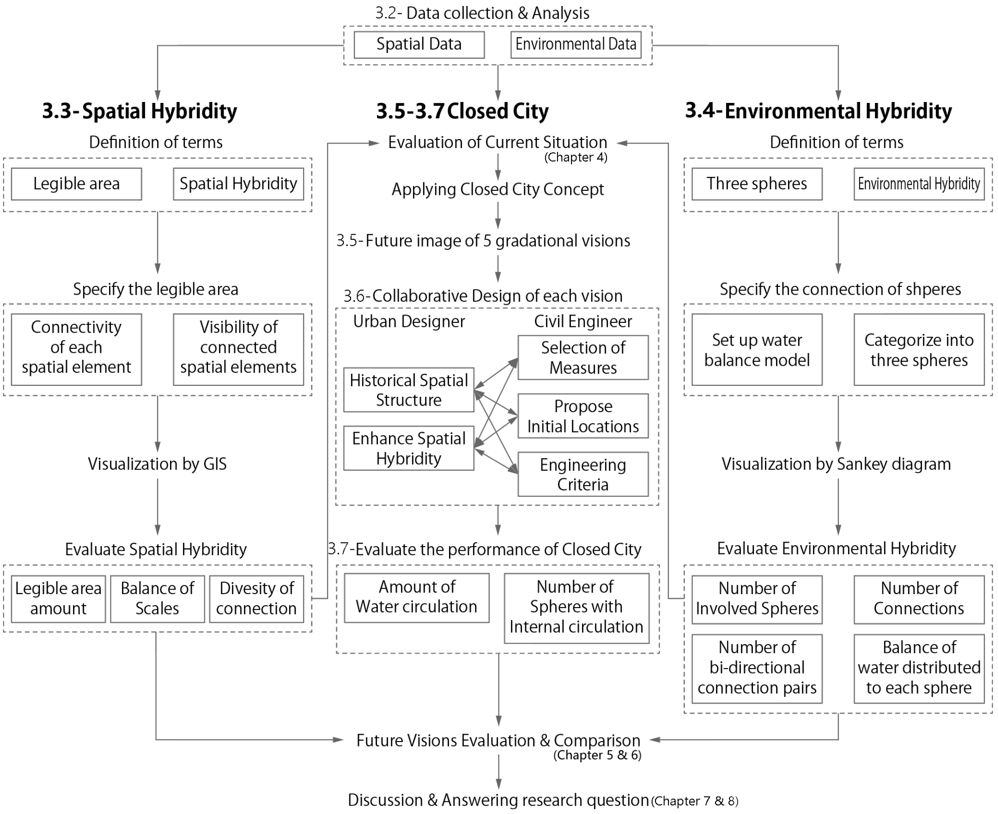


Figure 3.1: Research framework

Spatial data and environmental data are collected and analyzed as the first step. This work is a preparation for hybridity analysis. Land use identification will be carried out from spatial data, and environmental data will be used for water balance model. After data preparation, spatial and environmental hybridity analysis are applied to evaluate current situation in Zevenkamp. It is well-noted that all the results are visualized in the form of maps and diagrams before hybridity evaluation. Spatial calculations are based on the produced maps and environmental calculations are presented in diagrams so that all stakeholders, including general public, can get the most intuitive insights into the hybridity of urban water systems in current situation, as well as in each future vision.

Based on the results, five future visions are set up by applying closed city concept. Each future vision will install grey and green solutions, and the locations of these solutions will be determined through collaborative design between water management and urban design. The design phase will generate the urban layouts of each vision, and they will be evaluated in terms of the performance as a closed city, such as the amount of water circulation. Then the hybridity of each vision will be assessed. Finally, the evaluation results are compared and discussed, trying to answer the research questions.

3.2. Data preparation

3.2.1. Spatial data

Spatial data are provided by Rotterdam municipality, and the access to the municipality's internal GIS tool Gisweb 2.2 is also authorized. Land use identification is then operated on ArcGIS based on the spatial data and zoning plan from Gisweb. The identification of different land covers will be helpful to figure out the connections among spatial elements, and also gives the area of each land cover so that related water flows can be calculated by water balance model.

Land use for the following purposes are considered:

- **Buildings for different uses (Red):** Different uses include domestic houses, commercial companies and social buildings. This will be helpful when estimating drinking water consumption and wastewater production, as well as giving the area of rooftops for precipitation-related calculations. Industrial plants are special examples if they are found in study area, as they may have different water supply sources and on-site wastewater treatment facilities;
- **Streets (Grey):** Area of pavements are needed to figure out the amount of rainfall and consequent processes on the streets;
- **Unpaved area (Green):** Unpaved area can be used for public parks, private gardens, sports field or agricultural land. Besides processes that are related to precipitation, the amount of water for irrigation should be taken into account;
- **Surface water (Blue):** In our case, surface water can be canals and natural rivers/lakes.

3.2.2. Environmental data

Environmental data are mainly used as input values for water balance model. Hydrology-climate data are downloaded from official website of Royal Netherlands Meteorological Institute (KNMI, in its Dutch acronym). Data related to water supply, wastewater and sewer system are collected through interviews with Evides drinking water company, water board and Rotterdam municipality. More descriptions can be found in Appendix A.

3.3. Spatial hybridity

3.3.1. Definition of spatial hybridity

Before defining spatial hybridity and its methodology, an example of Het Nutshuis in The Hague is given in Figure 3.2. In this figure, all the spatial elements (i.e. red, grey, blue and green) are co-existing, and they are connected via water flows. For instance, buildings are disconnected from sewer system, rainwater on the rooftop is discharged to open water directly through downpout, thus red-blue connection can be observed. Similarly, storm water run-off on the disconnected streets will enter the open water too, forming visible grey-blue connection. As for green-blue connection, although subsurface infiltration and drainage processes are invisible, people can still feel the connections between green and blue by seeing the involved spatial elements. Therefore, Het Nutshuis is a legible area where people can understand the water system. In this research, a legible area is defined as the collective area of viewpoint where different spatial elements connected through water systems are visible.

Figure 3.2: Het Nutshuis showing different spatial elements

However, Het Nutshuis is only at architectural scale, which means people can only feel the connections at specific locations. To expand legible area to city level, it is essential to create more legible areas that are connected to each other. In this case, spatial hybridity refers to spatial continuity and diversity of legible areas located in city. People can feel the connections among different spatial elements through water systems in a sequential and diverse network of legible areas. These spatial elements are connected to each other either by artificial infrastructure or natural process. The example of connections by artificial infrastructure is the red-blue connection in Het Nutshuis, and example of connections by natural process is the green-blue connection in Het Nutshuis. Therefore, connections among and legibility of spatial elements are identified to analyze spatial hybridity.

3.3.2. Spatial analysis

Connectivity

Connectivity is the term used to describe the spaces that are connected via water systems. As there are four types of spatial elements included in spatial dimension, the connections could be diverse and complex. The most common connection is between two elements such as red-blue in Het Nutshuis. Connections among three or four elements are also possible such as red-green-blue and red-grey-green-blue. Four-element connections may be explained as follows, rainwater from the building that is disconnected from drainage system will flow to the street beside the building, the street is also disconnected from drainage system, so the water from building and run-off on this path will flow to the green space next to the street, most of the water will infiltrate and finally enter the river close to the green space, while a small amount of run-off will directly flow to the river.

To determine all the types of connections, it is done by analyzing spatial data on ArcGIS and Gisweb. The pipe network is examined to see if all red and grey spaces are connected to sewer system, and to understand how the water flows in the pipes. Blue and green connections are checked by studying GIS layer of groundwater, to see how subsurface flows are drained into open water.

Legibility

After all the types of connections having been identified, the legible area that consists of involved spatial elements are analyzed in each connection type. The legibility is defined to describe all the connected spatial elements can be clearly visible within the region of gaze from eye level of a person. It is assumed that all spatial elements in this area are visible. In reality, people can appear at any location that is in this region, so the collection of all these locations is the legible area of spatial connections.

Legible area is calculated based on the estimation of the average eye level of Dutch people in this research. First, the distance range is calculated. It can be seen from Figure 3.3, the average eye-level of Dutch people is $h = 1.65m$, and they have a viewing range of 60 °under normal situations such as standing and walking (i.e. $\theta = 30$ °). θ' is the central region of the depression angle, which is 80 °. Therefore, $a = h * tan\theta' = 9.36m$, $b = 2 * a * tan\theta = 10.8m$, and $c = a/cos\theta = 10.8m$. Since it is possible that people can have 360 °rotation at the viewpoint, the region where gaze is concentrated can be identified by drawing two circles with radius of 9.36 m and 10.8 m, as shown in Figure 3.3. As a result, 10.8 m is applied to determine the legible area.

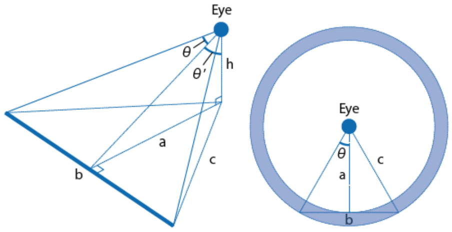
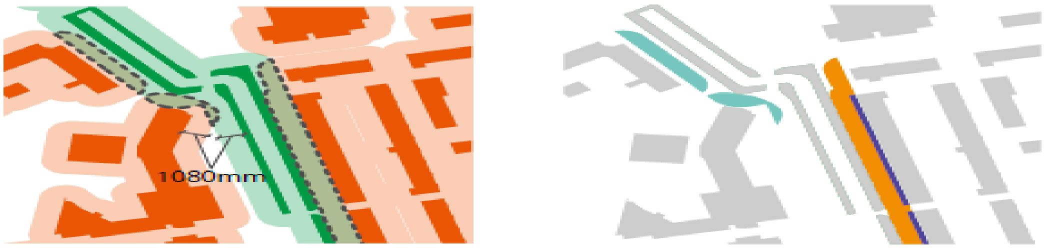


Figure 3.3: Calculating gaze concentrated region

Next, within the range of 0 to 10.8 m from connected spatial elements, the buffer area of each element is drew, see Figure 3.4a. If the buffer areas have intersecting parts, these intersecting parts are the legible area in which people can see all the connected spatial elements, shown in Figure 3.4b. When people enter legible areas, they will have opportunities to experience the water system connecting spatial elements.



(a) Drawing buffer area

(b) Legible area

Figure 3.4: Estimating Legible area of spatial connections

3.3.3. Spatial evaluation

It is assumed that spatial hybridity will be high if different types of connections can be experienced in sequential legible areas. Therefore, three indicators are selected to evaluate the sequence of legible areas and types of connections, which are explained in the following paragraphs.

Amount of legible area

The total legible area is the most important indicator among all three. Only the area is large enough, then there will be possibility to experience sequential and diversified connections. The amount of total legible area is calculated by internal geometry functions of ArcGIS. Then the percentage of legible area out of the whole study area will be calculated. This percentage is indicating the level of spatial hybridity in terms of legible area. Spatial hybridity is higher if the percentage value is larger.

Balance of scales

To ensure the legible areas are in a sequential network, it is essential to consider different locations for people to experience. Therefore, three spatial scales are recognized, which are housing, neighbourhood and regional scales. Imagine a person who is walking from his house to a park, if he can witness the connections along his journey from his private garden, walking through his community and finally in the park, he would have experienced a sequential contact with water systems, thus he would get strong perception of water flows. Spatial elements that are classified into three scales are listed below.

- Regional scale refers to the canals, streets, tram line, high way and public green structure which are connected with outside areas.
- Neighbourhood scale are the rest of streets and public green space.
- Housing scale are mainly private gardens.

The evaluation of sequence is carried out by assessing the balance of three scales.If the scales are more balanced in the city, people can understand not only parts of water system at housing or neighbourhood scales, but also the overall water structure at regional scale. Based on the definition of each scale, the legible area will be categorized into scales on ArcGIS and using its geometry function to obtain the area of each scale. Then the percentage of each scale out of the total legible area is calculated. Finally, the standard deviation of the three percentage values are calculated. This deviation number reflects how deviate among the three percentages. If deviation number is lower, three scales will be more balanced, and thus higher spatial hybridity.

Diversity of connections

If diverse connections can be found, this means different spatial elements are connected. This would offer more opportunities for people to feel the urban water systems. In addition, it also implies that more pathways are provided for water flows.

To evaluate the diversity, since legible area is analyzed in each connection type, so a GIS layer of legible area is generated in each connection analysis. We set all the layers have the same color and transparency, and put all the layers on ArcGIS successively. With the subsequent layer covering the previous layer, legible areas that have multiple connection types will display denser color while areas with single connection have lighter color. Then the areas with denser colors are calculated by ArcGIS. The diversity is then expressed by calculating the percentage of area with multiple connection types out of total legible area. A higher diversity percentage means higher spatial hybridity.

The table below is a summary of spatial hybridity analysis.

Table 3.1: Spatial hybridity methodology

Analysis		
Step	**Definition**	**Method**
Connectivity	Spatial elements that are connected via water systems.	Analyzing GIS data on ArcGIS/Gisweb.
Legibility	An area where connected spatial elements are visible so that people can feel water system.	Drawing on ArcGIS with 10.8 m.
Evaluation		
Indicator	**Method**	**High spatial hybridity if it is**
Amount of legible area	Percentage out of total study area	High
Balance of scales	Standard deviation of percentage out of total legible area	Low
Diversity of connections	Percentage of area with multiple connections out of total legible area	High

3.4. Environmental hybridity

3.4.1. Definition of environmental hybridity

Environmental hybridity in this research refers to the involvement of the three spheres and connections via water flows among them. The three spheres are the defined components of environmental hybridity, which are clarified here as follows.

- **Geosphere** is the collection of lithosphere, hydrosphere and atmosphere;
- **Biosphere** refers to fauna, flora and all ecosystems;
- **Technosphere** is composed of various technological artefacts.

One thing should be noted is, it is difficult to separate the three spheres, especially for biosphere and geosphere. Therefore, the boundary of three spheres is defined here. Since human and nature are the two beneficiaries when we discuss sustainable development, the three spheres of environmental hybridity should not go beyond the boundary of human and nature systems. According to Hooimeijer et al. [40], human and nature systems are inter-connected and they link all the living creatures, resources and spaces integrally, see Figure 3.5.

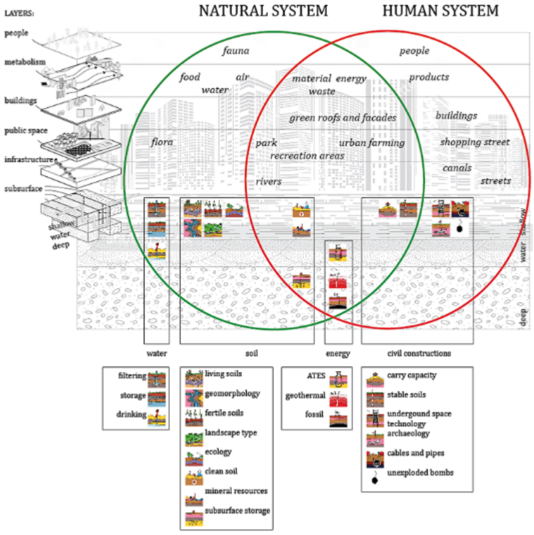


Figure 3.5: Inter-connections between human and nature systems (Hooimeijer,Maring and Van Campenhout 2016)

It can be inferred that the three spheres should also be inter-linked. As a result, the three spheres are overlapped on each other and lie within human and nature systems in our definition, as shown in Figure 3.6. For instance, buildings, streets and pipes belong to technosphere, while atmosphere, groundwater and rivers/lakes can be included in geosphere, and biosphere consists of fauna and flora. Later in Chapter 5, when we discuss Sankey diagram for environmental hybridity in future visions, the three spheres and their overlapped parts will be filled in with different solutions that are involved in urban water systems. The most vital message here is that the three spheres are intertwined and they are interacting with each other.

3.4.2. Environmental analysis

Water Balance

To look into how the three spheres contribute to environmental hybridity and how they are connected with each other by water flows, water balance analysis of the study area is selected as the main method. Water balance analysis is an entry point for investigating urban water systems [41][42]. For studying environmental hybridity, a water balance model is set up to calculate different water flows through the three spheres. From land use identification, the model will first calculate the water amounts on different land covers according to associated hydrological processes. Then the flows can be categorized into three spheres to be visualized.

The water balance model set-up is based on an existing spreadsheet model [43] from Deltares, a research institute in Delft. This spreadsheet model only considers the flow pathways in terms of precipitation, so we modify the model by adding water supply and wastewater amounts. Briefly speaking,

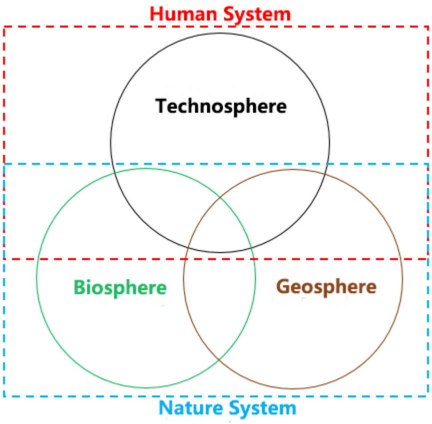


Figure 3.6: The three spheres are inter-linked and under human and nature systems

the water balance model considers five types of zoning areas, which are buildings, streets, unpaved space, open water and subsurface. At the city scale, there are generally four incoming sources, which are precipitation, water supply, surface water and groundwater. Correspondingly, the outflows are evapotranspiration (ET), wastewater, discharge to outside waters and groundwater recharge. Table 3.2 below summarizes major water flows through each identified sector. The time step of the model is in the daily base.

Table 3.2: Water flows through different sectors

Water Sector	Inflows	Outflows
Buildings	Precipitation Water Supply	Evaporation Wastewater Runoff to Sewer
Streets	Precipitation	Evaporation Runoff to Sewer Percolation
Unpaved Space	Precipitation Disconnected Runoff Irrigation	Evaporation Infiltration Surface Runoff
Subsurface	Infiltration Percolation	Transpiration GW Recharge GW Drainage
Open Water	Precipitation GW Drainage Sewer Overflow	Evaporation Pumping Out

- **Buildings**
  Buildings have two inflows. Drinking water enters through distribution pipes and is discharged into combined sewer system as wastewater. Precipitation drops on the rooftops of buildings. Part of the rainwater is intercepted and evaporates, while generated run-off is drained into combined sewer systems. If rooftops are disconnected to sewer network, it is assumed that run-off will go to unpaved space;
- **Streets**
  Precipitation is the only incoming flow for streets. Rainwater is intercepted and then evaporates. Storm water run-off enters combined sewer systems. If streets are disconnected to sewers, run-off is assumed to flow to unpaved space. Considering open pavements, which are partially pervious, intercepted water is assumed to directly recharge the groundwater if it is not completely emptied through evaporation;

- **Unpaved Space**
  Irrigation and precipitation are the main water sources for unpaved areas. Run-off from disconnected parts is also included. Water will either evaporate or infiltrate into subsurface area. It is assumed that surface run-off goes to open water. If there is no open water, run-off will remain at unpaved space to evaporate or infiltrate;

- **Subsurface**
  Subsurface area is further divided into two layers, unsaturated zone and saturated zone (groundwater). Water infiltrates into unsaturated zone from unpaved space, then part of water leaves unsaturated zone through transpiration and the rest continues to percolate downwards. Downward seepage will meet saturated zone, which will recharge deep groundwater and drain slowly to open water. There may be percolation upwards (e.g.capillary rise) from groundwater to unsaturated zone;

- **Open Water**
  Open water mainly receives two inflows, groundwater drainage and precipitation. Combined sewer overflows (CSO) may occur during rainy days, which have negative effects on open water. For Dutch polders, if surface water level is beyond controlled level, pumping stations will start to work to get rid of extra water to outside waters.

Detailed information about the model as well as the code can be found in Appendix A.

Visualizing water balance

Sankey diagram is selected to visualize the water balance results calculated by the model. A Sankey diagram distinguishes different fluxes from their sources to targets, by using the thickness proportionally to illustrate the amount of flows. Therefore, the incoming and outgoing flows of different water sectors that are listed in Table 3.2 can be illustrated in the Sankey diagram. Figure 3.7 below is an example that visualizes water balance calculations. This will directly show how different land covers are involved in the urban water system, and it will be helpful for categorizing each component into three spheres. To be consistent with the elements defined in spatial dimension, the colors used for buildings, streets, unpaved area and open water are red, grey, green and blue respectively. In addition, colors are also applied to represent different water flows, blue is the common water, grey color refers to wastewater while green color means ET. By this visualization, water system can be illustrated in a straightforward way so that all stakeholders can understand how incoming water is distributed in the study area and examine the pros and cons of water system. All the Sankey diagrams in this report are produced in Python language imported from Plotly [44].

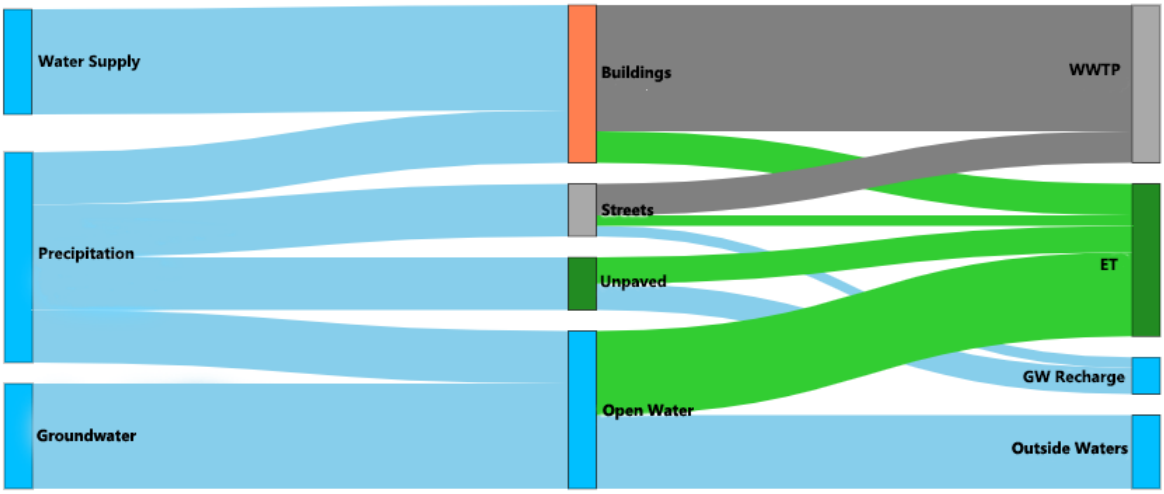


Figure 3.7: A detailed Sankey diagram example that visualizes water balance

Visualizing environmental hybridity

Based on the visualization of water balance, the next step is to categorize different water sectors into three spheres so that environmental hybridity can be visualized. For visualizing environmental hybridity, Sankey diagram is applied again. After all water sectors have been classified into three spheres, we can examine different water flows that are involved in different spheres, thus the level of environmental hybridity can be figured out. Figure 3.8 gives a simple example of our expected outcome.

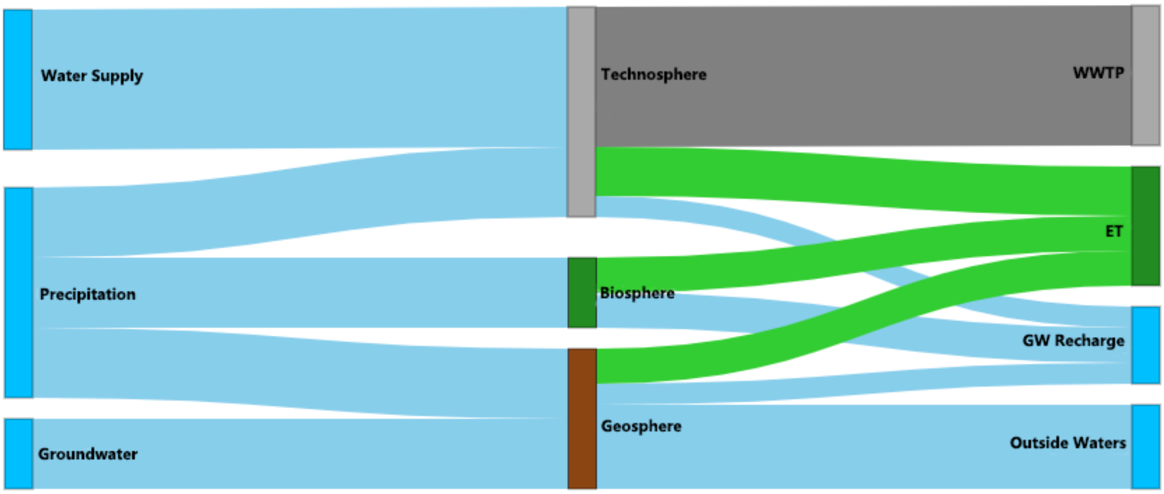


Figure 3.8: An example of Sankey diagram for visualizing environmental hybridity

The amount of different water flows in the figure 3.8 is obtained by adding up the calculated streams of different water sectors included in each sphere. Ideally, we hope to see all the three spheres are connected, and water consumption for each sphere can be balanced as much as possible. Under this condition, we assume the environmental hybridity is high.

3.4.3. Environmental evaluation

From Figure 3.6 and Figure 3.8, the Sankey diagram showing environmental hybridity will be summarized into a chart for evaluation, shown as Figure 3.9. From this chart, spheres are connected by arrows, which shows the flow direction. In addition, the overlapped spheres are also considered as one unit in the chart. In particular, the techno-bio-geosphere (T-B-G) is the overlapped part among all the three spheres. Therefore, if the chart illustrates more spheres and connections are involved, then the relations among three spheres are close and tight, and if water amount distributed to each sphere is balanced, then each sphere is equally important and one can be alternative pathway if failure occurs in other spheres, thus the environmental hybridity is high, as well as the robustness of water systems.

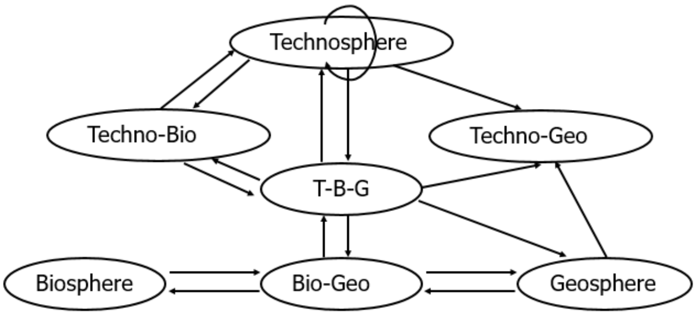


Figure 3.9: An example of environmental hybridity chart

Four indicators are set to assess the environmental hybridity:

Involved spheres

The number of involved spheres is counted from hybridity chart. If more spheres can be involved, then the connections might be more diverse, and therefore the environmental hybridity is higher. Ideally, all the spheres will be involved in future urban water systems, especially the overlapped ones.

Connections

After involved spheres having been determined, the connections between each other can be drew on the chart as the arrows. Then the number of arrows are counted from the chart. Environmental hybridity is higher if arrows are more.

Bi-directional connections

As shown in Figure 3.9, connections (i.e. arrows) between two spheres can be bi-directional, which means there will be flow exchange. This infers that the two spheres are dependent on each other and these bi-directional linkages could contribute to a robust water system. The number of bi-directional connections in pairs will be counted from the chart. Environmental hybridity is higher as the pair number increases.

Balance of water distributed to each sphere

If water that flows through each sphere is not balanced, almost all the water is involved in only one sphere, then the water system relies on this specific sphere too much. The system thus will be less robust if failure occurs in that sphere. Hence, each sphere should be the same importance to the water system. The balance of water distribution is shown by calculating the standard deviation of involved water quantity in each sphere. Water quantities are calculated by the water balance model. Environmental hybridity is higher if deviation number is lower.

The table below is a summary of environmental hybridity analysis.

Table 3.3: Environmental hybridity methodology

Analysis		
Step	**Method**	
Water balance analysis	Model calculation	
Visualizing water balance	Sankey diagram	
Visualizing environmental hybridity	Sankey diagram	
Evaluation		
Indicator	**Method**	**High environmental hybridity if it is**
Involved spheres	Number counted in hybridity chart	High
Connections	Number of arrows in hybridity chart	High
Bi-directional connections	Number of bi-directional arrows in pairs in hybridity chart	High
Balance of water distributed to each sphere	Standard deviation of involved water quantity in each sphere	Low

3.5. Future visions set-up

Both spatial and environmental analysis will be carried out for current situation in the study area Zevenkamp. Then possible future visions for Zevenkamp are assumed by applying closed city concept.

According to closed city, either grey or green solutions can be employed to solve water-related issues. Therefore, three types of future Zevenkamp are imaged.

- **Mechanical district:** All the solutions will be grey infrastructures so that water flows can be controlled in a sound pipe network. This is a strongly mechanical way.
- **Green district:** On the contrary, all the solutions can be green infrastructures to apply natural processes to treat water. This is a green vision of future cities.
- **Mixed district:** This district will install both grey and green infrastructures. However, the combination of grey and green can be different. Therefore, in the mixed district, three mixed visions will be discussed, which are more grey solutions are applied, more green solutions are applied, and balanced application of grey and green.

For the mixed type of Zevenkamp, the proportions of applied grey and green solutions can be different, therefore, three mixed visions will be discussed in terms of different combinations of solutions, which are more grey, more green and balanced. Finally, five future visions are produced. These five visions are in a gradational change from completely grey solutions to totally green solutions in the future city.

3.6. Collaborative design

Based upon the five future images, the design of future urban layouts are needed so that each vision can be evaluated regarding to spatial and environmental hybridity, as well as their performances as a closed city. This design phase is a collaborative step when the two disciplines, water management and urban design are working together and reflecting to each other to design future Zevenkamp by improving its water system. This section explains how the design phase goes on and how design criteria from two different expertise are finally merged, detailed descriptions on collaborative design phase can be found in Appendix C.

From the perspective of water management, grey and green solutions are first selected as closed city proponents. Rainwater and treated wastewater can be recycled/reused, so rainwater harvesting (RWH), decentralized wastewater treatment systems (DEWATS) and reed bed are selected. The closed city should also be climate-resilient and less bothered by urban flooding, so green solutions such as wadi, green roof and rain garden are applied. Besides, existing grey infrastructure can be improved as well by replacing combined sewer with separated sewer. Solutions that will be discussed in this project are summarized in Table 3.4.

Table 3.4: Selected solutions for future Zevenkamp

Type				
Grey	DEWATS	RWH	Separated sewer	
Green	Reed bed	Green roof	Rain garden	Wadi

Next, potential locations of the solutions are proposed from water management side. For instance, RWH can be applied on sloping roofs, while green roofs are installed on flat roofs. Wadi and reed bed need to be placed in public green area, while rain garden are in private gardens. The location of DEWATS is referred to a pilot-scale project in China [45], in the basement of a building within the neighbourhood. Meanwhile, some engineering criteria are considered. For example, the area of reed bed is related with the population number, each person needs approximately 4 m^2 helophyte and each reed bed needs at least 200 m^2 [46] [47]. Reed bed and wadi should have connections to open water, while rain garden has some distance requirement to avoid moisture issues to buildings. These criteria are considered for proposing the initial locations of all solutions.

Afterwards, these initial locations are discussed with urban designers. According to urban design expertise, the original spatial structure provides a network that can be transformed into high spatial hybridity. Therefore, different solutions need to be located at the places where they can create connections to the historical spatial structure. In addition, the final locations should also contribute to high spatial hybridity. By drawing and modifying the locations on ArcGIS, the final places for applied solutions are determined through discussions and reflections back and forth between two disciplines.

3.7. Performance of closed city

The closed city concept is trying to reduce the environmental footprint of urban area, as well as its dependence on external water resources. By applying grey and green solutions, occurrence of combined sewer overflow is reduced, thus decreasing emission of pollution. Moreover, these solutions will help circulate potential local water resources such as rainwater and treated wastewater so that water supply could be secured.

Since all the applied solutions eliminate combined sewer overflows in each future vision, in this research, the performance of closed city will be evaluated in terms of their ability of water circulation, and two indicators are applied for evaluation.

- **Amount of water circulation**
  Selected measures in this research for recycling/reusing rainwater and treated wastewater are RWH, DEWATS and reed bed, as mentioned in the previous section. Therefore, if more local water resources can be collected, then the dependence on external water resources can be reduced. The amount of circulated water from each solution is calculated by water balance model, then the total amount of water circulation is calculated by summing up the amount of all applied solutions in each vision. If more water can be circulated, the performance of closed city is better.

- **Number of spheres with internal circulation**
  The application of RWH and DEWATS are the type of grey infrastructure, thus they belong to the technosphere of environmental hybridity. Collected rainwater and treated wastewater will be recycled back to buildings for non-potable use, which are also included in technosphere. Therefore, there would be an internal circulation in technosphere. If pathways for water flows entering technosphere are unfortunately all blocked, the internal circulation would strengthen the ability of technosphere under extreme conditions, and thus make water systems more robust. The number of spheres with internal circulation is counted from the hybridity chart, see the example of Figure 3.9. If one sphere has internal circulation, a rotated arrow will be added on this sphere in the chart. If the number of spheres with internal circulation is higher, then the performance of closed city is better.

Afterwards, the spatial and environmental hybridity of each vision are also analyzed and evaluated. The evaluation results of each vision in terms of performance of closed city and hybridity are compared and presented in Chapter 6. By comparing the five visions, the contributions of grey and green solutions to closed city, as well as the relations between environmental hybridity and spatial hybridity can be discussed, which will answer the research questions raised in the beginning.

4

Current situation of Zevenkamp

4.1. Study site, Zevenkamp

Zevenkamp is located in Prins Alexanderpolder to the north-east of Rotterdam city center, as Figure 4.1 shows. The main structure of Zevenkamp was planned in 1976 and built in the following 10 years by filling sand on highly-compressed peat and clay [48] [49], as a result, Zevenkamp becomes the second largest district that was developed in the 1970s in the Netherlands, covering an area of around 200 hectares.

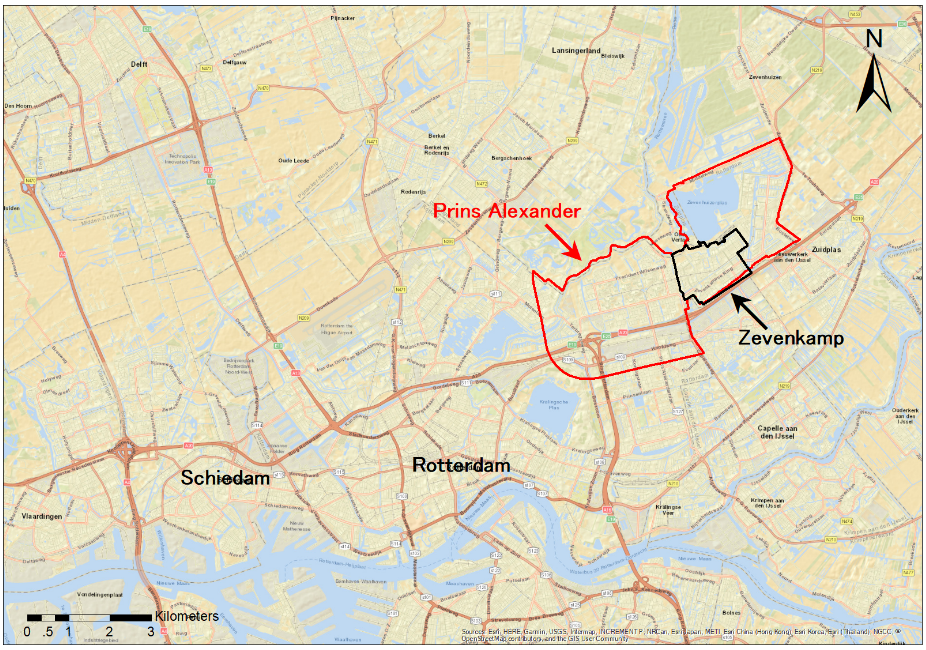


Figure 4.1: Location of Zevenkamp District

Zevenkamp is adjacent to Ommoord district on the west and eastern Nesselande. At southern border of the district lies the national highway A20. The center of Zevenkamp is surrounded by a ring road that provides access to outside. A tram line goes from west to the east in the polder creating public connection to central Rotterdam, with three stations are positioned in Zevenkamp.

Canals in Zevenkamp are fed by River Rotte through culverts in the north-western corner of the district. Ommoortse Tocht is the main canal that runs parallel to the tramway. There is currently no water shortage issues but water quality problems in Zevenkamp. As rainfall events in the Netherlands are usually pretty intensive during a short period, the existing combined sewer system has difficulty dealing with such events. Sewer overflow often occurs and the nutrients contained in the overflow have undesirable impacts on canals. The growth of weeds and algae can be commonly found in Zevenkamp. In addition, due to the low elevation of Prins Alexanderpolder, high groundwater table causes some moisture problems to some buildings.

Most Dutch housing properties were constructed in the 1970s and it has been 40 years since the development. While these districts are still functioning, some signals can be observed, such as stagnant housing price and falling population [48]. These signals are indicating the district is deteriorating, which means interventions are necessary to renew the district so that values can be preserved and large-scale re-structuring is saved. By studying Zevenkamp area, it will give an example for regeneration of other 1970s districts, as well as the promotion of sustainable urban water system nationwide if it is practical in this low-lying polder.

The land use in Zevenkamp district is illustrated in Figure 4.2.

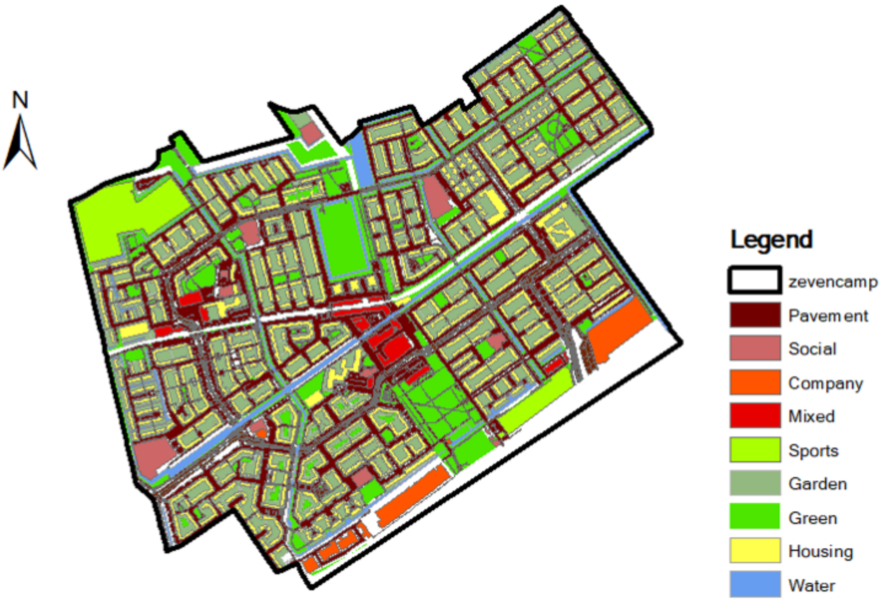


Figure 4.2: Land use in Zevenkamp

For unpaved area, it covers 48 % of Zevenkamp, which is the biggest share. There are three types use, which are public green, private gardens and sports fields. Private gardens contribute to almost half of pervious area, while the second comes public parks, which is 30 %. There are also some unpaved small pathways alongside the canals. These pathways, as well as sports fields, are categorized as other unpaved area, counted as 21 % of pervious area. Currently, agricultural lands are not existing in Zevenkamp.

The land use for buildings comes after unpaved area, which is 20 % of total area. There are generally four types of purposes for buildings. Residential use is the majority, which is nearly third-fourth of all buildings. Mixed buildings consist of different stores such as restaurant, supermarkets and gyms. To simplify, mixed buildings and companies are categorized as business use, which occupies 16 % buildings. The rest are social buildings, including schools and daily care centers. There are no industrial plants in Zevenkamp.

Pavements in Zevenkamp have two types, open and closed. Open pavements are partially pervious, which means a small amount of rainwater can infiltrate into subsurface. While the closed ones have to be connected to sewer systems so that surface run-off can be discharged. The total area of streets is 54 ha, with the major 47 hectares are open pavements.

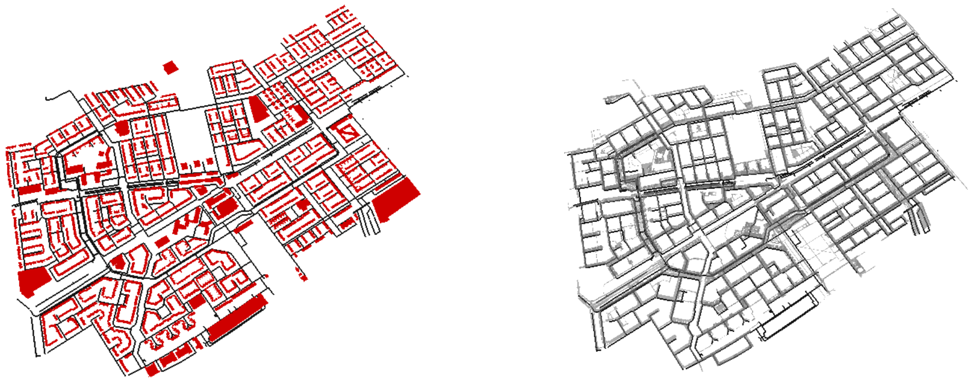
There are no natural lakes in Zevenkamp, almost all surface water is canals. The total area of open water in Zevenkamp is 11 hectares.

4.2. Spatial hybridity of current Zevenkamp

4.2.1. Results of spatial analysis

Connectivity

Currently in Zevenkamp, both red and grey are connected to combined sewer network, as shown in Figure 4.3. All the storm water run-off and wastewater are transported to WWTP. Therefore, there are no connections between red and other spatial elements, so does grey. There is only one situation when combined sewer overflow occurs, then red and grey are connected to blue. However, this connection causes negative impacts on water quality, and thus it should be avoided in the future cities. This negative connection is then not considered.



(a) Red and sewer network

(b) Grey and sewer network

Figure 4.3: Red and grey are connected to combined sewer system in current Zevenkamp

Blue and green are connected normally via infiltration and subsurface flows. During rainfall events, if run-off is generated on the surface of green space, it will directly flow to the canals nearby. The green and blue areas are shown in Figure 4.4. Green-blue connection is the only type of connection in current Zevenkamp.

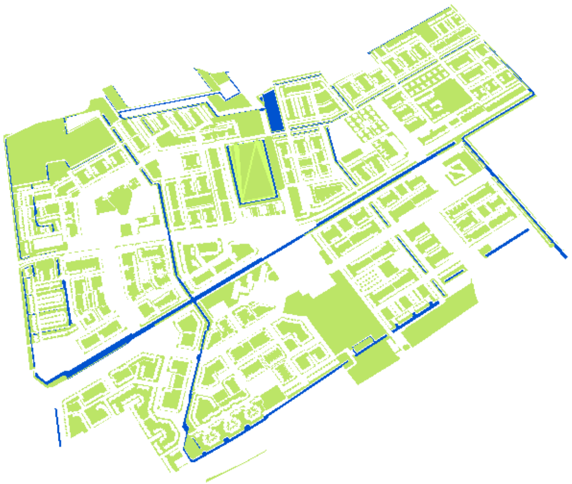


Figure 4.4: Green and blue are connected in current Zevenkamp

Legibility

Legible area where people can feel the green-blue connections are presented in Figure 4.5. It can be observed that although unpaved space has the largest share in land use of Zevenkamp, the legible area of green-blue connection is limited to the river bank. This is in accordance with the explanation of legible area. Since people can feel the connections only the connected spatial elements are visible to them, in the green space that is out of 10.8 m away from the water, water system is not legible to people. Therefore, the location of green space and the area of open water should be taken into consideration when trying to create the green-blue connection.

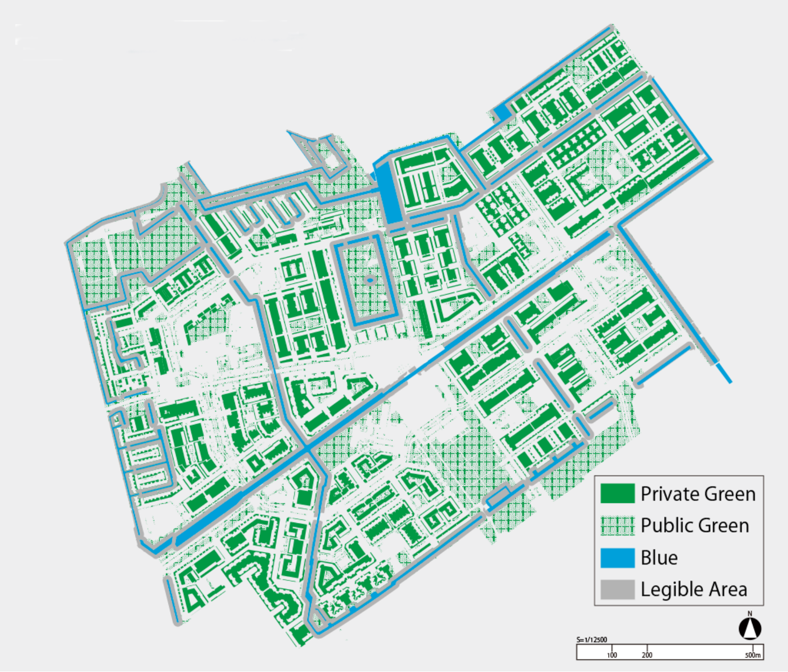


Figure 4.5: Legible area of green-blue connection in current Zevenkamp

4.2.2. Results of spatial evaluation

Amount of legible area

From Figure 4.5, the amount of legible area is calculated to be 26 hectares by ArcGIS. The percentage of legible area out of total Zevenkamp is then $26/200 * 100\% = 13\%$. It can be seen from the map that legible area is sequentially connected as the canal network.

Balance of scales

The legible area is categorized into three scales, as shown in Figure 4.6a. Areas that are in the scale of regional, neighbourhood and housing are 5 ha, 18 ha and 3 ha, respectively. Therefore, the percentage of each scale out of total legible area is 19 % regional, 69 % neighbourhood and 12 % housing. The standard deviation value of the three percentages is calculated as 25.1.

As neighbourhood scale has the biggest percentage, currently in Zevenkamp, public green space in communities are the main places for local people to experience water system. Residents can feel the spatial connections at housing scale when there are canals next to their own gardens, such as western part of Zevenkamp in Figure 4.6a. Legible area of regional scale is also limited, which may give no chance for people travelling through Zevenkamp to recognize the spatial connections via water.

Diversity of connections

Since there is only green-blue connection in current Zevenkamp, from Figure 4.6b, no other layers of legible area are loaded, therefore, the diversity of connections is 0 for current Zevenkamp. People can only experience one type of connection, which is not helpful for urban water systems to be perceived.

(a) Legible area in three scales

(b) Diversity of connections in legible area

Figure 4.6: Maps for spatial evaluation of current Zevenkamp

4.3. Environmental hybridity of current Zevenkamp

4.3.1. Results of environmental analysis

Water Balance

From interviews with Rotterdam municipality, Evides drinking water company and water board, three incoming flows into Zevenkamp are identified: water supply, precipitation and groundwater drainage; four outflows are wastewater to WWTP, ET, groundwater recharge and pumping to outside waters. A summary of current water balance in Zevenkamp can be found in Table 4.1.

Table 4.1: Water Balance of Zevenkamp in 2016 (Unit: $10^6 m^3$)

Label	Inflow	Outflow
Water Supply	1.01	
Precipitation	1.78	
Groundwater	0.7	
WWTP		1.35
ET		0.81
GW Recharge		0.41
Outside Waters		0.68
Total	3.49	3.25
Δ S	0.24	

Precipitation takes up about half of incoming flows, which makes it the biggest contributor. Annual potable water supply is the second largest inflow. The water supply amount in Table 4.1 has already considered leakage from distribution system and groundwater infiltration into pipes. Groundwater drainage is about 20 % of total inflows. As mentioned before, there are moisture issues in some buildings due to high groundwater table. Drainage pipes are installed to discharge this amount of water directly to open canals, which is not included in the table due to insufficient information.

WWTP receives the largest outflow from Zevenkamp. Due to combined sewer system, this amount of water consists of rainwater and wastewater, which gives much pressure to treatment plant. ET is the second outflow, which is not surprising as unpaved area covers most area in Zevenkamp. The next highest flow is the water that is pumped outside. In 2016, several sewer overflows actually occurred. The total amount of overflow is about 25,000 m^3. This amount is present in the Sankey diagram in Figure 4.7 and 4.8. Groundwater recharge flow is approximately 13 % of total outflows. It is calculated based on the assumption that downward seepage is a constant flux.

The difference between total inflows and outflows seems to be a bit large. This could be explained by the storage change in the soil. However, it might also be attributed to the quality and compatibility of data from different sources and performance of the model. More discussions on the cause of this difference will be included later in Chapter 7.1.

A detailed Sankey diagram is produced based on model calculations. From Figure 4.7, three columns can be read. The first column represents incoming flows to different water sectors in the middle. It can be seen that different colors are applied to different water sectors. This is corresponding to the elements defined in spatial hybridity (i.e. red, grey, green and blue). Finally the third column lists the four outflows.

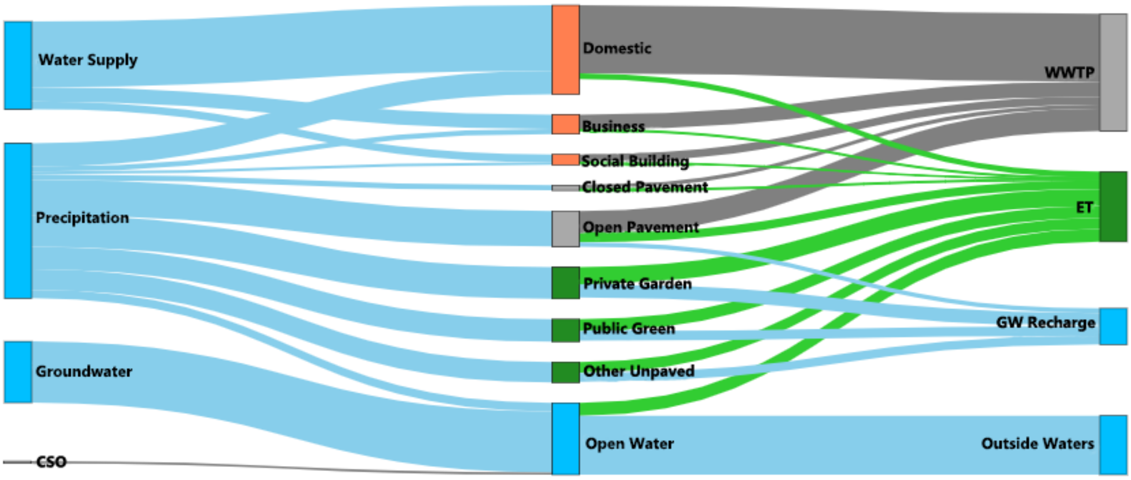


Figure 4.7: A detailed Sankey diagram of Zevenkamp in 2016

It is clear from the visualized diagram that how different sectors are involved in urban water system, e.g. for a specific water user, the diagram illustrates how many inflows and outflows are related and how much different flows contribute to the water balance of this user. To be short, the diagram shows all the pathways of water in urban water systems. This will give the most intuitive insight into the performance of urban water system and can indicate potential solutions to improve the system. For instance, in Figure 4.7, most of the incoming rainfall will end up in WWTP. Instead, by installing separated sewer system or even rainwater collection pipes, the pressure of WWTP can be released, as well as the negative impacts on canals from sewer overflows. Besides, the dependence on external water supply can be reduced if rainwater can be recycled in the district, which may pave the way towards closed city.

Visualizing environmental hybridity

Different water sectors in Figure 4.7 are categorized into three spheres to draw a Sankey diagram that can show environmental hybridity. The visualized product is shown in Figure 4.8 and the connections among different spheres are summarized in Figure 4.9.

Inflows and outflows are the same as Figure 4.7. For technosphere, it includes all the buildings, pavements and pipes. Hence, sewer overflows can be considered as outflows from technosphere, but with adverse effects on canals. Unpaved surface is recognized as biosphere, which involves infiltration and evaporation. The infiltrated water enters into root zone, which is defined as the overlapped part between biosphere and geosphere (i.e. bio-geosphere). Two outflows from root zone are the transpiration of vegetation and downward seepage to deeper subsurface area, the geosphere. From geosphere, the water will be stored for groundwater recharge. It should be noted that the incoming groundwater drainage is also from geosphere. For the canals, they are categorized into overlapped part between technosphere and geosphere, the techno-geosphere, because they are man-made rivers. In fact, Figure 4.8 is different from the expected diagram given in Figure 3.8. First, the connections between biosphere and geosphere through root zone was not recognized in the example. Since un-

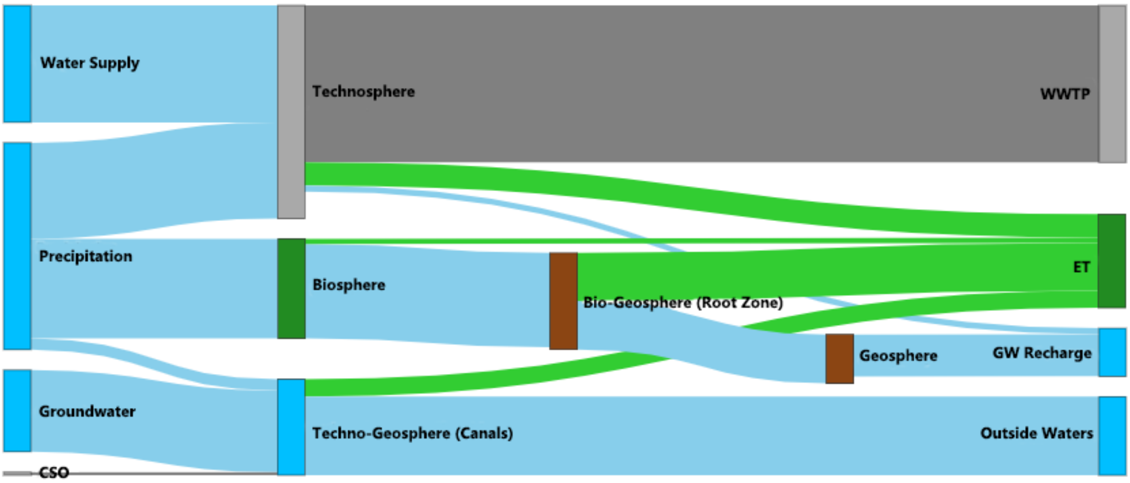


Figure 4.8: Sankey diagram of environmental hybridity of Zevenkamp in 2016

paved surface and subsurface are closely linked, these connections are actually natural and cannot be neglected. Second, the actual hybridity is more complex than anticipation. Hence, the overlapped parts are equally important and can contribute to environmental hybridity.

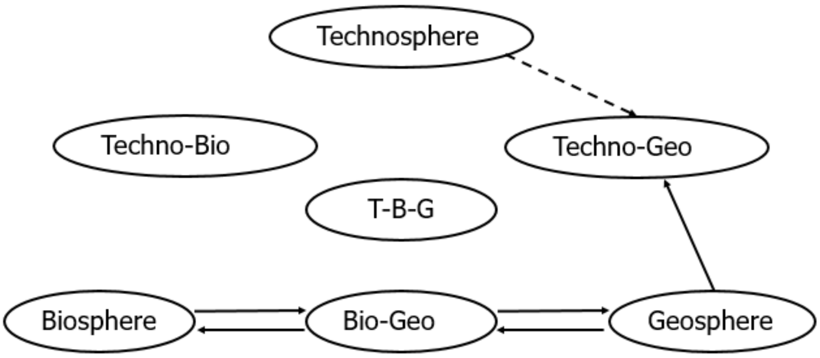


Figure 4.9: Environmental hybridity chart of Zevenkamp in 2016

4.3.2. Results of environmental evaluation

Involved spheres

Currently, only five spheres are involved in environmental hybridity, which are technosphere, biosphere, geosphere, techno-geosphere and bio-geosphere. There are few green solutions applied now in Zevenkamp, and this could be the reason for the other two spheres being unrelated.

Connections

In total there are six connections. However, the dashed-line arrow from technosphere to techno-geosphere represents the CSO occurrence. The negative impact caused by this connection is undesirable and thus should be eliminated in the future.

Bi-directional connections

There are two pairs of bi-directional connections, which can be found between biosphere and bio-geosphere, bio-geosphere and geosphere. These interactive connections refer to exchange flows between two spheres, for example, water infiltrates into root zone from biosphere, while capillary rise takes place from root zone to biosphere. Actually, these connections are the natural processes, thus in any city, at least two pairs of bi-directional connections should be present.

Balance of water distributed to each sphere

Water quantity of each connection is listed in Table 4.2 below. The standard deviation value of all water amounts is $3.15 * 10^5$. Most water amounts are between biosphere and geosphere, and this could be attributed to the largest percentage of unpaved area in Zevenkamp. The two biggest water quantities are from biosphere to bio-geosphere, and from geosphere to techno-geosphere (i.e. canals). This is corresponding to the spatial green-blue connection in current Zevenkamp.

Table 4.2: Water distribution to each sphere in current Zevenkamp

From	**To**	**Amount [m^3]**
Technosphere	Techno-Geo	25000
Geosphere	Techno-Geo	704000
Biosphere	Bio-Geo	813000
Bio-Geo	Geosphere	420000
Geosphere	Bio-Geo	54000
Bio-Geo	Bioshpere	112000

4.4. Summary

From the results of spatial hybridity, in current Zevenkamp, the area of unpaved space, including public green and private gardens is considerable. This may be good for flora and fauna. However, the sequence of legible green-blue area is following the open water network of Zevenkamp, while the area of open water is the smallest part of land use, which limits the legible area for visualizing green-blue connection. Local residents can feel the water system mostly in public parks of their neighbourhoods, only a small part of inhabitants living by water can experience green-blue connection at their private gardens. Observation of green-blue connection at regional scale is also limited, this will reduce the ability of local residents to understand the relations between water system of Zevenkamp and that of outer-Zevenkamp area. Besides, the limited regional-scale legible area also fails to provide opportunities for tourists who travel through Zevenkamp to recognize the spatial connections via water system. Red and grey are still separated to connect with other spatial elements. To diversified the connection types and increase spatial hybridity, grey and green solutions could be essential.

In terms of environmental hybridity, technosphere produces a significant amount of wastewater that puts WWTP under stress. In the future, measures need to be taken to reduce wastewater. This could be realized by recycling treated wastewater as an alternative water resource from closed city concept. The negative impacts of CSO from technosphere should be avoided in the future. Separated sewer system is one option. Further, the value of storm water can be treasured. Clean rainwater can be collected for non-potable use. Biosphere and geosphere are highly interactive by considerable water flows, which is related to the spatial connection between green and blue. To enhance environmental hybridity, more spheres should be included, as well as more connections. This could be achieved by grey and green solutions too.

5

Future visions of Zevenkamp

5.1. Future uncertainties

Before setting up the future visions, uncertainties should be taken into account so that urban water system has flexibility to adapt to any future changes. In this report, climate change and demographic change are considered. These two factors will be discussed in this section, and they will be included in water balance calculation.

5.1.1. Climate change

The future climate of Netherlands could present a big challenge to urban water systems. According to KNMI [50] [51], the mean temperature will increase in the future, leading to mild winter and hotter summer. Consequently, average precipitation amount is getting larger in all seasons except summer. The duration of summer rain events will decrease while the intensity is stronger. Sea level will continue to rise.

KNMI considers two variables, global temperature and air circulation pattern, to set up future climate scenarios. In KNMI's assumption, the rise of global temperature could be moderate (G) or warm (W), while the change of air circulation pattern will lead to either high values (H) or low values (L). As a result, the combinations of two variables generate four scenarios, which are GH, GL, WH and WL. These scenarios can be applied to predict climate change around 2050 and 2085. In this project, the WH scenario for 2050 is selected, which is more extreme condition. Predicted change values are taken from KNMI reports and used to modify the input 2016 climate data of water balance model. A summary is present below in Table 5.1.

Table 5.1: Climate change values in 2050 of KNMI scenario (WH)

Season	**Variable**	**Indicator**	**Change**
Spring (Mar-May)	Temperature Precipitation	average average	+2.1 °C +9 %
Summer (Jun-Aug)	Temperature Precipitation Evaporation	average average potential (Makkink)	+2.3 °C -13 % +11 %
Autumn (Sep-Nov)	Temperature Precipitation	average average	+2.3 °C +7.5 %
Winter (Dec-Feb)	Temperature Precipitation	average average	+2.7 °C +17 %

5.1.2. Demographic change

Population change could influence the water demand and wastewater production. In 2016, there are 16,000 inhabitants living in Zevenkamp. Although Rotterdam is experiencing a stagnation of population, it is expected that in the future the city will attract more people to settle down and the population will increase slowly. Based on the prediction of UN Population Division [52], the average growth of Zevenkamp is 0.3 %. Therefore, approximately 17,500 residents will live in Zevenkamp by 2050.

5.2. Introduction of future visions

The results of spatial and environmental hybridity in three future visions will be given in the following sections. The first vision is a mechanical district where solutions are all in the type of grey infrastructures. The second vision is a green district in which all nature-based solutions are applied. The third vision is the combination of grey and green solutions, with different proportions. Mixed 1 vision has more grey solutions than green, while mixed 3 vision has more green solutions than grey. Mixed 2 vision applies both solutions in a balanced way. Solutions that are discussed here are listed in Table 3.4, but they are put below again.

Table 5.2: Selected solutions for future Zevenkamp

Type				
Grey	DEWATS	RWH	Separated sewer	
Green	Reed bed	Green roof	Rain garden	Wadi

During the collaborative design phase, the final locations for all solutions are determined, as shown in Figure 5.1. Different solutions will be installed at these locations in each vision. The process of selecting these locations can be found in Appendix C. There are three types of locations, which are along the streets, private gardens inside district and public green space.

Figure 5.1: Locations of all applied solutions in this research

The location of each solution is explained here as below:

- DEWATS will be installed in a small building (water housing) constructed in the public green of each community in Zevenkamp. A small pond will be dug next to the DEWATS house to store extra treated wastewater. If it is difficult to transform public green to water housing, such as insufficient space, then the DEWATS will be still placed in the basement of one building in the community. Details about how DEWATS is designed as water housing can be found in Appendix C.
- RWH systems are applied to all sloping roofs. The collection pipe will be located on the facade of the buildings so that people can witness along the streets.
- Separated sewer system will replace the existing combined sewer system. Since the pipe network is all buried underground, it is difficult for people to understand how water flows in pipes. Therefore, separated sewer is considered not to enhance spatial hybridity, and thus is not discussed in spatial analysis.
- Reed bed is installed in the public green of each neighbourhood in Zevenkamp. Since reed bed should always be connected to open water, there are two types of locations for reed bed. The first is along the canals so that extra water can be discharged directly. The other one is similar to water housing, a water pond is dug surrounded by reed bed to store the water.
- Extensive green roofs are installed on all flat roofs. However, if the buildings are too high to view green roofs for people, then it will not contribute to spatial hybridity. Therefore, green roofs are not included when discussing spatial hybridity.
- Rain gardens are installed in backyard private gardens by using 8 meters away from buildings as a safety distance to avoid moisture issues. In some parts, to regenerate the original polder structure, rain gardens are placed in the front yard of buildings so that people can view when traveling along the streets. For these rain gardens, a safety distance of 3 meters is applied [53]. More details can be found in Appendix C.
- Wadi is installed in public green areas of Zevenkamp. In addition, the locations of Wadi consider the connection to open water so that storm water can be discharged to canals afterwards.

5.3. 1st vision: Mechanical district

5.3.1. Selected solutions

For the mechanical vision, all the grey infrastructures are selected. The locations are indicated in Figure 5.2a.

Table 5.3: Selected solutions and locations in mechanical vision

Location	Solution
Public Green	DEWATS (water housing)
Along Street	RWH

5.3.2. Spatial hybridity of mechanical Zevenkamp

Results of spatial analysis

Connectivity

There are two types of connections identified in the mechanical Zevenkamp. The first is blue-green connection which is the same as in current situation, see Figure 4.4. The other type is red-green connection. This connection is created by water housing (i.e. DEWATS) and RWH. Produced wastewater in each community is transported to the water housing, where part of the treated wastewater is supplied back to buildings for recycling, while the rest is discharged into the pond in the public green area. For RWH system, rainwater is collected in the storage tank and used later for non-potable use, including irrigating plants, thus it connects red and green.

Legibility

Legible area of green-blue connection in mechanical district is the same as Figure 4.5. The legible area of red-green connection is shown in Figure 5.2a. Solutions along street are RWH systems, and water housing (DEWATS) is in public green area of neighbourhood. From the map we can see, the locations of water housing and RWH are fragmentally positioned compared to Figure 5.1, which may not be easily identified in a sequential network of legible area. By integrating the legible area of green-blue connection, the total legible area in mechanical Zevenkamp is shown in Figure 5.2b.

(a) Legible area of red-green connection

(b) Total legible area in mechanical vision

Figure 5.2: Legible area of mechanical Zevenkamp

Results of spatial evaluation

Amount of legible area

Based on the map of Figure 5.2b, the total legible area is 31.5 hectares, in which legible area of red-green connection is 5.8 hectares. Compared to the area of Zevenkamp, total legible area takes up $31.5/200*100\% = 15.8\%$. By applying grey solutions, the total legible area is increased. However, due to the fragmented distribution of applied solutions, the increased legible area of red-green connections are also fragmented and has limited connection to green-blue legible area.

Balance of scales

The legible area in each scale is given in Figure 5.3. Area of each scale is 5.1 ha of regional, 22.2 ha of neighbourhood and 4.2 ha of housing scale. The percentage of each area out of total legible area is 16.2 %, 70.5 % and 13.3 % in regional, neighbourhood and housing scales. Standard deviation number of three percentages is 26.3.

Legible area in neighbourhood scale still has the largest percentage among three scales, and the percentage even increases compared to current situation. From the map and also the definition of each scale in Section 3.3.3, the locations of water housing are in the public green of neighbourhood, and rainwater harvesting is along the streets inside the community, therefore the increased legible area are mainly in the neighbourhood scale.

Diversity of connections

By loading the legible area of green-blue connection and that of red-green connection on ArcGIS, the overlapped part between two layers is 0.3 ha, which is about 1 % of total legible area. It is not easy to find out this small amount of area in Figure 5.2b. While it can be inferred from numerical calculations. The total legible area is 31.5 ha, while the sum of legible area of green-blue (26 ha) and red-green (5.8 ha) is 31.8 ha. Therefore, the difference between the total legible area and the sum of legible area of each connection is 0.3 ha. In these overlapped areas, people can feel two types of connections at the same time, which are created through artificial infrastructure (i.e. water housing and RWH) and natural process (i.e. infiltration and subsurface flows) of water systems respectively.

Figure 5.3: Legible area in three scales in mechanical vision

5.3.3. Environmental hybridity of mechanical Zevenkamp

Results of environmental analysis

Water balance

Water balance results of mechanical vision are listed in Table 5.4. From this table, precipitation is still the largest incoming flow. Water supply amount is assumed to be the same as current situation. Because climate change is considered in future visions, both precipitation and groundwater drainage increase.

Table 5.4: Water Balance of mechanical vision (Unit: $10^6 m^3$)

Label	Inflow	Outflow
Water Supply	1.01	
Precipitation	1.87	
Groundwater	0.74	
WWTP		0.04
ET		0.95
GW Recharge		0.41
Outside Waters		1.51
Total	3.62	2.91
Recycle by DEWATS	0.37	
Recycle by RWH	0.05	
Δ **S**	0.3	

In mechanical Zevenkamp, the outflows to WWTP is decreased significantly. Most of the wastewater goes to DEWATS. Regarding to the calculations of DEWATS, it is assumeed that each DEWATS can treat 80 m^3/day and 50 % of purified water is reused based on the Chinese pilot project [45], and the rest of the water will be discharged to open water. Hence, discharge amount from DEWATS is the same as the recycling water by DEWATS. Groundwater recharge amount is the same as current situation, as we assume the recharge is at a constant rate. Since separated sewer is applied in mechanical vision, around 560,000 m^3 rainwater is discharged directly to canals through storm water drainage system (SWDS) annually. As the considerable amount of discharge from SWDS and DEWATS, water that needs to be pumped out is more than doubled of current situation. This might ask for more pumping stations in Zevenkamp. RWH system can collect about 45,000 m^3 from sloping roofs.

Sankey diagram of water balance in mechanical vision is given in Figure 5.4. It is clear that most wastewater is going to DEWATS and the burden of WWTP is reduced significantly. While on the other hand, the application of DEWATS and replaced SWDS increases the working load of pumping stations.

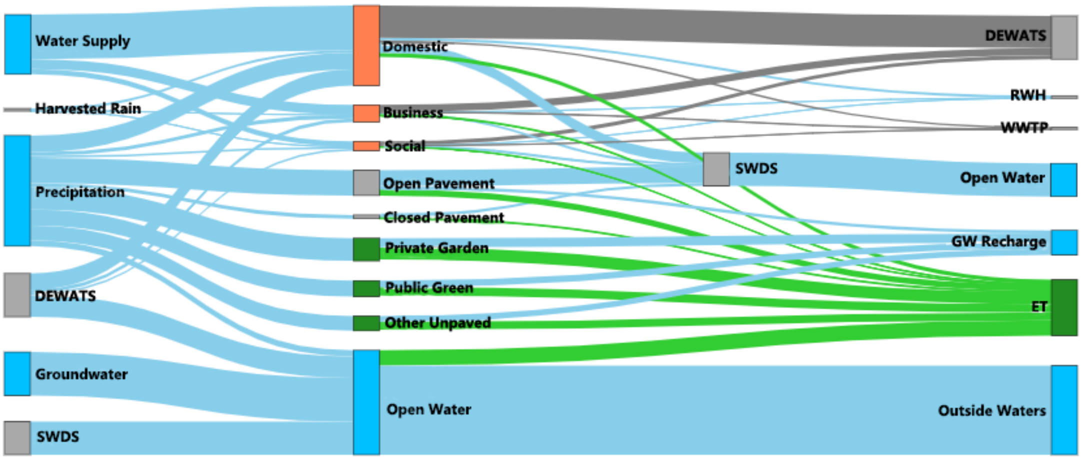


Figure 5.4: Sankey diagram of water balance in mechanical Zevenkamp

Visualizing environmental hybridity

Environmental hybridity of mechanical district is then visualized in Figure 5.5 and summarized in the environmental hybridity chart, Figure 5.6. Applied grey solutions of DEWATS, storm water drainage system (SWDS) and RWH are categorized into technosphere. Same as current situation, buildings and streets are included in technosphere, unpaved surface is in biosphere and it is connected to geosphere via bio-geosphere (i.e. root zone). Groundwater drainage into canals is from geosphere. It can be observed that water involved in technosphere is a big amount.

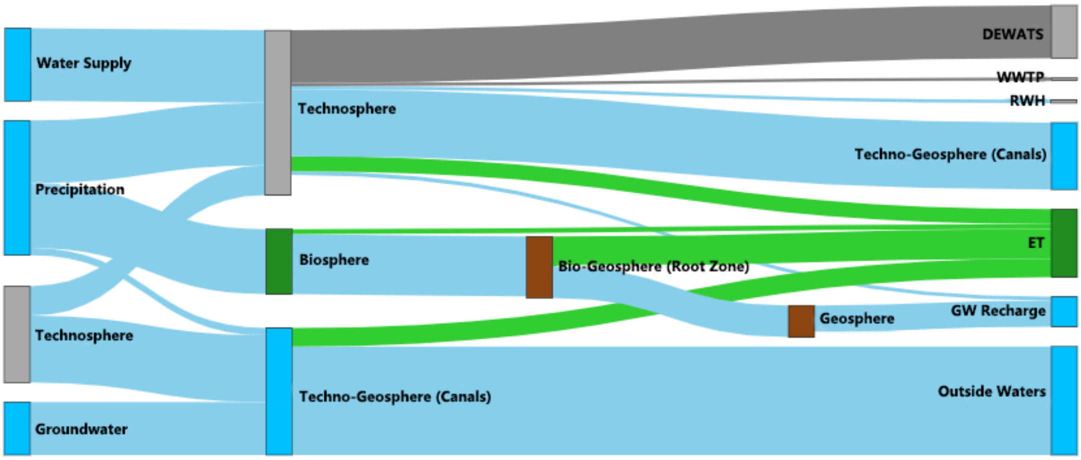


Figure 5.5: Sankey diagram of environmental hybridity in mechanical Zevenkamp

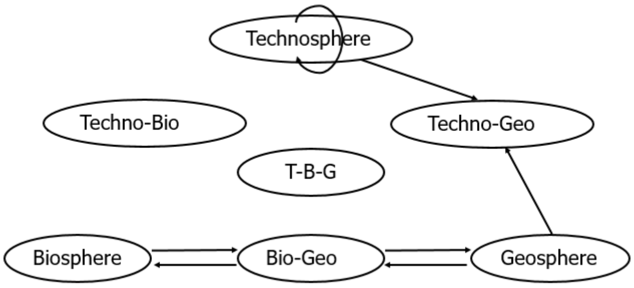


Figure 5.6: Environmental hybridity chart of mechanical Zevenkamp

Results of environmental evaluation

Involved spheres

The number of involved spheres is five, which is the same as current situation. Hence, applying only grey infrastructures cannot involve more spheres.

Connections

There are six arrows connecting the five spheres, which is also the same as current situation. But comparing to current Zevenkamp, the negative connection caused by CSO has been eliminated, no adverse effect from technosphere to techno-geosphere is existing. DEWATS and RWH from technosphere supply water to buildings in the same sphere, and discharge extra water to canals (i.e. techno-geosphere). By installing separated sewer system, clean rainwater is discharged to canals via SWDS in technosphere. Connections among biosphere, bio-geosphere and geosphere are the same as current situation.

Bi-directional connections

This number of bi-directional pairs is also the same as current situation. Two bi-direction pairs can be found between biosphere and bio-geosphere, bio-geosphere and geosphere.

Balance of water distributed to each sphere

The standard deviation of water amounts involved in each sphere of mechanical vision is calculated as $3.18 * 10^5$. This is a bit larger than current situation, which means water distribution in each sphere is more deviate. Most water is related to technosphere. This could be attributed to the applications of grey infrastructures. The quantity of water flows through each sphere are listed in the tables in Appendix D.

5.3.4. Performance of closed city in mechanical vision

Water circulation in mechanical Zevenkamp is realized by DEWATS and RWH. DEWATS treats wastewater from buildings in technosphere and supplies back, while rainwater from sloping roofs is collected and buildings with sloping rooftops use harvested rain for non-potable use.

Amount of water circulation

The total amount of water circulation is $0.42 * 10^6 m^3$, in which $0.37 * 10^6 m^3$ is from DEWATS and $0.05 * 10^6 m^3$ from RWH.

Number of spheres with internal circulation

Only technosphere has internal circulation, because DEWATS and RWH are in technosphere, all treated wastewater and harvested rain are circulated within technosphere.

5.4. 2nd vision: Green district

5.4.1. Selected solutions

For the green vision, all the nature-based solutions are selected. The locations are indicated in Figure 5.7.

Table 5.5: Selected solutions and locations in green vision

Location	Solution
Public Green	Reed Bed Wadi
Inside District	Rain Garden
Along Street	Rain Garden

5.4.2. Spatial hybridity of green Zevenkamp

Results of spatial analysis

Connectivity

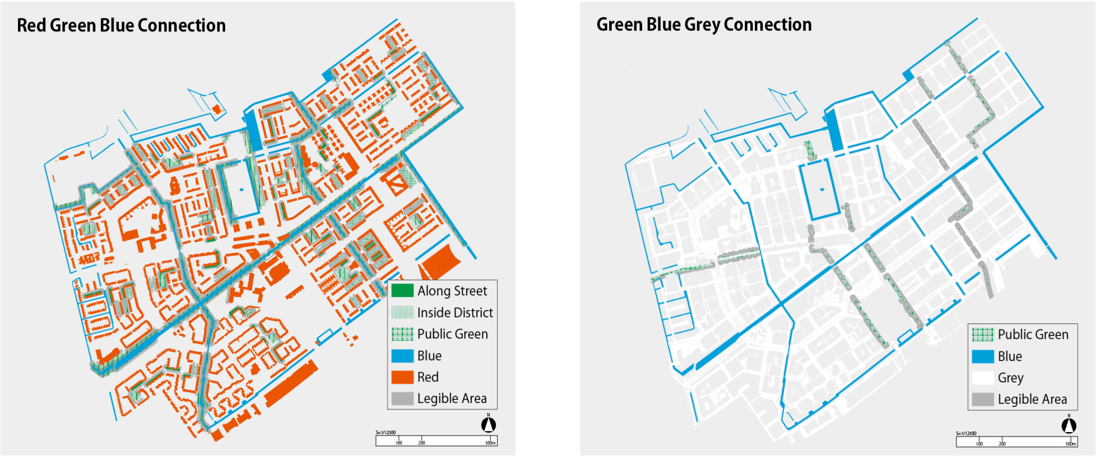
The applications of rain garden and reed bed create new connections among red, green and blue. Wastewater from buildings are treated by reed bed, and then extra treated water is discharged to open water. Rainwater from buildings without green roofs is flowing to rain garden and discharged to canals through drainage pipes. Therefore, there are red-green, green-blue and red-green-blue connections generated.

Installing wadi generates new types of connections among grey, green and blue. Storm water run-off on the disconnected pavements flows to wadi and is retained. It will infiltrate into subsurface and finally drain into canals, or will be discharged by pipes to the nearest open water if the amount is too large. Therefore, the application of wadi creates grey-green, green-blue and grey-green-blue connections.

In addition, the green-blue legible area in current Zevenkamp is still existing. Hence, in green vision, there are seven types of connections in total.

Legibility

Legible area of green-blue connection that is already existing is the same as Figure 4.5. The legible area of new connections in green vision is shown in Figure 5.7. A network of sequential legible areas are formed along the canals, as well as in the districts.



(a) Legible area of red-green-blue connections (b) Legible area of grey-green-blue connections

Figure 5.7: Legible area of each connection in green vision

Results of spatial evaluation

Amount of legible area

The total legible area is 45 hectares, which is 22.6 % of Zevenkamp, see Figure 5.8a. For connections set up by rain gardens and reed bed, legible area of red-green connection is 15.6 ha, green-blue area is 11.5 ha and red-green-blue legible area is 2.4 ha. While for connections created by wadi, grey-green area is 6.1 ha, green-blue legible area is 0.3 ha and legible area of grey-green-blue connection is 0.2 ha.

(a) Total legible area in green vision

(b) Legible area in three scales in green vision

Figure 5.8: Legible area and scales in green vision

Balance of scales

Legible area in three scales is shown in Figure 5.8b. It can be seen that legible area of regional scale is increasing, and these areas form two regional-scale legible zones which are crossed at the center of Zevenkamp. The legible areas of neighbourhood and housing scales are connected with regional-scale zones. In some parts, legible areas in three scales can be experienced sequentially.

The legible area of each scale is 9 ha for regional scale, 27.3 ha for neighbourhood scale and 8.7 ha for housing scale, which are 19.9 %, 60.7 % and 19.4 % of total legible area, respectively. The standard deviation is 19.3.

Diversity of connections

From Figure 5.8a, areas with denser color can be found along the canals and these overlapped areas are in a sequence. Legible area with more than one connection type is 17 ha, which is the difference between total legible area (45 ha) and the sum of legible area of each connection (62 ha). The percentage of diversity area out of total legible area is calculated as $17/45 * 100\% = 37.8\%$.

5.4.3. Environmental hybridity of green Zevenkamp

Results of environmental analysis

Water balance

Water balance results of green vision are listed in Table 5.6. Water supply and incoming rainwater remain the same as mechanical vision. Groundwater drainage increases slightly while the recharge amount drops a little. The reason could be the application of all green solutions. Infiltration process is enhanced by installing nature-base solutions, while these solutions also have drainage pipe underneath to discharge extra rainwater, thus rainwater goes to recharge is reduced. Wastewater to WWTP is halved compared to current situation. Although sewer network is still combined sewer system in green Zevenkamp, but there is no CSO occurring. ET increases because of the application of green infrastructures. Water that needs to be pumped out is large due to the discharge of extra water from green solutions. During model calculation, the total area of reed bed is calculated based on population in 2050, which is $17500*4 = 70000m^2$. This is because each person needs 4 m^2 reed bed for treatment [54]. Reed bed is installed to treat grey water, which is about 70 % of produced wastewater [55]. It is assumed the efficiency of reed bed is the same as DEWATS in mechanical vision, 50 % of treated water is supplied for recycling.

Table 5.6: Water Balance of green vision (Unit: $10^6 m^3$)

Label	Inflow	Outflow
Water Supply	1.01	
Precipitation	1.87	
Groundwater	0.76	
WWTP		0.64
ET		1.08
GW Recharge		0.37
Outside Waters		0.95
Total	3.64	3.04
Recycle by Reed Bed	0.27	
Δ S	0.33	

Sankey diagram of water balance in green vision is shown in Figure 5.9. Because the sewer network is still combined sewer system, SWDS is only installed for green roof, rain garden and wadi. For buildings without green roofs, it is assumed storm water run-off from rooftop is flowing into rain gardens. Wastewater from buildings with green roofs and unpaved roofs goes to reed bed for treatment, and extra water is directly discharged to open water.

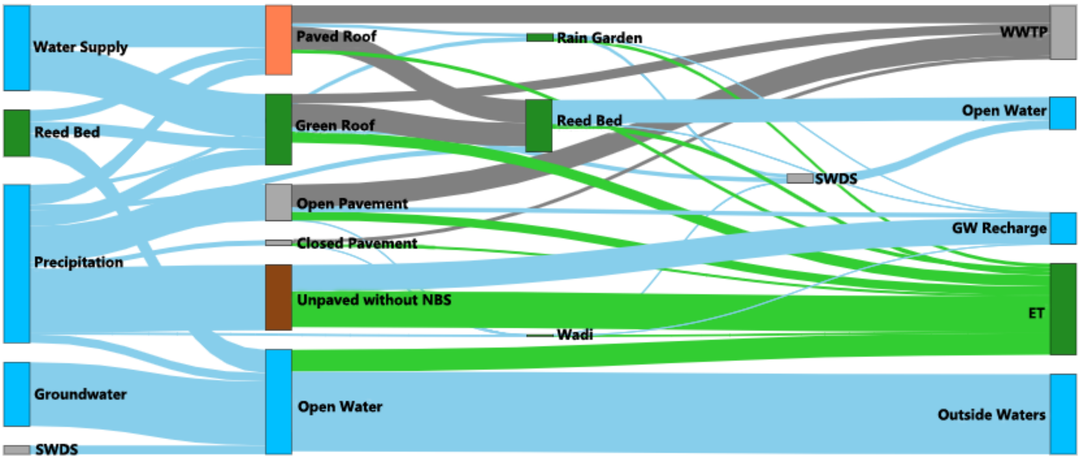


Figure 5.9: Sankey diagram of water balance in green Zevenkamp

Visualizing environmental hybridity

Based on the water balance visualization, the Sankey diagram of environmental hybridity in green vision is given in Figure 5.10 and summarized in Figure 5.11. Green roof is categorized into techno-biosphere, because it is installed on the top of building and the extra water is discharged through drainage system of technosphere, thus there is neither infiltration nor recharge to subsurface of Zevenkamp area by green roof. It can be seen from the diagram that many spheres are involved and the connections are really diverse and complex.

For reed bed, rain garden and wadi, they are categorized as techno-bio-geosphere (T-B-G) because they apply both natural hydrological processes and drainage pipes within them to discharge water.

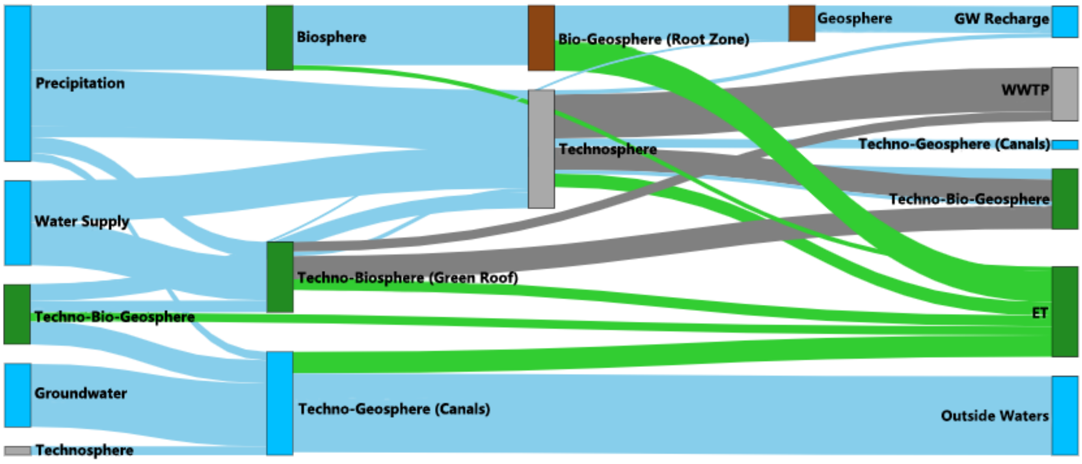


Figure 5.10: Sankey diagram of environmental hybridity in green Zevenkamp

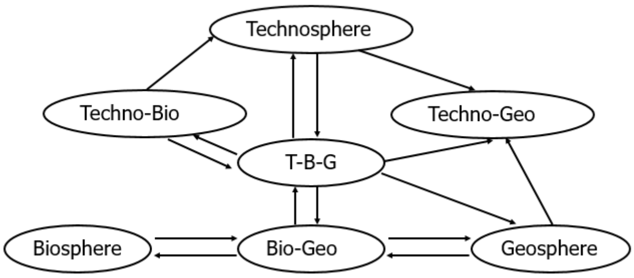


Figure 5.11: Environmental hybridity chart of green Zevenkamp

Results of environmental evaluation

Involved spheres

The number of involved spheres is seven, which means all the spheres are included, especially those overlapped spheres. Since green solutions combine both technological parts and natural processes, the application of NBS can connect technosphere to biosphere and geosphere by involving more overlapped spheres.

Connections

In total there are 15 connections. Although combined sewer system is kept, there is no negative impacts occurring caused by CSO. Technosphere receives extra rainwater from green roofs in techno-biosphere and from rain garden and wadi in T-B-G. The storm water is then discharged to techno-geosphere via SWDS in technosphere. Wastewater from technosphere goes to reed bed in T-B-G, and storm water run-off from roofs and streets goes to rain garden and wadi of T-B-G. Wastewater from techno-biosphere is treated by reed bed in T-B-G and then recycled back. For connections between T-B-G and bio-geosphere, similar to the natural processes described in current situation, they refer to exchange flows between two spheres, such as infiltration and capillary rise. The application of reed bed in T-B-G discharges extra water directly to techno-geosphere, and also a small amount of water goes to geosphere from applied measures in T-B-G.

Bi-directional connections

Five bi-directional pairs can be found, which are between technosphere and T-B-G, techno-biosphere and T-B-G, T-B-G and bio-geosphere, and the original biosphere and bio-geosphere, bio-geosphere and geosphere. The connections have been described above.

Balance of water distributed to each sphere

The standard deviation of water amounts involved in each sphere of green vision is $2.3 * 10^5$. This value is less than current situation ($3.15 * 10^5$), which means although more spheres are involved, water distribution to each sphere is in a more balanced way. However, water amounts between T-B-G and geosphere are not large. This could be explained as extra storm water flowing to green solutions are drained to open water via installed pipes so that less water infiltrates into subsurface. The quantity of water flows through each sphere are listed in the tables in Appendix D.

5.4.4. Performance of closed city in green vision

Water circulation in green Zevenkamp is realized by reed bed. Grey water from buildings with and without green roofs is treated by reed bed and is recycled back for non-potable use.

Amount of water circulation

The total amount of water circulation is $0.27 * 10^6 m^3$.

Number of spheres with internal circulation

No sphere has internal circulation in green vision. Because buildings with green roofs are in techno-biosphere and those without green roofs are in technosphere, while reed bed is included in T-B-G, therefore, no internal circulation can be found.

5.5. 3rd vision: Mixed district

For all the three mixed visions, grey infrastructures including RWH and separated sewer system, and NBS including green roof, rain garden and wadi are applied. The difference is the solution for treating wastewater, so mixed vision 1 is applying only DEWATS to recycle treated wastewater, while mixed vision 3 installs only reed bed for water circulation. In mixed vision 2, half of the neighbourhoods have DEWATS and the rest are applying reed bed. Through these three combinations, both environmental hybridity and the ability of water circulation can be compared in the mixed vision.

5.5.1. Mixed vision 1: More mechanical

Selected solutions

For mixed vision 1, both grey and green solutions are applied, but recycling treated wastewater only by DEWATS, which is considered as in a more mechanical way. The locations are indicated in Figure 5.12.

Table 5.7: Selected solutions and locations in mixed vision 1

Location	Solution
Public Green	DEWATS (water housing) Wadi
Inside District	Rain Garden
Along Street	RWH Rain Garden

Spatial hybridity of mixed vision 1

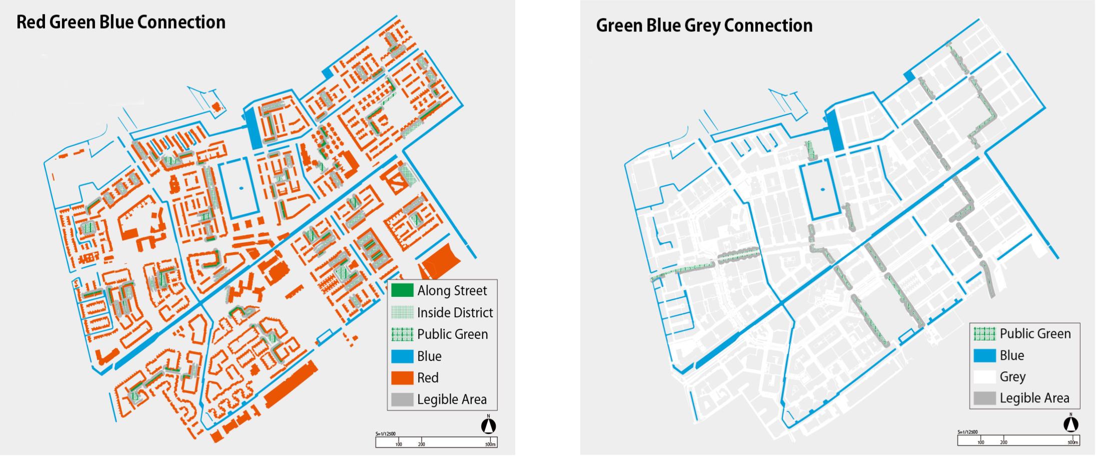
Results of spatial analysis

Connectivity

Connections among red, green and blue are created by applying RWH, water housing and rain garden, which are red-green, green-blue and red-green-blue. The application of wadi contributes to connections among grey, green and blue, which are grey-green, green-blue and grey-green-blue types. In addition, the green-blue legible area in current Zevenkamp is also included. Therefore, there are seven types of connections in mixed vision 1.

Legibility

Legible area of green-blue connection that is already existing is the same as Figure 4.5. The legible area of connections among red, green and blue is shown in Figure 5.12a. Comparing the two figures, it can be seen legible area of grey-green-blue is more sequentially connected than that of red-green-blue.



(a) Legible area of red-green-blue connections (b) Legible area of grey-green-blue connections

Figure 5.12: Legible area of each connection in mixed vision 1

Results of spatial evaluation

Amount of legible area

From the map of Figure 5.13a, the total legible area is 41.9 hectares, which is 21 % of whole Zevenkamp area. For connections among red, green and blue, legible area of red-green connection is 10.4 ha, green-blue area is 0.5 ha and red-green-blue legible area is 0.2 ha. While for connections created by wadi, grey-green area is 6.1 ha, green-blue legible area is 0.3 ha and legible area of grey-green-blue connection is 0.2 ha.

(a) Total legible area in mixed vision 1 (b) Legible area in three scales in mixed vision 1

Figure 5.13: Legible area and scales in mixed vision 1

Balance of scales

Legible area in three scales is shown in Figure 5.13b. The legible area of each scale is 8.2 ha for regional scale, 25.5 ha for neighbourhood scale and 8.2 ha for housing scale. These areas are 19.6 %, 60.9 % and 19.5 % of total legible area respectively. It can be seen from the map that two regional-scale legible zones are crossed at central Zevenkamp, while legible areas of neighbourhood and housing scales are connected with regional zones. The standard deviation is 19.5.

Diversity of connections

It is not easy to distinguish legible area with denser color from Figure 5.13a. Overlapped layers can be found only at the edge of some parts. The overlapped area is 1.8 ha, which is only 4.3 % of total legible area.

Environmental hybridity of mixed vision 1

Results of environmental analysis

Water balance

Water balance results of mixed vision 1 are given in Table 5.8. The amount of inflows is the same as green vision. While the wastewater transported to WWTP is reduced significantly due to the application of DEWATS. The ET amount increases from current situation due to the installation of some green infrastructures. However, the combination of DEWATS and green solutions puts pressure on pumping station, a large amount of water needs to be pumped outside ($1.44 * 10^6 m^3$).

Table 5.8: Water Balance of mixed vision 1 (Unit: $10^6 m^3$)

Label	Inflow	Outflow
Water Supply	1.01	
Precipitation	1.87	
Groundwater	0.76	
WWTP		0.04
ET		1.03
GW Recharge		0.37
Outside Waters		1.44
Total	3.64	2.88
Recycle by DEWATS	0.37	
Recycle by RWH	0.05	
Δ S	0.35	

Sankey diagram of water balance in mixed vision 1 is given in Figure 5.14. The burden of WWTP is reduced significantly because of DEWATS, while DEWATS, replaced SWDS and applied green solutions increase the working load of pumping stations.

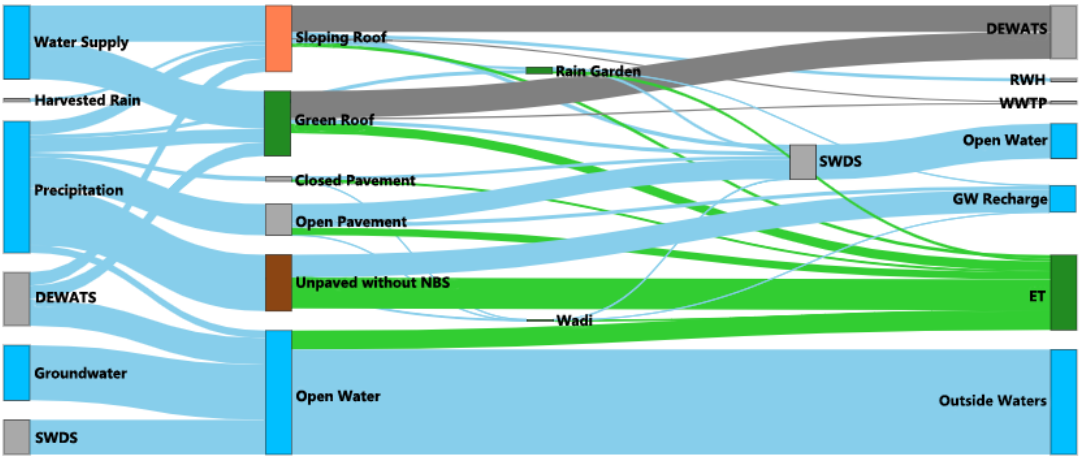


Figure 5.14: Sankey diagram of water balance in mixed vision 1

Visualizing environmental hybridity

Environmental hybridity in mixed vision 1 is visualized based on the Sankey diagram of water balance and summarized in hybridity chart, see Figure 5.15 and 5.16. DEWATS, RWH and SWDS are included in technosphere, green roofs are categorized into techno-biosphere, while rain garden and wadi are in the T-B-G.

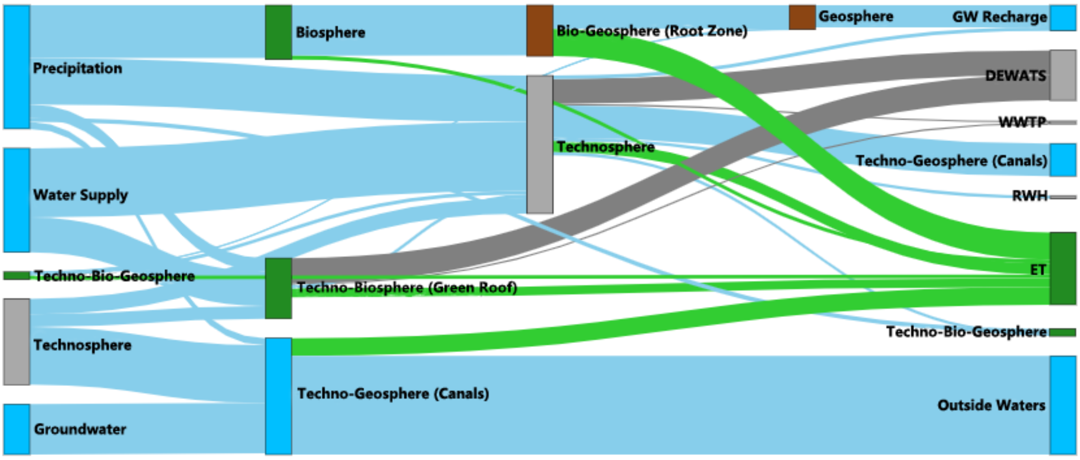


Figure 5.15: Sankey diagram of environmental hybridity in mixed vision 1

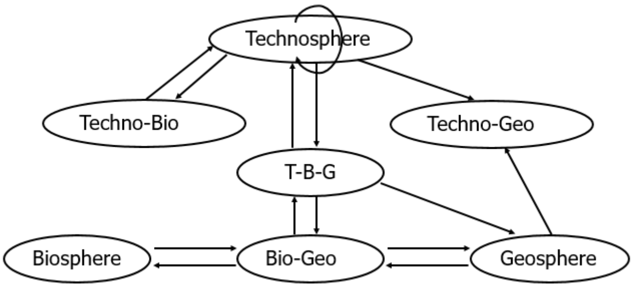


Figure 5.16: Environmental hybridity chart of mixed vision 1

Results of environmental evaluation

Involved spheres

The number of involved spheres is seven. Since NBS are applied, overlapped spheres (i.e. techno-biosphere and T-B-G) are included.

Connections

There are in total 13 connections in mixed vision 1. Although techno-biosphere and T-B-G are involved, there are no connections between these two spheres. Technosphere receives extra rainwater from green roofs in techno-biosphere and then discharges to techno-geosphere via SWDS. In addition, generated wastewater from techno-biosphere is treated by DEWATS in technosphere and sent back. Between technosphere and T-B-G, storm water run-off from buildings and streets goes to rain garden and wadi, and extra rainwater is discharged to open water through SWDS in technosphere. From wadi and rain garden in T-B-G, a small amount of water goes to geosphere. For connections between T-B-G and bio-geosphere, similar to the natural processes described in current situation, they refer to exchange flows between two spheres, such as infiltration and capillary rise. Connections among biosphere, bio-geosphere and geosphere are the same as current situation.

Bi-directional connections

The number of bi-directional pairs is five in this vision, which are between technosphere and techno-biosphere, technosphere and T-B-G, T-B-G and bio-geosphere and the original two in current situation.

Balance of water distributed to each sphere

The standard deviation of water amounts involved in each sphere of mixed vision 1 is calculated as $2.52 * 10^5$. As more mechanical measures are installed, more water is involved in technosphere. The quantity of water flows through each sphere are listed in the tables in Appendix D.

Performance of closed city in mixed vision 1

Water circulation in mixed vision 1 is realized by DEWATS and RWH, same as in mechanical vision.

Amount of water circulation

The total amount of water circulation is $0.42 * 10^6 m^3$, in which $0.37 * 10^6 m^3$ is from DEWATS and $0.05 * 10^6 m^3$ is from RWH.

Number of spheres with internal circulation

Only technosphere has internal circulation. However, because DEWATS also provides water to green roofs in techno-biosphere, not all treated wastewater is recycled within technosphere. The amount of internal circulation is $0.23 * 10^6 m^3$.

5.5.2. Mixed vision 2: Balanced

Selected solutions

For mixed vision 2, both grey and green solutions are applied, including the measures for water circulation. There are 23 neighbourhoods in Zevenkamp, so DEWATS is installed in 12 neighbourhoods, while the rest have reed bed. The locations of selected solutions are indicated in Figure 5.17.

Table 5.9: Selected solutions and locations in mixed vision 2

Location	Solution
Public Green	DEWATS (water housing) Reed Bed Wadi
Inside District	Rain Garden
Along Street	RWH Rain Garden

Spatial hybridity of mixed vision 2

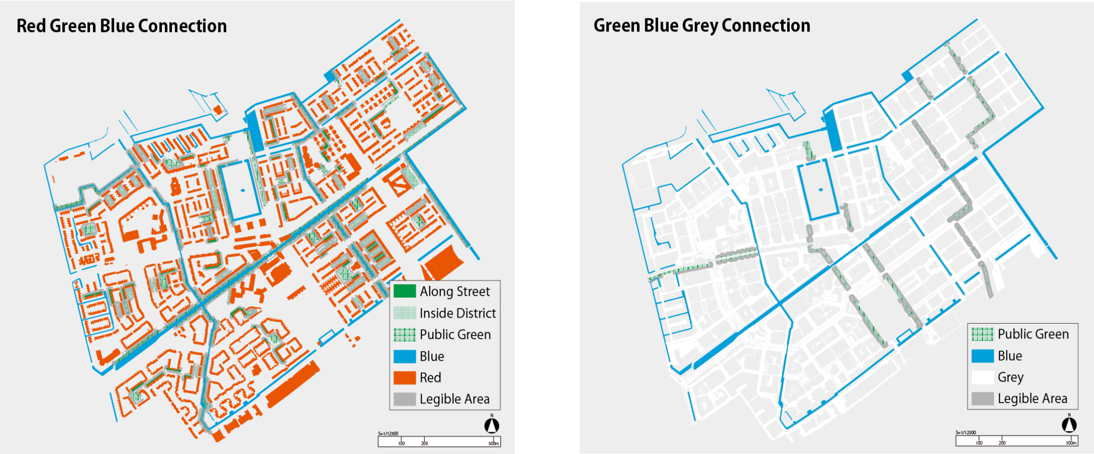
Results of spatial analysis

Connectivity

Connections among red, green and blue are created by applying RWH, water housing, rain garden and reed bed, which are red-green, green-blue and red-green-blue. The application of wadi contributes to connections among grey, green and blue, which are grey-green, green-blue and grey-green-blue types. In addition, the green-blue legible area in current Zevenkamp is also included. Therefore, there are seven types of connections in mixed vision 2.

Legibility

Legible area of green-blue connection that already existing is the same as Figure 4.5. The legible area of connections among red, green and blue is show in Figure 5.17a. Along the streets are rain gardens and RWH. Rain gardens are also located in private gardens inside district. In public green area, there are reed bed and water housing. Figure 5.17b shows the legible area of Wadi, and the locations are in public green area. From the two figures, some legible areas in a sequence can be observed.



(a) Legible area of red-green-blue connections

(b) Legible area of grey-green-blue connections

Figure 5.17: Legible area of each connection in mixed vision 2

Results of spatial evaluation

Amount of legible area

The total legible area in mixed vision 2 is 44.2 hectares, which is 22.1 % of Zevenkamp, see Figure 5.18a. For connections among red, green and blue, legible area of red-green connection is 14.3 ha, green-blue area is 9 ha and red-green-blue legible area is 1.9 ha. While for connections created by wadi, grey-green area is 6 ha, green-blue legible area is 0.3 ha and legible area of grey-green-blue connection is 0.2 ha.

(a) Total legible area in mixed vision 2

(b) Legible area in each scale in mixed vision 2

Figure 5.18: Legible area and scales in mixed vision 2

Balance of scales

From the map of Figure 5.18b, legible area of each scale is 8.8 ha for regional scale, 26.8 ha for neighbourhood scale and 8.6 ha for housing scale. These areas are 20 %, 60.6 % and 19.4 % of total legible area respectively. Two regional-scale legible zones meet at the center of Zevenkamp, and legible areas in the other two scales are connected with regional zones. The standard deviation is 19.3.

Diversity of connections

Legible areas with diverse connections can be found along the waterways sequentially, see Figure 5.18a. The area people can experience more than one connection is 13.5 ha, which is the difference between total legible area (44.2 ha) and the sum of legible area of each connection (57.7 ha). The percentage of diversity area out of total legible area is calculated as $13.5/44.2 * 100\% = 30.5\%$.

Environmental hybridity of mixed vision 2

Results of environmental analysis

Water balance results of mixed vision 2 are listed in Table 5.10. Incoming water supply and precipitation are the same as mechanical vision and green vision. While the amounts of groundwater drainage and recharge are slightly different from green vision. This is due to the proportion of applied nature-based solutions is changed. Compared to current situation, the burden of WWTP is reduced a lot. However, the pressure of pumping station is heavy ($1.41 * 10^6 m^3$), because of water discharge from applied measures.

Table 5.10: Water Balance of mixed vision 2 (Unit: $10^6 m^3$)

Label	Inflow	Outflow
Water Supply	1.01	
Precipitation	1.87	
Groundwater	0.77	
WWTP		0.11
ET		1.07
GW Recharge		0.38
Outside Waters		1.41
Total	3.65	2.97
Recycle by DEWATS	0.18	
Recycle by Reed Bed	0.15	
Recycle by RWH	0.05	
Δ **S**	0.31	

Sankey diagram of water balance in mixed vision 2 is shown in Figure 5.19. It can be seen that part of wastewater from buildings is flowing to DEWATS and reed bed for recycling, while water enters open water is a large amount compared to other sectors.

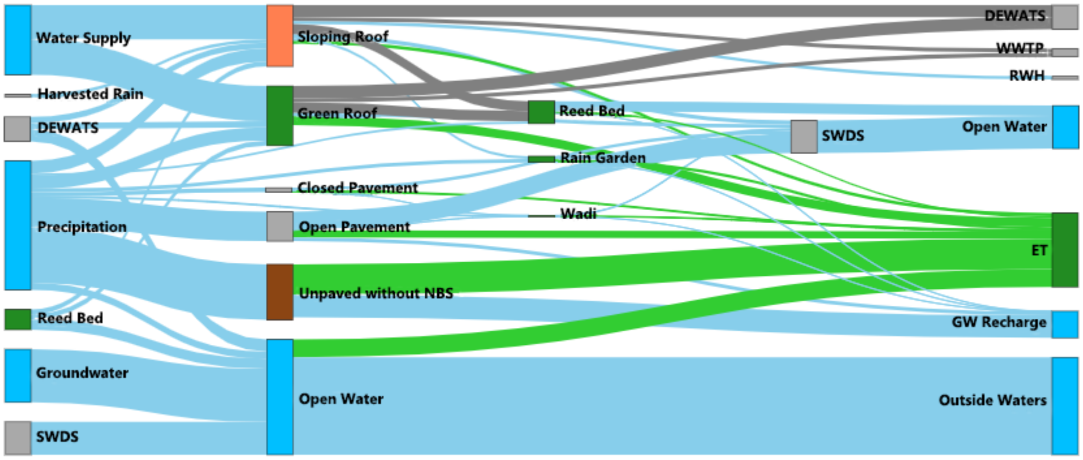


Figure 5.19: Sankey diagram of water balance in mixed vision 2

Visualizing environmental hybridity

Based on the water balance visualization, the Sankey diagram of environmental hybridity in mixed vision 2 is given in Figure 5.20 and then summarized in the chart of Figure 5.21. DEWATS, RWH and SWDS are included in technosphere, green roof is in techno-biosphere, while reed bed, rain garden and wadi are categorized into T-B-G.

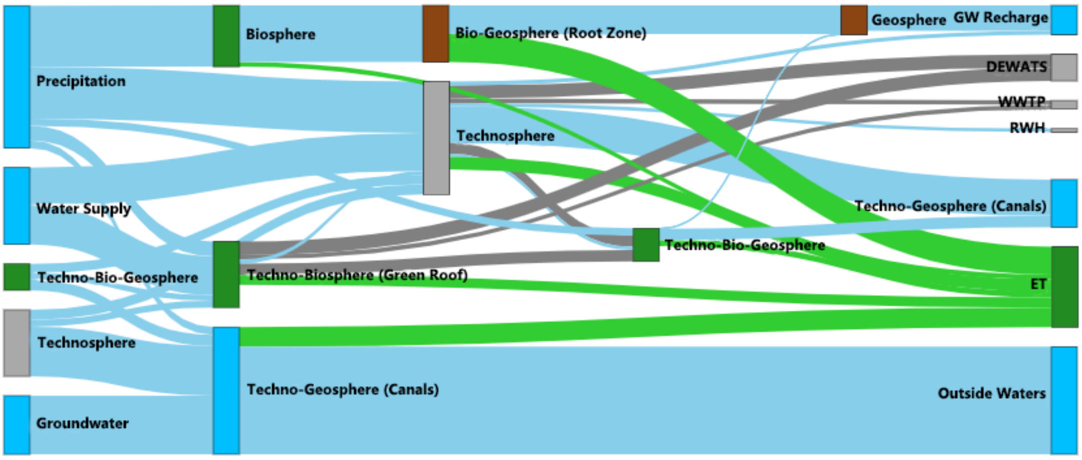


Figure 5.20: Sankey diagram of environmental hybridity in mixed vision 2

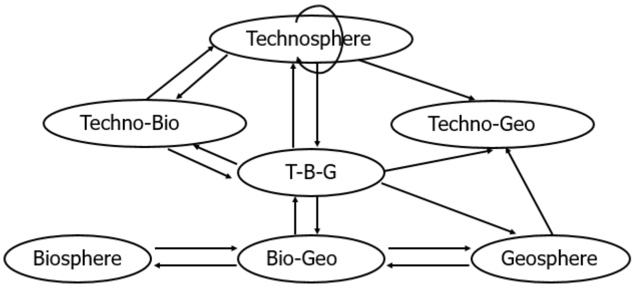


Figure 5.21: Environmental hybridity chart of mixed vision 2

Results of environmental evaluation

Involved spheres

The number of involved spheres is seven. Since all proposed NBS are applied, so all the spheres are involved.

Connections

There are in total 16 connections. Because reed bed and DEWATS are both installed, generated wastewater from green roofs in techno-biospheres is treated in technosphere and T-B-G and then recycled back. Technosphere receives extra rainwater from green roofs in techno-biosphere and from rain garden and wadi in T-B-G, and then storm water is discharged to techno-geosphere via SWDS. Storm water from roofs and streets in technosphere goes to rain garden and wadi in T-B-G. From reed bed in T-B-G, extra water is discharged directly to techno-geosphere. Because of applied green solutions in T-B-G, a small amount of water goes to geosphere. For connections between T-B-G and bio-geosphere, similar to the natural processes described in current situation, they refer to exchange flows between two spheres, such as infiltration and capillary rise. Connections among biosphere, bio-geosphere and geosphere are the same as current situation.

Bi-directional connections

There are six bi-directional pairs in this vision, which are between technosphere and techno-biosphere, techno-biosphere and T-B-G, T-B-G and bio-geosphere, and the original two pairs between biosphere and bio-geosphere and between bio-geosphere and geosphere.

Balance of water distributed to each sphere

The standard deviation of water amounts involved in each sphere of mixed vision 2 is $2.34 * 10^5$. The quantity of water flows through each sphere are listed in the tables in Appendix D.

Performance of closed city in mixed vision 2

Water circulation in mixed vision 2 is realized by DEWATS, RWH and reed bed.

Amount of water circulation

The total amount of water circulation is $0.38 * 10^6 m^3$, in which $0.18 * 10^6 m^3$ is from DEWATS, $0.05 * 10^6 m^3$ is from RWH and $0.15 * 10^6 m^3$ is from reed bed.

Number of spheres with internal circulation

Only technosphere has internal circulation because of DEWATS and RWH. However, because DEWATS also provides water to green roofs in techno-biosphere, not all treated wastewater is recycled within technosphere. The amount of internal circulation is $0.13 * 10^6 m^3$.

5.5.3. Mixed vision 3: More green

Selected solutions

For mixed vision 3, both grey and green solutions are applied, but recycling treated wastewater by applying reed bed, which is considered as in a more green way. The locations of selected measures are indicated in Figure 5.22.

Table 5.11: Selected solutions and locations in mixed vision 3

Location	Solution
Public Green	Reed Bed Wadi
Inside District	Rain Garden
Along Street	RWH Rain Garden

Spatial hybridity of mixed vision 3

Results of spatial analysis

Connectivity

Connections among red, green and blue are created by applying RWH, rain garden and reed bed, which are red-green, green-blue and red-green-blue. Installing wadi contributes to connections among grey, green and blue, which are grey-green, green-blue and grey-green-blue. In addition, the green-blue legible area in current Zevenkamp is also included. Therefore, there are seven types of connections in mixed vision 3.

Legibility

Legible area of green-blue connection that already existing is the same as Figure 4.5. The legible area of connections among red, green and blue is shown in Figure 5.22a. RWH systems are located along the streets. Rain gardens can be found along the streets and in the private gardens inside district. Wadi and reed bed are applied at public green space, and the legible area among grey, green and blue is shown in Figure 5.22b. It can be seen from both figures that legible areas are in a sequence mostly along the canals.

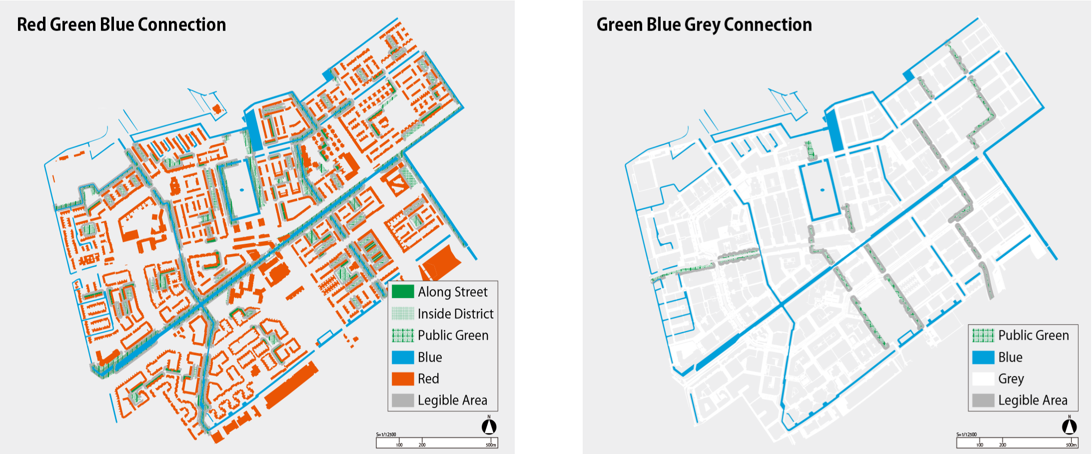
Results of spatial evaluation

Amount of legible area

From the map of Figure 5.23a, the total legible area is 45 hectares, which is 22.5 % of Zevenkamp area. For connections among red, green and blue, legible area of red-green connection is 15.6 ha, green-blue area is 11.5 ha and red-green-blue legible area is 2.4 ha. While for connections created by wadi, grey-green area is 6.1 ha, green-blue legible area is 0.3 ha and legible area of grey-green-blue connection is 0.2 ha.

Balance of scales

Legible area in three scales is shown in Figure 5.23b. The legible area of each scale is 9 ha for regional scale, 27.3 ha for neighbourhood scale and 8.7 ha for housing scale. These areas are 19.9 %, 60.7 % and 19.4 % of total legible area respectively.The standard deviation is 19.3.



(a) Legible area of red-green-blue connections (b) Legible area of grey-green-blue connections

Figure 5.22: Legible area of each connection in mixed vision 3

(a) Total legible area in mixed vision 3 (b) Legible area in three scales in mixed vision 3

Figure 5.23: Legible area and scales in mixed vision 3

Diversity of connections

Most legible areas that have diverse connections are sequentially located along the waterways. The overlapped area is 17 ha, which is 37.8 % of total legible area.

Environmental hybridity of mixed vision 3

Results of environmental analysis

Water balance

Water balance results of mixed vision 3 are given in Table 5.12. The amount of incoming flows is the same as green vision. Wastewater amount to WWTP is much less than current situation, due to replacement of combined sewer system and recycling by reed bed. However, pumping station is also under pressure in this vision ($1.35 * 10^6 m^3$).

Sankey diagram of water balance in mixed vision 3 is visualized in Figure 5.24. Reed bed treats grey water from buildings with and without green roofs. Because of water recycling solutions and SWDS, the burden of WWTP is reduced. While discharge from reed bed and SWDS leads to more water pumped outside.

Table 5.12: Water Balance of mixed vision 3 (Unit: $10^6 m^3$)

Label	Inflow	Outflow
Water Supply	1.01	
Precipitation	1.87	
Groundwater	0.76	
WWTP		0.22
ET		1.08
GW Recharge		0.37
Outside Waters		1.35
Total	3.64	3.02
Recycle by Reed Bed	0.28	
Recycle by RWH	0.05	
Δ **S**	0.3	

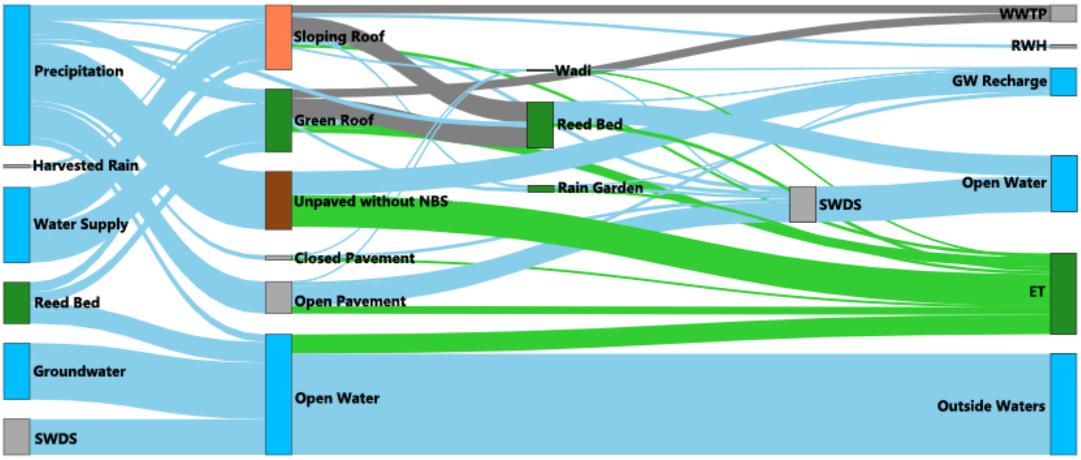


Figure 5.24: Sankey diagram of water balance in mixed vision 3

Visualizing environmental hybridity

Environmental hybridity in mixed vision 3 is visualized based on the Sankey diagram of water balance and summarized in environmental hybridity chart, see Figure 5.25 and 5.26. RWH and SWDS are included in technosphere, green roofs are categorized into techno-biosphere, while reed bed, rain garden and wadi are in the T-B-G.

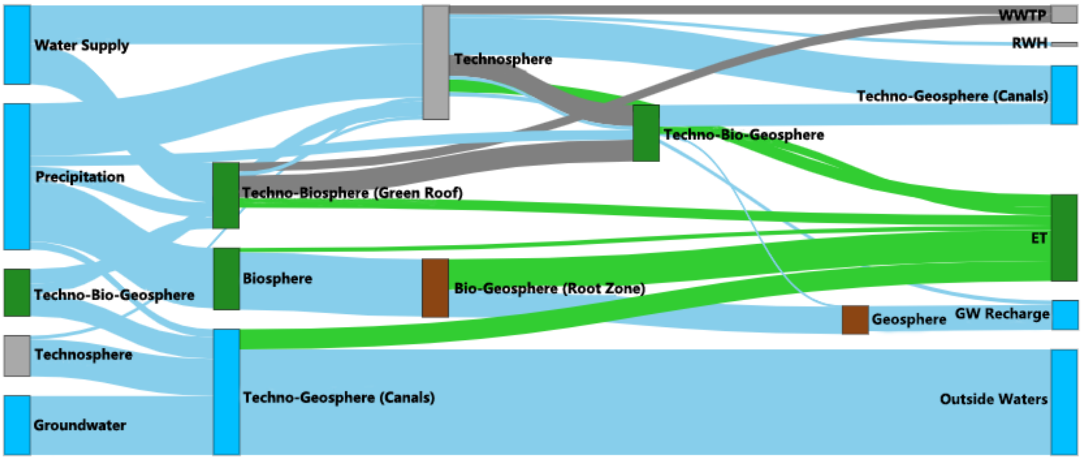


Figure 5.25: Sankey diagram of environmental hybridity in mixed vision 3

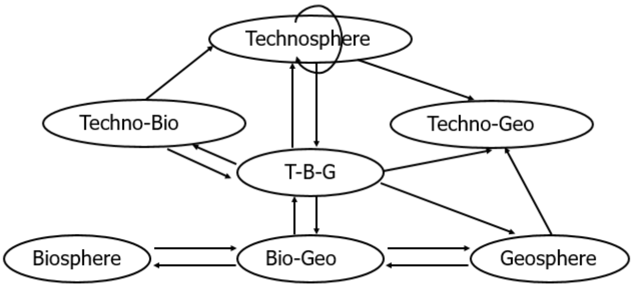


Figure 5.26: Environmental hybridity chart of mixed vision 3

Results of environmental evaluation

Involved spheres

All the seven spheres are involved in mixed vision 3 due to all proposed green solutions are applied.

Connections

The number of connections is in total 15. There are no flows from technosphere to techno-biosphere because DEWATS is not applied. Technosphere only receives extra rainwater from techno-biosphere, and also extra rainwater from rain garden and wadi in T-B-G. Then the storm water is discharged to techno-geosphere via SWDS. Reed bed in T-B-G receives generated wastewater from techno-biosphere and technosphere, and the treated wastewater is sent back to the two spheres for recycling. Storm water run-off from roofs and streets goes to rain garden and wadi. Extra water from reed bed is discharged to techno-geosphere directly and because of the green solutions in T-B-G, a small amount of water goes to geosphere. For connections between T-B-G and bio-geosphere, similar to the natural processes described in current situation, they refer to exchange flows between two spheres, such as infiltration and capillary rise. Connections among biosphere, bio-geosphere and geosphere are the same as current situation.

Bi-directional connections

Bi-directional pairs are five in this vision, which are between technosphere and T-B-G, techno-biosphere and T-B-G, T-B-G and bio-geosphere, and the original two as in current situation.

Balance of water distributed to each sphere

The standard deviation value of water amounts involved in each sphere of mixed vision 3 is $2.33 * 10^5$. The quantity of water flows through each sphere are listed in the tables in Appendix D.

Performance of closed city in mixed vision 3

Water circulation in mixed vision 3 is realized by RWH and reed bed. The rotated arrow in the hybridity chart represents RWH.

Amount of water circulation

The total amount of water circulation is $0.33 * 10^6 m^3$, in which $0.05 * 10^4 m^3$ is from RWH and $0.28 * 10^6 m^3$ is from reed bed.

Number of spheres with internal circulation

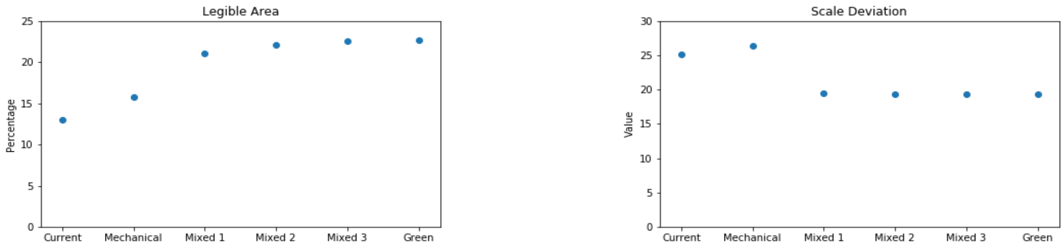
Only technosphere has internal circulation because of RWH. All harvested rainwater is circulated within technosphere. The amount of internal circulation is $0.05 * 10^6 m^3$.

6

Evaluation of future visions

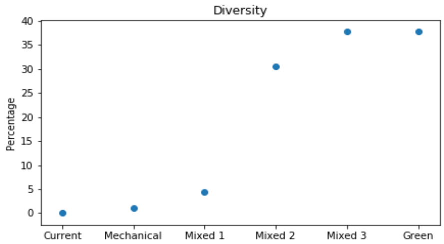
6.1. Spatial hybridity

Based upon three evaluation indicators and produced maps of each vision, spatial hybridity is compared and the results are given below.



(a) Amount of legible area

(b) Balance of scales



(c) Diversity of connections

Figure 6.1: Comparisons of spatial hybridity for all visions

6.1.1. Amount of legible area

The value of each vision in Figure 6.1a refers to the percentage of total legible area out of Zevenkamp area (200 ha). Current situation has the least legible area (13 %) while percentage is increasing gradually as more green solutions are installed in the district, from 15.8 % in mechanical vision, 21 % in mixed vision 1, 22.1 % in mixed vision 2 and 22.5 % in mixed vision 3 and to the highest value 22.6 % in green vision.

For current situation, there is only one type of connection, i.e. green-blue connection, and the legible area is mostly along the canals.

In mechanical vision, although legible area has increased, these new areas are fragmented due to the similarly fragmented distribution of applied grey infrastructures.

For mixed visions and green vision, the amount of legible area is almost the same, a network of legible area can be found in the districts and along the open water. This is due to reed bed and wadi applied in public green area.

Therefore, both mixed visions and green vision can be seen to have higher spatial hybridity than mechanical vision and current situation in terms of total legible area.

6.1.2. Balance of scales

Balance of three scales is reflected as the standard deviation of the percentages of legible area in each scale out of total legible area. The deviation value for each vision is 25.1 in current situation, 26.3 in mechanical vision, 19.5 in mixed vision 1 and 19.3 in the other two mixed visions and green vision.

Legible area in neighbourhood scale has the largest percentage in all visions. In current situation, public green in communities is the main place to experience water system. For mechanical vision, because grey solutions are mostly applied along the streets and in public green that are both in neighbourhood, the percentage of neighbourhood scale is even larger thus the deviation is larger. Regional scale and housing scale are limited in both visions, which makes the linkage among the three scales limited as well.

For mixed visions and green vision, NBS are applied in public green and along the canals, thus legible area of regional scale increases and two regional-scale legible zones crossed at the center of Zevenkamp can be found. The formation of regional zones can connect the other two scales and thus a network of legible area can be found.

In terms of the balance of scales, mixed visions and green vision therefore have more balance distribution of legible area.

6.1.3. Diversity of connections

Current situation has no diversity due to only green-blue connection can be experienced. While for future visions, the percentage of legible area with diverse connection types out of total legible area is 1 % in mechanical district, 4.3 % in mixed vision 1, 30.5 % in mixed vision 2, 37.8 % in both mixed vision 3 and green vision.

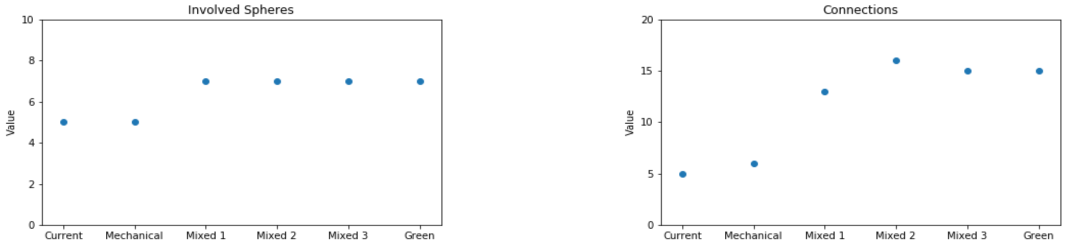
It can be seen that there is a distinct increase from mixed vision 1 to mixed vision 2. Since in mechanical vision and mixed vision 1, completely or more mechanical solutions are applied, as the proportion of green solutions increases, it will contribute to the diversity of connections.

Therefore, mixed vision 2, 3 and green vision can be seen to have higher spatial hybridity in terms of diversity.

In summary, from the three indicators of spatial evaluation, spatial hybridity of mixed vision 2, 3 and green vision are higher than the others.

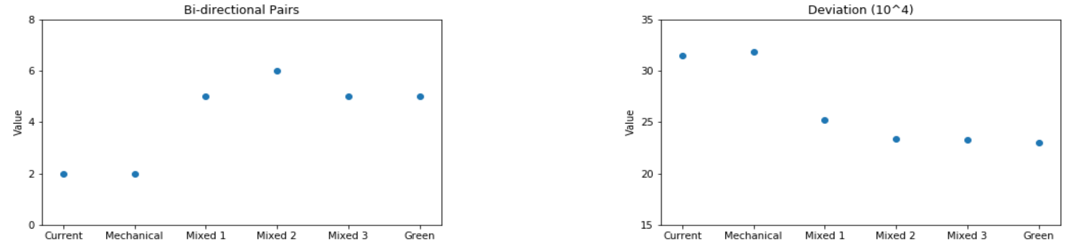
6.2. Environmental hybridity

From environmental hybridity charts of current Zevenkamp and its five future visions, environmental hybridity of each vision is compared based on the four evaluation indicators, the results of comparison are given below.



(a) Involved spheres

(b) Connections



(c) Bi-directional pairs

(d) Deviation of water to each sphere

Figure 6.2: Comparisons of environmental hybridity for all visions

6.2.1. Involved spheres

In current Zevenkamp and mechanical vision, only five spheres are involved, which are technosphere, biosphere, geosphere, techno-geosphere and bio-geosphere. While all the spheres are involved in the other visions.

Since only grey infrastructures are applied in mechanical vision, they are categorized into technosphere and thus no new spheres are involved in environmental hybridity, while the applications of green solutions include techno-biosphere and T-B-G. Therefore, in terms of the number of involved spheres, mixed visions and green vision could have higher environmental hybridity.

6.2.2. Connections

The number of connections in each vision is 6 in both current Zevenkamp and mechanical vision, 13 in mixed vision 1, 16 in mixed vision 2, and 15 in both mixed vision 3 and green vision. The rotated arrow in technosphere is not considered as a connection as it doesn't connect two spheres.

Although current Zevenkamp and mechanical vision have the same number of connections, in current Zevenkamp, the connection between technosphere and techno-geosphere is actually negative, which is a dashed line in Figure 4.9. This connection is caused by the occurrence of CSO. While in mechanical vision, separated sewer replaces existing combined sewer and thus no CSO occurs.

Mixed vision 3 and green vision have the same number of connections. Both visions are applying the same green solutions. While grey infrastructures including separated sewer and RWH are installed in mixed vision 3, separated sewer only contributes to the connection between technosphere and techno-geosphere, and RWH recycles rainwater within technosphere, which is not connecting two spheres.

Mixed vision 1 has two less connections than mixed vision 3 and green vision. The missing two are between techno-biosphere and T-B-G, and T-B-G and techno-geosphere. Because reed bed is not applied in mixed vision 1, wastewater from techno-biosphere goes to DEWATS in technosphere, and then the treated wastewater is sent back from technosphere, thus connections between techno-biosphere and T-B-G are replaced by the connection from technosphere to techno-biosphere. The missing connection between T-B-G and techno-geosphere is also caused by excluding reed bed. Extra water from reed bed is directly discharged to open water, while water from wadi and rain garden have to be discharged to open water through pipes in technosphere.

Therefore, mixed vision 2 have the most connections due to the applications of both DEWATS and reed bed, and this vision has the highest environmental hybridity in terms of connections.

6.2.3. Bi-directional connections

Current Zenkamp and mechanical vision have both 2 pairs of bi-directional connections, which are between biosphere and bio-geosphere, and bio-geosphere and geosphere. These two pairs of connections refer to exchange flows between unpaved area and subsurface, which are actually natural processes. Hence, these two pairs should be found at any city.

Mixed vision 1, mixed vision 3 and green vision all have five pairs of bi-directional connections. For mixed vision 1, the connections are between technosphere and techno-biosphere, technosphere and T-B-G, T-B-G and bio-geosphere, and the two pairs as current Zevenkamp and mechanical vision. While for mixed vision 3 and green vision, bi-directional connections can be found between T-B-G and techno-biosphere instead of between technosphere and techno-biosphere in mixed vision 1, and the other four pairs are the same. The cause of this change is again due to different applications in either DEWATS or reed bed, which is explained above.

While in mixed vision 2, there are 6 pairs of bi-directional connections. Both DEWATS and reed bed are applied, therefore, the connections between technosphere and techno-biosphere and between T-B-G and techno-biosphere are both included. In this case, mixed vision 2 has the highest environmental hybridity regarding to the number of bi-directional connections.

6.2.4. Balance of water distributed to each sphere

The standard deviation value of each vision is $3.15 * 10^5$ in current situation, $3.18 * 10^5$ in mechanical vision, $2.52 * 10^5$ in mixed vision 1, $2.34 * 10^5$ in mixed vision 2, $2.33 * 10^5$ in mixed vision 3 and $2.3 * 10^5$ in green vision. Mechanical vision has the highest value, which means water distributed to each sphere is the most unbalanced, while water involved in each sphere of green vision is the most balanced among all the visions.

Since more water is involved in technosphere because of applying grey infrastructures and no new spheres are involved in mechanical vision, thus the water distribution to each sphere is more deviate.

While in green vision, although more spheres are involved, water distributed to each sphere is in a more balanced way. However, water amounts between T-B-G and geosphere are not large. This could be explained as extra storm water flowing to green solutions are drained to open water via installed pipes so that less water infiltrates into subsurface.

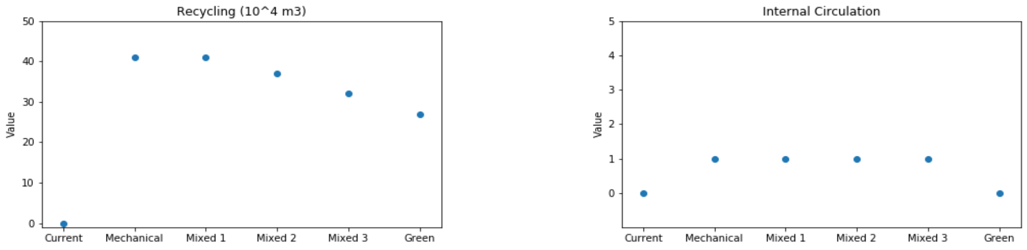
For the three mixed visions, because the combination of grey and green solutions is in a gradational change, therefore, the deviation is also similar to this trend. Mixed vision 1 has the higher deviation value because it is more mechanical, while the value of mixed vision 3 is lower due to more green solutions, and deviation of mixed 2 vision is between the other two mixed visions.

Hence, green vision has the least deviation thus could be considered as the highest environmental hybridity among all visions. But it can be observed from Figure 6.2d that mixed vision 2 and 3 are really close to green vision, therefore, these two mixed visions might be acceptable if all the other factors (i.e. spatial hybridity and performance of closed city) are integrally considered.

In summary, mixed vision 2 can be considered to have the highest environmental hybridity among all the visions in this research.

6.3. Performance of closed city

Based on the two indicators for evaluating the performance of closed city, current Zevenkamp and each future vision are compared and the results are given below.



(a) Amount of water circulation

(b) Spheres with internal circulation

Figure 6.3: Comparisons of performance of closed city for all visions

6.3.1. Amount of water circulation

The total amount of water circulation is calculated by summing up the recycling water from DEWATS, RWH and reed bed in each vision.

Mechanical vision and mixed vision 1 have the strongest ability to recycle water $(0.42 * 10^6 m^3)$, while green vision has the least amount of water circulation $(0.27 * 10^6 m^3)$. Water circulation quantity in mixed vision 2 and mixed vision 3 are reduced gradually from that in mechanical vision, which are $0.38 * 10^4 m^3$ and $0.33 * 10^4 m^3$ respectively. For current Zevenkamp, there is no circulation measures installed, therefore, no water recycling takes place in current situation.

It is not surprised that mechanical vision can recycle the most water amount. As DEWATS and RWH are applying certain advanced technologies to treat water, their ability is stronger than reed bed which only employs natural processes to treat water.

6.3.2. Number of spheres with internal circulation

There are no internal circulation in current Zevenkamp and green vision, while for the other visions, only technosphere can recycle water internally. This is attributed to the application of grey solutions. Because they are categorized into technosphere, and treated water from them are supplied to buildings which are also included in technosphere, then the internal circulation is formed. In green vision, water circulation is realized by applying reed bed, and recycled water is provided from T-B-G to technosphere.

However, due to different proportions of grey solutions in each vision, the amounts of internal circulation are different. Similar to the total amount of water circulation, mechanical vision has the most amount $(0.42 * 10^4 m^3)$. Mixed vision 1 has $0.23 * 10^4 m^3$ recycled in technosphere less than mechanical vision. This is different from the results of total water circulation, because part of the water is supplied to green roofs (i.e. techno-biosphere).

Mixed vision 2 is less than mixed vision 1, only $0.13 * 10^6 m^3$ is circulated within technosphere. This is because only half of the neighbourhoods are installed with DEWATS, making the internal circulation less. For mixed vision 3, the internal circulation is the least $(0.05 * 10^6 m^3)$ due to only RWH is applied in this vision.

In summary, based on the two indicators of evaluating performance of closed city, both mechanical vision and mixed vision 1 can have better performance than the others.

6.4. Summary

Table 6.1, 6.2 and 6.3 below summarize the comparison results from spatial hybridity, environmental hybridity and the performance as a closed city.

Table 6.1: Spatial hybridity of all visions

	Legible area %	**Balance of scales**	**Diversity %**	**Hybridity**
Current	13	25.1	0	Lower
Mechanical	15.8	26.3	1	Low
Mixed 1	21	19.5	4.3	Low
Mixed 2	22.1	19.3	30.5	Higher
Mixed 3	22.5	19.3	37.8	Higher
Green	22.6	19.3	37.8	Higher

Table 6.2: Environmental hybridity of all visions

	Sphere	**Connections**	**Bi-directions**	**Balance of water distribution (10^5)**	**Hybridity**
Current	5	6	2	3.15	Low
Mechanical	5	6	2	3.18	Low
Mixed 1	7	13	5	2.52	High
Mixed 2	7	16	6	2.34	Higher
Mixed 3	7	15	5	2.33	High
Green	7	15	5	2.3	High

Table 6.3: Performance as closed city of all visions

	Circulation ($10^6 m^3$)	**Internal circulation**	**Performance**
Current	0	0	Lower
Mechanical	0.42	1	Higher
Mixed 1	0.42	1	Higher
Mixed 2	0.38	1	High
Mixed 3	0.33	1	High
Green	0.27	0	Low

7

Discussion and analysis

7.1. Water balance model

7.1.1. Data reliability

It is already mentioned in Section 4.3 that the difference between inflows and outflows is a bit larger. This can also be observed in Figure 4.7 that there is a distinct quantity gap between inflows and outflows through buildings. Comparing the thickness of incoming drinking water and rainfall with the thickness of wastewater production, wastewater amount is lesser than expected. Therefore, since water supply and wastewater are managed by different organizations (i.e. Evides and water board), the reliability of data is analyzed before model verification.

From the data provided by Evides drinking water company, the average water supply to Zevenkamp is around 2,800 m^3/day. On the other hand, water board uses empirical values (see Appendix B) to calculate wastewater generation in different water sectors, including domestic, business and social buildings. The wastewater amount is thus estimated to be around 2,100 m^3/day, while 25 % of water supply is missing. One possible explanation could be that this missing amount of water is used for irrigating private gardens. However, this data mismatch implies the lack of information exchange between the two organizations, and more precise measurements of wastewater are required to replace empirical method.

7.1.2. Model verification

Despite the error caused by data, the model needs to be validated, i.e. how much water enters should equal how much water exits. Therefore, the model is verified in the case excluding water supply and wastewater production. The incoming flows are precipitation and groundwater drainage, while the outgoing flows are rainwater transported to WWTP through combined sewer system, ET, groundwater recharge and pumping water outside. Table 7.1 and Figure 7.1 show the results of model verification.

Table 7.1: Water balance of Zevenkamp in 2016 excluding drinking water and wastewater (Unit: $10^6 m^3$)

Label	Inflow	Outflow
Precipitation	1.78	
Groundwater	0.71	
CSO	0.02	
WWTP		0.58
ET		0.83
GW Recharge		0.41
Outside Waters		0.67
Total	2.51	2.49
Δ S	0.02	

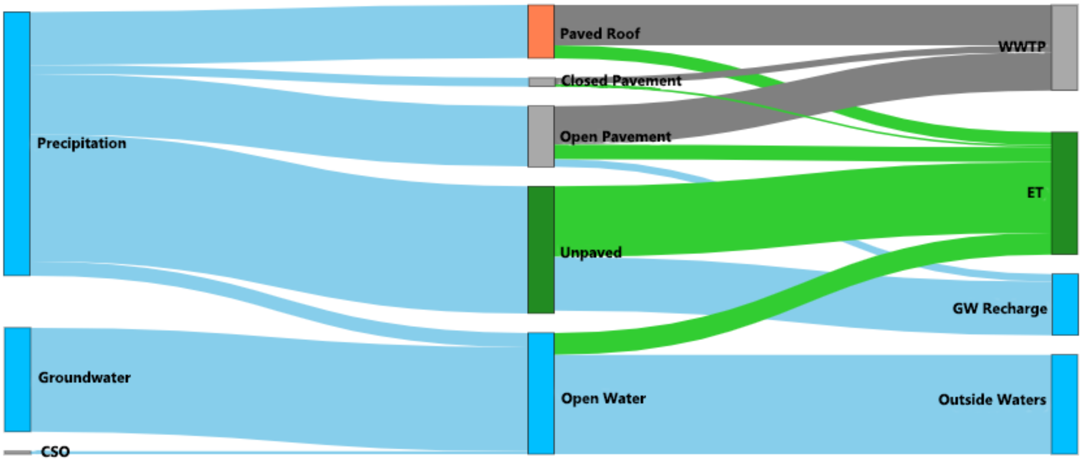


Figure 7.1: Water balance of Zevenkamp in 2016 excluding drinking water and wastewater

From the results, we can say the model is well-functioned. Inflows are almost the same as outflows, with the difference of only 1,9000 m^3. This amount is reflected in Figure 7.1, where the outflows from unpaved area is slightly less than the inflows. The possible reason could be the change in soil moisture. In addition, several parameters are used in the model calculation, so the sensitivity of parameters will be discussed to see their influences on model outputs.

7.1.3. Sensitivity analysis

The main parameters and their values used in the model are listed in Table 7.2.

Table 7.2: Main parameters used in water balance model

Parameter	IntStorCap_PR	IntStorCap_CP	IntStorCap_OP	InfCap_OP
Value	1.5 mm	1.5 mm	1.5 mm	1 mm/day
Parameter	InfCap_UP	Ksat_UZ	w	Qseep
Value	48 mm/day	8 mm/day	100 day	1 mm/day

In which:

- **IntStorCap** is the pre-defined interception storage capacity for paved roof (PR), closed pavement (CP) and open pavement (OP).
- **InfCap** is the pre-defined infiltration capacity for open pavement (OP) and unpaved area (UP).
- **Ksat** is the pre-defined saturated permeability of unsaturated zone (UZ) when calculating percolation.
- **w** is the input value of groundwater drainage resistance.
- **Qseep** is the input value of constant downward seepage flux.

To examine the uncertainty of the model, each parameter in Table 7.2 will be considered separately. By adjusting the input value of each parameter, the changes in the model output will be compared with the initial output. The principle of adjusting input value is based on adding/reducing different percentages of initial value. In this sensitivity analysis, the percentages are ±50%, ±20% and ±10%. Figure 7.2 gives the result of parameter sensitivity.

IntStorCap parameter of PR, CP and OP remains almost the same under different percentage changes. On impermeable surface (e.g PR and CP), the flows have relatively fixed routes, either enters the sewer system or evaporates. Since the incoming precipitation will not change, modifying

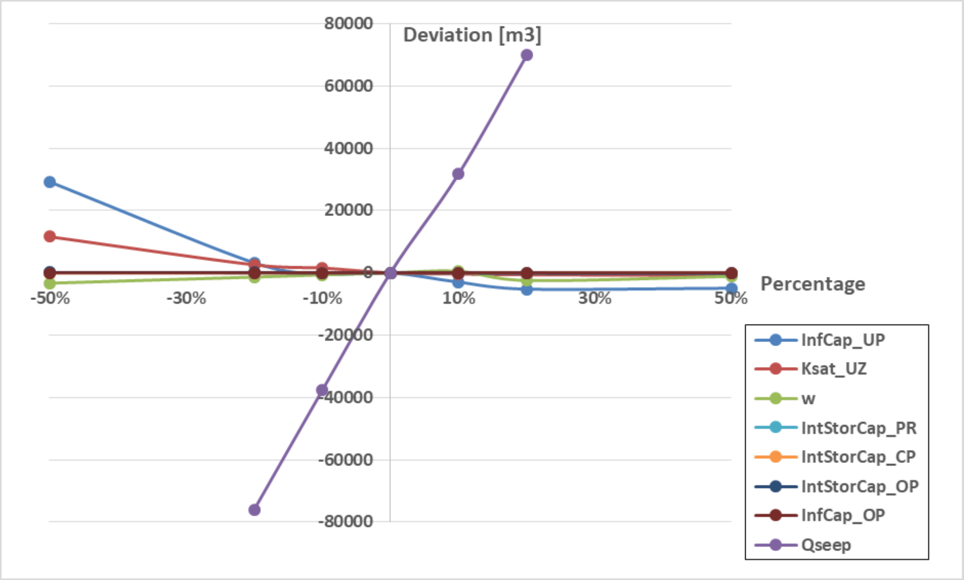


Figure 7.2: Sensitivity analysis of main parameters in water balance model

the interception storage capacity will only affect the storm water amount that is distributed to different routes. Therefore, the difference in this water distribution has little influence on the total amount of outflows, meaning the IntStorCap parameter is less sensitive. As for partially permeable surface like OP, it only has one more route than PR and CP, which is downward infiltration, while the situation is similar. This also explains changing the infiltration capacity of OP (InfCap_OP) does not affect model performance too much.

On the unpaved area, if the infiltration capacity (InfCap_UP) decreases too much, the influence on the model output would be more significant than increasing the value. This is because more rainwater will be remained on surface for evaporation and run-off, the evaporation amount becomes larger which almost achieves potential evapotranspiration if InfCap is small enough. The same situation is found on Ksat_UZ. The K parameter represents the hydraulic conductivity of the porous media. Similarly, decreasing Ksat leads to more evapotranspiration. For groundwater drainage resistance (w), the change from different values is slight. Since groundwater drainage is a relatively slow process, the influence of w may be more significant in smaller time scales.

The most sensitive parameter is defined downward seepage flux (Qseep). Since the change is too evident, Figure 7.2 only shows the result by changing ±20% and ±10%. In this project, the seepage of study area is assumed to be constant. Hence, changing this parameter causes strong variation in the output for groundwater recharge. However, the seepage can also be defined to be dependent on groundwater level and flow resistance. This way of defining seepage leaves space for further testing model performance.

We can see that parameters related to subsurface processes can be more sensitive to those related to impermeable surface. Since subsurface flow is more dynamic, it is difficult to precisely measure relevant parameters and thus poses a challenge for modelling.

7.2. Sankey diagram

Sankey diagram turns out to be useful for visualizing water balance. However, it can be observed that all the flows in the produced Sankey diagram are from left to right. In the case of recycling water, the visualized method is simply to add the solutions on the left side of the diagram. This is a drawback of the tool that is applied from Plotly [44], the flows of this tool can only be presented from left to right, therefore, some problems are caused during visualization. For instance, in green vision, see Figure 5.9, reed bed is put in the column of water sources together with water supply, precipitation and groundwater, to recycle treated wastewater back to buildings, while there is also a block of reed bed on the right side to receive the wastewater from buildings and discharge to open water. The drawback make it not possible to indicate the recycled flows from reed bed, thus there is a mismatch between inflows of outflows of reed bed.

It will be better to illustrate water circulation in the Sankey diagram. For future analysis, more advanced tools for producing Sankey diagram may be recommended.

7.3. Results of hybridity

7.3.1. Spatial hybridity

Green-blue connection can be found in current situation, as well as in all future visions. In fact, unpaved green area is always connected to open water through natural processes such as infiltration and groundwater drainage. Therefore, as long as there are green and blue areas in the city, these two spatial elements are connected by groundwater.

If more connection types can be created, the amount of legible area is increased and thus the distributions to different spatial scales and the chance to feel diverse connections can be discussed. All these three indicators contribute to the spatial hybridity. In the urban area with high spatial hybridity, discontinuous spatial elements are connected via water flows to form an ordered urban space, in which people can recognize and experience the harmony of different spatial elements.

Moreover, the balance of three scales (i.e regional, neighbourhood and housing) is important not only for local inhabitants but also for outsiders who are travelling through the city. Legible area in different scales would help local residents better understand the urban water system and embrace the benefits of more harmonized space, such as recreational and aesthetic values. While for outsiders, usually they travel through major transportation ways that are categorized as regional scale in this project. The balance of scales can ensure outsiders have chances to experience continuous legible area of regional scale that connects the city to outside. This would also give outsiders the first impression on the features of urban water system.

7.3.2. Environmental hybridity

Similar to the connection between blue and green space, biosphere and geosphere are connected through natural processes such as infiltration and subsurface drainage. Therefore, biosphere and geosphere should be always connected via water flows in any city.

Environmental hybridity is higher when more spheres and more (bi-directional) connections are involved, as well as more balanced water distribution to each sphere. This reflects closer and tighter relations among three spheres are set up by more water flow pathways. Therefore, more interactive flow exchange can be expected and this could contribute to a robust water system.

It is well noted that the balance of water distribution to each sphere should be also paid attention to. In mechanical vision, as all the grey solutions are completely applied, much water is involved in technosphere, if failure occurs in technosphere, then the system would also lose its function. Therefore, each sphere is equally important and thus the balance of water distribution to each sphere is important.

From the environmental hybridity charts of all visions, one can observe that there are no connections between biosphere and T-B-G or biosphere between techno-biosphere. For connections between biosphere and T-B-G, as there is a safety distance between building and rain garden, during rainfall events, storm water retained in private gardens might also flow into rain garden. From this, it can be seen that there are some connections between biosphere and T-B-G. This amount of water cannot be specified due to the limitation of the model, so for further research on enhancing environmental hybridity, more precise calculations can be carried out.

As for the connections between techno-biosphere (green roof) and biosphere, if extra water from green roofs can be discharged directly to private gardens instead of going to SWDS, then techno-biosphere can have connections with biosphere. Hence, different forms of one solution may also contribute to environmental hybridity. This could be a recommendation for further research.

7.3.3. Linkages between two types of hybridity

There are some relations between spatial hybridity and environmental hybridity. First, this relations can be reflected between the elements included in each hybridity. For example, red and grey space are categorized into technosphere, green space is put into biosphere and blue is in the geosphere. These elements are thus linked and can influence each other. Hence, the connections between spatial elements could indicate the connections between spheres, and would generate similar evaluation results of hybridity.

Secondly, applying solutions to enhance environmental hybridity would help to predict the connection type for spatial hybridity, or on the other hand, trying to connect specific spatial elements for spatial hybridity would indicate possible solutions in environmental hybridity. However, it can be seen in Table 6.1 and 6.2 that producing higher spatial hybridity does not mean environmental hybridity can be higher simultaneously. The reason could be explained as follows. In this project, the connections between spatial elements are determined based on whether the elements can be visible by people at the same time, thus underground pipes and green roofs are difficult to be seen under normal conditions for people and they are not discussed in spatial hybridity. While in environmental analysis, elements such as pipes and green roofs are necessary to create connections among spheres, hence they are included in environmental hybridity.

Therefore, it can inferred from above discussion that spatial hybridity and environmental hybridity do have some linkages but there are also slight differences, environmental hybridity can be applied to evaluate each new drainage system design, while spatial hybridity can be used for each urban design. Therefore, hybridity concept cannot be applied as a simple tool to solve water issues, in fact, it provides a mindset and requires more collaboration and expertise to be involved.

7.4. Hybridity and collaborative work

In this research, intensive collaborative work and back-and-forth discussions between two disciplines mainly take place during the design phase for future visions, as described in Appendix C.

First the selection of different solutions would influence their classification into three spheres, and thus would influence the results of environmental hybridity. Therefore, the solutions installed in the future visions need to fill in the missing spheres in current situation, so nature-based solutions including reed bed, wadi, rain garden and green roofs are selected. Meanwhile, selected solutions also affect the results of spatial hybridity. At first, treatment facilities of DEWATS are proposed to be placed in the basement, while this cannot contribute to enhance spatial hybridity. After discussions, a form of water housing is designed so that new connection type (i.e. red-green) is generated without compromising the results of environmental hybridity.

Secondly, locations of solutions are needed for both spatial and environmental analysis. In spatial analysis, locating solutions at different places would influence the amount of legible area and also be able to regenerate the original polder structure, thus the locations can influence the spatial hybridity results. While for environmental analysis, as there are some engineering criteria for solutions such as the requirement of space and safety distance to buildings, the locations should also pay attention not to violate the criteria and affect environmental hybridity results.

Therefore, taking hybridity concept into consideration during the collaborative phase ensures the way of communication and work. For different cities, there could be different water-related issues, thus different solutions and more inter-disciplinary work needed, the hybridity concept could then be applied to guide and promote the collaborative phase.

7.5. Hybridity and grey/green solutions

By evaluating the hybridity of different combinations of grey and green solutions, it can be observed that both grey and green are able to enhance hybridity, and the combination of grey and green can generate even higher hybridity.

For environmental hybridity, combining both types of measures can involve more spheres (e.g.green solutions involve T-B and T-B-G) and eliminate the negative impacts of CSO (i.e. installing SWDS). While for spatial hybridity, green solutions can create more connections (e.g. 2 types in mechanical vision but 7 in green vision). Although grey infrastructure itself may not directly enhance spatial hybridity, in the example of designing DEWATS into water housing, improved forms of grey infrastructure can contribute to spatial hybridity. This would also inspire the water managers to think about changing conventional underground solutions to above-ground solutions.

In addition, in Table 6.3, it can be seen better performance of closed city needs grey solutions to operationalize water circulation. Therefore, from the perspective of hybridity, combination of grey and green solutions is important, which is not conflicting with the debate of trade-off between two types of measures in recent years [34].

7.6. Hybridity for improving closed city

From the results of all future visions, as only the amount of water circulation and spheres with internal circulation are discussed, more mechanical solutions would be better, about 40 % of incoming drinking water can be recycled and only a small amount of water goes to WWTP. If more and stronger mechanical solutions are applied, theoretically all the incoming drinking water can be circulated. However, this would ask for more space and put much pressure on pumping station. Hence, a city cannot be completely closed spatially and environmentally. External supports are still needed (e.g. water supply, WWTP or pumping station). By applying different solutions, however, the dependency of the city on those external sources can be reduced. It will always have spatial connections to neighbouring areas, and environmental linkages to nature such as precipitation and subsurface flows cannot be cut.

On the other hand, only pursuing better performance of closed city cannot get along with hybridity. For spatial hybridity, the three proposed types of closed city (see Figure 2.1) can secure water circulation while it cannot generate new connections types among spatial elements. This is similar to environmental hybridity, some spheres might be excluded in the proposed layouts.

Therefore, hybridity concept would give an improved version of closed city. By the combination of grey and green solutions, spatial hybridity and environmental hybridity can be both enhanced in the city. Based on the applied technologies (i.e. solutions), this would promote inhabitants' feelings of urban water system, and thus enhance public awareness and generate benefits such as emotional values.

7.7. Room for improvement

There is still some room to improve this research. First, as different solutions are discussed in different future visions, it is better to also carry out the cost-benefit analysis to discuss about the feasibility of each system. While there are plenty of studies on the performance of grey and green solutions, data related to the cost of the measure are still lacking. Therefore, due to insufficient information, cost-benefit part is not discussed here.

Secondly, water quality for both in the canals and treated water from applied solutions are not discussed. In fact, as closed city proposes, water in the local canals/lakes can also be used for water supply. If water quality can be secured, then the dependency on external water sources can be reduced further. Moreover, this would also promote the behaviour change of local residents as their actions may cause undesirable effects on the local water resources.

Thirdly, in the future vision set-up, only demographic change and climate change are considered as future uncertainties. Actually, as population number grows, densification will take place and the mobility in the future cities can change. These uncertainties should also be taken into account for a more holistic decision-making process.

Finally, water resources can also be linked to other resources such as food and energy. All of these resources are necessary to support the function of the city so that urban development can be more sustainable. In this case, other solutions can also be discussed when considering all related resources in urban areas.

7.8. Relations to the project

As it is introduced in Chapter 1 that this master thesis is a part of the DIMI project, by learning the spatial hybridity and environmental hybridity, public awareness and appreciation on urban water systems can be promoted. This would enhance the social inclusiveness and engagement of citizens. Besides, from the Sankey diagram of water balance in each vision, it can be seen that as different solutions have been added, the management of installed solutions would involve more stakeholders and from the maps of spatial hybridity, the locations of the management can be identified. This however lays beyond the scope of this master thesis research project, but it can guide the next step of the DIMI project to analyze governance hybridity.

8

Conclusions

Population boom and intensive urbanization have rung the alarm on the way towards sustainable development. It can be foreseen that urban areas will be the main field in the future to deal with all the challenges to human, and since water is one of the most fundamental elements to both human and nature, to develop a more integrated water management approach could turn challenges into opportunities. Based on an IUWM model, closed city, this research identified the hybridity concept as one important character of water systems, and thus discussed how it can contribute to a more sustainable urban water management. The case study in this research does prove that the hypothesis of hybridity can be operationalized by splitting it into spatial, environmental and governance hybridity, and at least two of the three components can be studied (i.e. spatial and environmental hybridity). The added values of quantifying both components are demonstrated.

First, hybridity addresses the importance of collaborative and inter-disciplinary work. The hybridity of water system involves three dimensions (i.e. spatial, environmental and governance) which can influence each other and finally affect the relations between human and nature. Therefore, expertise related to each dimension should be involved to work together in a more holistic manner. From this report, it can be observed that spatial hybridity and environmental hybridity have linkages although both are addressing hybridity from a different perspective on urban water systems. While both disciplines have the common understandings on the hybridity concept, the collaboration and communication can then be carried out between two disciplines based on hybridity without compromising goals of each other. Therefore, hybridity concept also provides a way of thinking that could promote multi-disciplinary collaboration.

Second, hybridity concept strengthens the importance of combination of grey and green solutions from a broader perspective. This is not conflicting with recent debate on the trade-off between grey infrastructures and nature-based solutions. In fact, enhancing the hybridity of urban water systems pays attention to not only the water security but also the 'soft' benefits that urban water system can offer. This leads to the next conclusion.

Third, considering hybridity concept would improve the way in which urban water managers normally think. As closed city concept simply tries to connect houses to open water by creating more space for canals (e.g. the ring type), it somehow ignores the connections between other spatial elements such as grey and green. By applying the hybridity concept, different spatial elements can be harmonized via water systems so that local residents can actually experience and appreciate urban water systems. People then would take more care for their urban water system and spontaneously engage into urban water management. Therefore, hybridity of urban water system could inspire urban water management approach for more comprehensive understandings.

Although further steps are still needed to solidify the hybridity concept (e.g. governance hybridity), this report examines urban design and water management disciplines can actually be bridged by the analysis of hybridity of water system. The discussions on the work between the two fields of expertise can help guide the direction in the future when more disciplines are involved, which is more complex. Therefore, studying hybridity concept in this report makes a strong step to push forward the transformation to a more integrated and sustainable urban water management.

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A

Water Balance Model

More detailed information about the water balance model used in this project can be found in this appendix.

At the city scale, there are generally four incoming water flows, which are precipitation, water supply, surface water and groundwater. Correspondingly, the outflows are evapotranspiration (ET), wastewater, discharge to outside waters and groundwater recharge. Based on the types of flows, the model first identifies different land cover within urban areas that are related to different hydrologic regimes, see Table 3.2. This is the principle used to formulate the structure of the model.

Model structure

There are five types of identified land use, which are buildings, streets, unpaved space, subsurface and open water. Further, they are divided into eight sectors, which is illustrated in Figure A.1.

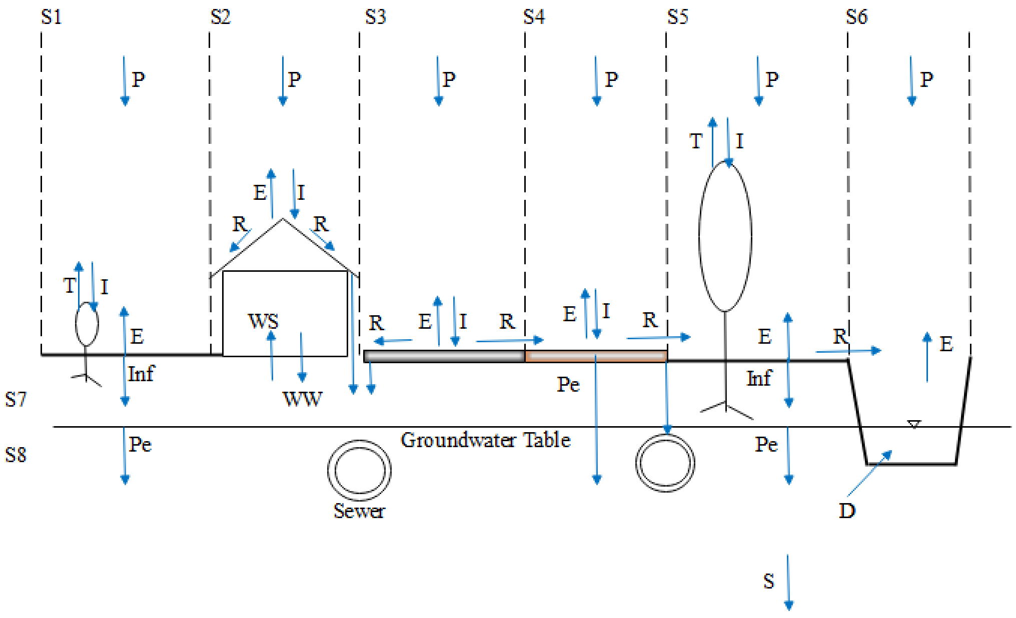


Figure A.1: Water flows on different land use. In which: P (Precipitation), T (Transpiration), I (Interception), E (Evaporation), R (Run-off), WS (Water Supply), WW (Wastewater), Inf (Infiltration), Pe (Percolation), D (Drainage), and S (Seepage).

Based on the figure, explanations of different calculation modules in their sequence of the model are described below. The unit of time step size is day.

- **Buildings (S2)**
  Buildings have two ways to be involved into urban water system. Externally on the rooftop,

interception of the precipitation is calculated, followed by the calculated amount of evaporation from interception storage. Generated run-off will enter sewer depending on the types of system (i.e. combined sewer system or separated sewer system). If there are some drainage solutions applied, such as rainwater harvesting, this amount of water should be subtracted from that enters sewer. In case some buildings are disconnected from sewage, the run-off is assumed to be discharged to unpaved area, such as private gardens. Internally, drinking water is supplied through distribution system, and produced wastewater is discharged to sewer system.

- **Closed pavement (S3)**
  Closed pavement here refers to impervious streets. Precipitation first fills in interception storage, and then it evaporates. Generated run-off enters either drainage system or combined sewer, or in the case there are some water-retained solutions are applied, such as Wadi. In addition, for streets that are not connected with pipes, run-off is assumed to discharged to unpaved space, such as public park.

- **Open pavements (S4)**
  The only difference between open pavements and closed ones is that open streets are partially permeable, thus part of intercepted rainwater would infiltrate. This infiltration is assumed to directly recharge groundwater here, given its position is before the calculation of unsaturated zone in the model structure.

- **Unpaved area (S1, S5)**
  In Figure A.1, two kinds of unpaved space are illustrated, which are private garden (S1) and public green (S5). The hydrologic processes are same. Vegetation intercepts precipitation and evaporates.Once the storage capacity of vegetation reaches, incoming precipitation and run-off from roofs and streets infiltrate into unsaturated zone, of which the amount is related to the soil type and available space in the root zone. Generated run-off is assume to flow into surface water. Otherwise it will remain on the surface of unpaved area to evaporate or infiltrate if there is no surface water. Drainage measures are considered in the calculation, so the generated run-off will deduct this water amount.

- **Unsaturated zone (S7)**
  To determine the available space for infiltration and water for transpiration, there is a set initial soil moisture content before running the model. In addition, initial groundwater table should also be known as an input to calculate the soil moisture content and capillary rise. Percolation from unsaturated zone to groundwater is limited by the saturated permeability of the soil. By adding incoming infiltration to previous moisture content, the current moisture content is calculated by subtracting transpiration and percolation.

- **Groundwater (S8)**
  In each time step, the groundwater table is calculated by deducting the downward seepage flux to deep groundwater and drainage to surface water. Seepage can be calculated based on how it is defined, either it is a constant flux or is related to groundwater level. In this project, the seepage is assumed to be constant.

- **Sewer system**
  Sewer system calculation is an implicit sector in Figure A.1. Discharge of generated run-off and wastewater are summed up here, including flows from water solutions if applicable. Water from separated storm water drainage system is directly discharged into open water, and overflows occur if incoming flows are beyond the known drainage capacity. For the scenario of combined sewer system, discharge is transported to WWTP based on the pre-defined capacity of the system. Once the flows go beyond the capacity, overflow will occur and it will discharge to open water. The final storage of the system can be calculated after all inflows and outflows are discussed.

- **Open water (S6)**
  For open water, in our case, the canals have three incoming waters, precipitation run-off from surface and outflow from sewer systems. Evaporation from canals equals the amount of potential evaporation. The water that is pumped out of the area is determined by the controlled water level, this is a pre-defined water table above which the pumping station starts to work.

Data collection

Some data are needed as inputs to run the model, and this section gives the data sources. Data used for model calculation are based on the year of 2016.

Climate data such as precipitation and evapotranspiration are downloaded from official website of Royal Netherlands Meteorological Institute (KNMI, in its Dutch acronym).

From Evides drinking water company, water supply data is collected through interviews with water distribution consultant. While for sewer system and wastewater, data are obtained through consultation with Rotterdam Municipality and Water Board Schieland en de Krimpenerwaard (HHSK).

Parameters used in modules of unsaturated zone and groundwater, such as saturated permeability of root zone, groundwater level and groundwater drainage resistance, are taken from national websites, which are DINOloket (`https://www.dinoloket.nl`), Groundwatertools (`https://www.grondwatertools.nl`) and official website of Dutch Hydrological Instrumentarium (`http://www.nhi.nu`).

Codes of water balance model

The Python codes for calculating current water balance of Zevenkamp district are provided here.

```
for i in range(1, len(t)):

    # Paved Roof Calculation
    Int_PR[i] = min(IntStorCap_PR, max(0, IntStor_PR[i-1] + P_atm[i]))
    E_atm_PR[i] = min(E_pot_OW[i], Int_PR[i])
    IntStor_PR[i] = Int_PR[i] - E_atm_PR[i]
    R_PR_css[i] = 1 * 1 * max(0, P_atm[i]-E_atm_PR[i]-(IntStor_PR[i]-IntStor_PR[i-1]))
    # There are no drainage measure on roof components and here only combined sewer system is discussed

    # Closed Pavement Calculation
    Int_CP[i] = min(IntStorCap_CP, max(0, IntStor_CP[i-1] + P_atm[i]))
    E_atm_CP[i] = min(E_pot_OW[i], Int_CP[i])
    IntStor_CP[i] = Int_CP[i] - E_atm_CP[i]
    R_CP_css[i] = css_factor * connected_rate_CP * max(0, P_atm[i]-E_atm_CP[i]-(IntStor_CP[i]-IntStor_CP[i-1]))

    # Open Pavement Calculation
    Int_OP[i] = min(IntStorCap_OP, max(0, IntStor_OP[i-1] + P_atm[i]))
    E_atm_OP[i] = min(E_pot_OW[i], Int_OP[i])
    IntStor_OP[i] = Int_OP[i] - E_atm_OP[i]
    P_OP_gw[i] = max(0, min(P_atm[i]-IntStorCap_OP+IntStor_OP[i-1], Inf_cap_OP*1))
    R_OP_css[i] = css_factor * connected_rate_OP * max(0, P_atm[i]-E_atm_OP[i]-(IntStor_OP[i]-IntStor_OP[i-1])-P_OP_gw[i])}

    # Unpaved Area Calculation
    Init_stor_UP[i] = Fin_stor_UP[i-1] + P_atm[i] + irri_UP[i]
    Act_infcap_UP[i] = min(Infcap_UP*1, Mois_UZ_max-H_UZ[i-1]+min(Mois_UZ_max-H_UZ[i-1], 1*K_sat_UZ))

    if E_pot_OW[i]+Act_infcap_UP[i] <= 0:
        Tfac_UP[i] = 0
    else:
        Tfac_UP[i] = min(1, Init_stor_UP[i]/(E_pot_OW[i]+Act_infcap_UP[i]))

    E_atm_UP[i] = Tfac_UP[i] * E_pot_OW[i]
    I_uz_UP[i] = Tfac_UP[i] * Act_infcap_UP[i]
    Fin_stor_UP[i] = max(0, min(Init_stor_UP[i]-E_atm_UP[i]-I_uz_UP[i], IntStorCap_UP))
    R_ow_UP[i] = max(0, Init_stor_UP[i]-E_atm_UP[i]-I_uz_UP[i]-IntStorCap_UP)
    # It is assumed that runoff from unpaved area will flow to open water
    # If there is no open water, the water will be stored on surface and only can evaporate or infiltrate

    # Unsaturated Zone Calculation
    I_up_UZ[i] = I_uz_UP[i]  # it is assumed UZ and UP areas are equal

    if E_ref[i] < 1:
        H3_UZ[i] = H3low_UZ
    elif E_ref[i] > 5:
        H3_UZ[i] = H3high_UZ
    else:
        H3_UZ[i] = H3low_UZ + (E_ref[i] - 1) / 4 * (H3high_UZ - H3low_UZ)

    if H_UZ[i-1]+I_up_UZ[i] > H1_UZ:
        T_alfa_UZ[i] = 0
    elif H_UZ[i-1]+I_up_UZ[i] > H2_UZ:
        T_alfa_UZ[i] = 1 - (H_UZ[i-1] + I_up_UZ[i] - H2_UZ) / (H1_UZ - H2_UZ)
    elif H_UZ[i-1]+I_up_UZ[i] > H3_UZ[i]:
        T_alfa_UZ[i] = 1
    elif H_UZ[i-1]+I_up_UZ[i] > H4_UZ:
        T_alfa_UZ[i] = 1 - (H_UZ[i-1] + I_up_UZ[i] - H4_UZ) / (H3_UZ[i] - H4_UZ)
    else:
        T_alfa_UZ[i] = 0

    T_atm_UZ[i] = T_alfa_UZ[i] * E_ref[i]

    GWL_up_UZ[i] = round(GWL_GW[i-1],1)
    if GWL_up_UZ[i] < 2.5:
        GWL_low_UZ[i] = GWL_up_UZ[i] + 0.1
    elif GWL_up_UZ[i] < 3:
        GWL_low_UZ[i] = 3
        GWL_up_UZ[i] = 2.5
    elif GWL_up_UZ[i] < 4:
        GWL_low_UZ[i] = 4
        GWL_up_UZ[i] = 3
    elif GWL_up_UZ[i] < 5:
        GWL_low_UZ[i] = 5
```

```
    GWL_up_UZ[i] = 4
else:
    GWL_low_UZ[i] = 10

# Calculating equilibrium soil moisture content in the root zone [mm]
if GWL_GW[i-1] < 10:
    H_eq_UZ[i]=dict_soil[str(round(GWL_low_UZ[i],1))]+(GWL_low_UZ[i]-GWL_GW[i-1])/(GWL_low_UZ[i]-GWL_up_UZ[i])
    *(dict_soil[str(round(GWL_up_UZ[i],1))]-dict_soil[str(round(GWL_low_UZ[i],1))])
else:
    H_eq_UZ[i] = dict_soil['10']

# Calculating maximum capillary rise in the root zone [mm]
if GWL_GW[i-1] < 10:
    Capris_max_UZ[i]=dict_capi[str(round(GWL_low_UZ[i],1))]+(GWL_low_UZ[i]-GWL_GW[i-1])/(GWL_low_UZ[i]-GWL_up_UZ[i])
    *(dict_capi[str(round(GWL_up_UZ[i],1))]-dict_capi[str(round(GWL_low_UZ[i],1))])
else:
    Capris_max_UZ[i] = dict_capi['10']

if H_UZ[i-1]+I_up_UZ[i]-T_atm_UZ[i] > H_eq_UZ[i]:
    P_gw_UZ[i] = min(H_UZ[i-1]+I_up_UZ[i]-T_atm_UZ[i]-H_eq_UZ[i], 1*K_sat_UZ)
else:
    P_gw_UZ[i] = -1 * min(H_eq_UZ[i]-(H_UZ[i-1]+I_up_UZ[i]-T_atm_UZ[i]), 1*Capris_max_UZ[i])

H_UZ[i] = H_UZ[i-1] + I_up_UZ[i] - T_atm_UZ[i] - P_gw_UZ[i]

# Groundwater Calculation
P_GW[i] = (P_gw_UZ[i] * UZ_area + P_OP_gw[i] * OP_area) / GW_area + leak_gw[i]
# Total percolation from unsaturated zone, open paved area and leakage of drainage and sewer system during current time step [mm]

if GWL_GW[i-1] < 10:
    SC_GW[i]=dict_stor[str(round(GWL_low_UZ[i],1))]+(GWL_low_UZ[i]-GWL_GW[i-1])/(GWL_low_UZ[i]-GWL_up_UZ[i])
    *(dict_stor[str(round(GWL_up_UZ[i],1))]-dict_stor[str(round(GWL_low_UZ[i],1))])
else:
    SC_GW = dict_stor['10']

if SEEP_DEF > 0.5:
    H_GW[i]= -((P_GW[i]/1000)*w*c-H_deepGW*w-OWL_OW[i-1]*c)/(w+c)+(-(GWL_GW[i-1]+SOL_GW[i-1])-
    (P_GW[i]/1000*w*c-H_deepGW*w-OWL_OW[i-1]*c)/(w+c))*math.exp(-t_step*(w+c)/(SC_GW[i]*w*c))
    S_out_GW[i] = 1000 * (H_deepGW - 0.5 * (H_GW[i] - (GWL_GW[i-1] + SOL_GW[i-1]))) / c * t_step
else:
    H_GW[i]=-(w*(P_GW[i]-Qseep)/1000.0-OWL_OW[i-1]+(-(GWL_GW[i-1]+SOL_GW[i-1])-
    (w*(P_GW[i]-Qseep)/1000.0-OWL_OW[i-1]))*math.exp(-t_step/(SC_GW[i]*w)))
    S_out_GW[i] = t_step * Qseep
# GW level depends on how the seepage is defined, by a constant flux or by a deep GW level and flow resistance
# In our case, seepage is defined as 0

D_ow_GW[i] = P_GW[i] - S_out_GW[i] - SC_GW[i] * (GWL_GW[i-1] + SOL_GW[i-1] - H_GW[i]) * 1000

GWL_GW[i] = max(0, GWL_GW[i-1]-(P_GW[i] - S_out_GW[i] - D_ow_GW[i]) / (1000 * SC_GW[i]))

SOL_GW[i] = -1 * max(0, -(GWL_GW[i-1]-(P_GW[i] - S_out_GW[i] - D_ow_GW[i]) / (1000 * SC_GW[i])) * SC_GW[i])

# Sewer System Calculation
R_css[i] = (R_PR_css[i]*PR_area + R_CP_css[i]*CP_area + R_OP_css[i]*OP_area) / CSS_area + wwater

Q_out_css[i] = min(Stor_css[i-1]+R_css[i], Q_out_css_cap)

Q_ow_css[i] = max(0, min(Stor_css[i-1]+R_css[i]-Q_out_css[i], Q_ow_css_cap))

SO_css[i] = max(0, Stor_css[i-1]+R_css[i]-Q_out_css[i]-Q_ow_css[i]-Stor_css_cap)

Stor_css[i] = max(0, Stor_css[i-1]+R_css[i]-Q_out_css[i]-Q_ow_css[i]-SO_css[i])
# The predefined Q_out_css_cap is the sewer discharge capacity above which overflow to open water will occur. NL 6-7/year.
# It is assumed overflow is drained to open water at the same time step

# Open Water Calculation
Prec_OW[i] = P_atm[i]

E_atm_OW[i] = E_pot_OW[i]

R_OW[i] = R_ow_UP[i] * UP_area / OW_area

D_OW[i] = D_ow_GW[i] * GW_area / OW_area

Q_OW[i] = (Q_ow_css[i] * CSS_area) / OW_area

SO_OW[i] = (SO_css[i] * CSS_area) / OW_area

Q_out_OW[i]=OW_area/tot_area*min(t_step*Q_out_OW_cap*tot_area/OW_area,
1000*(OWL_target-OWL_OW[i-1])+Prec_OW[i]-E_atm_OW[i]+R_OW[i]+D_OW[i]+Q_OW[i]+SO_OW[i])

OWL_OW[i] = OWL_OW[i-1] - (Prec_OW[i] - E_atm_OW[i] + R_OW[i] + D_OW[i] + Q_OW[i] + SO_OW[i] - tot_area / OW_area * Q_out_OW[i]) / 1000
```

Codes of Sankey diagram

The Python codes for drawing a simple Sankey diagram are provided here. More information can be referred to `https://plot.ly/python/sankey-diagram/`

```
import plotly
import matplotlib.pyplot as plt
import plotly.plotly as py

data = dict(
    type='sankey',
    node = dict(
      pad = 15,
      thickness = 20,
      line = dict(
```

```
        color = ”black”,
        width = 0.5
      ),
      label = [”A1”, ”A2”, ”B1”, ”B2”, ”C1”, ”C2”],
      color = [”blue”, ”blue”, ”blue”, ”blue”, ”blue”, ”blue”]
    ),
    link = dict(
      source = [0,1,0,2,3,3],
      target = [2,3,3,4,4,5],
      value = [8,4,2,8,4,2],
      color = [”blue”, ”grey”, ”blue”, ”blue”, ”green”, ”blue”]

  ))

layout =  dict(
    title = ”A simple Sankey diagram”,
    font = dict(
      size = 10
    )
)

fig = dict(data=[data], layout=layout)
py.iplot(fig, validate=False)
```

B

Empirical values for wastewater calculation

Empirical values for calculating wastewater production is given by water board Schieland and the Krimpenerweaard, the original Dutch description is given below.

> Uitgangspunten afvalwater woningen, kantoren en industrie:
>
> - In een woning zijn gemiddeld 2,5 personen aanwezig die gemiddeld 12 liter afvalwater per uur produceren;
> - Gemiddelde belasting kantoren: 0,5 m^3 per hectare/uur1;
> - Gemiddelde belasting industrie 0,5 tot 2,5 l/s/ha bruto-oppervlak voor industrie. Voor bedrijven is in de berekening uitgegaan van 1,0 l/s/ha;
> - Gemiddelde school: 2 tot 3 liter per uur/per leerling, in de berekening is uitgaan van 2,5 l/uur. Het maximaal aantal leerlingen is berekend door de bruto vloeroppervlakte van het gebouw te delen door de ruimte per leerling (ongeveer 7 m^2 voor middelbare scholen, ongeveer 3,5 m^2 voor basisscholen). Voor de berekening is uitgegaan van 5 m^2 ruimte per leerling;
> - Voor detailhandel, horeca en dienstverlening zijn de kengetallen voor kantoren gebruikt.

C

Collaborative design

Since the locations of applied solutions have to be determined, so that each future vision can be analyzed and evaluated by the defined methodology. Therefore, the collaborative design phase will finalize the locations through a series of discussions and reflections back and forth between researchers and students from two disciplines. This is an important step to integrate water management and urban design for sustainable urban water systems and thus sustainable urban development.

Step 1: Selecting water solutions - Water Management

By applying closed city concept, both grey and green infrastructures are identified to solve water-related issues, as well as facing future uncertainties such as climate change. According to the closed city concept, rainwater is an alternative resource. Therefore, rainwater harvesting (grey) is selected. Moreover, treated wastewater can also have potential to be recycled for non-potable use. Hence, DEWATS (grey) and reed bed filter (green) are picked. To reduce the occurrence of CSO, separated sewer system (grey) is proposed to replace existing combined sewer. In addition, some green solutions such as green roof, rain garden and wadi are chosen to function as storm water retention facilities.

Step 2: Enhancing environmental hybridity - Water Management

When the boundary of three spheres in environmental hybridity has been identified, the proposed solutions in Step 1 is checked to see how they will be categorized into three spheres. Since the environmental hybridity in this research refers to the involvement of the three spheres and connections via water flows among them, and the overlapped spheres are equally important, therefore, if more spheres can be involved, then there would be more opportunities to enhance environmental hybridity. In this case, it is better to select solutions that are not included in the missing spheres of current Zevenkamp, which are techno-biosphere and techno-bio-geosphere (T-B-G).

Grey infrastructures selected in Step 1 including DEWATS and rainwater harvesting are both considered as technosphere. For nature-based solutions, since they apply natural processes to solve water-related issues, and have pipes installed, most of them are categorized into T-B-G. Therefore, green roofs are finally selected and they become necessary to enhance environmental hybridity in this project because they are categorized into techno-biosphere. As rainwater on the green roof will infiltrate and finally be discharged into drainage pipes, there is no direct connections with geosphere of Zevenkamp area. Hence, green roofs are in the techno-biosphere.

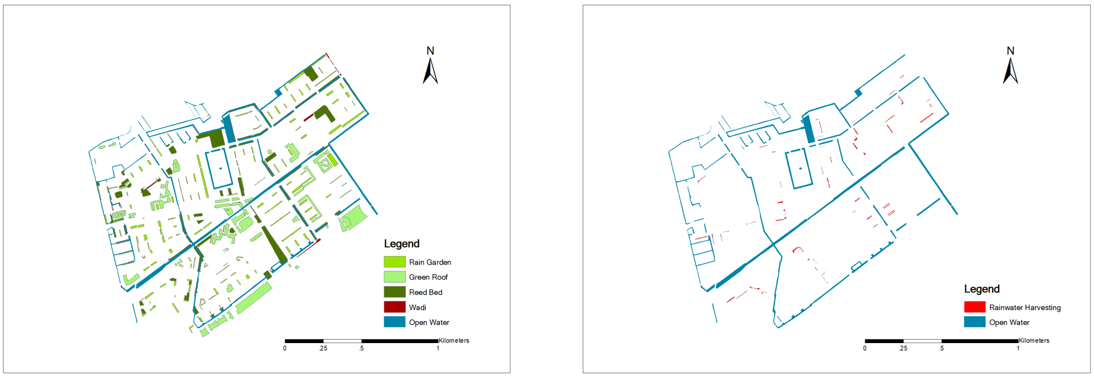
Now that selected solutions have the potential to involve all the three spheres and the overlapped parts, the following steps are trying to determine the locations for each measure.

Step 3: Selecting initial locations - Water Management

Initial locations are determined at first only from water management perspective. These locations have to be determined at this stage so that the area of each applied solution can be calculated on ArcGIS and then be served for water balance model calculation.

- DEWATS are proposed to be installed for each neighbourhood in Zevenkamp. Based on a pilot-scale project in an urban district in China [45], treatment facilities of DEWATS are placed in the basement of one building within the neighbourhood.
- Rainwater harvesting systems are applied on the sloping roofs. Because of the slope, storm water run-off can be easily generated and more rainwater can be collected, thus the efficiency of rainwater harvesting might be optimized.
- Separated sewer pipes are invisible, thus they are not discussed in this project. But for model calculation, it is assumed existing combined sewer will be the storm water drainage system, while new wastewater sewage pipe will be installed. Data of combined sewer system are provided by water board.
- Reed bed filter is also proposed to be installed in each neighbourhood. Therefore, public green areas in each neighbourhood are examined to see if they can be transformed to reed bed. As the area of reed bed filter is relevant to the population number, so the selected locations should meet the spatial requirement of reed bed. In addition, there are recreational facilities such as playground in some public green area, these areas are remained to reserve recreational values for residents.
- Extensive green roofs are proposed to install on all flat roofs, as extensive green roofs are less expensive than intensive ones and they can be installed on existing buildings more easily. Flat green roofs may also create extra recreational values for residents living in the building.
- Rain garden is proposed to be applied in all the private gardens. Rain garden should be located in a distance that won't cause moisture issues to the building foundation (1.5 m) and cellars (8 m) [56], and we take 8 meters as a safe distance to install rain garden.
- Wadi is also applied in public green area. Similar to reed bed, public green with recreational facilities are reserved. In addition, wadi should always have connections with open water, therefore, the location of wadi should not be too far from canals.

The initial locations are shown in Figure C.1. Locations of DEWATS and separated sewer network are not included since they are all invisible.



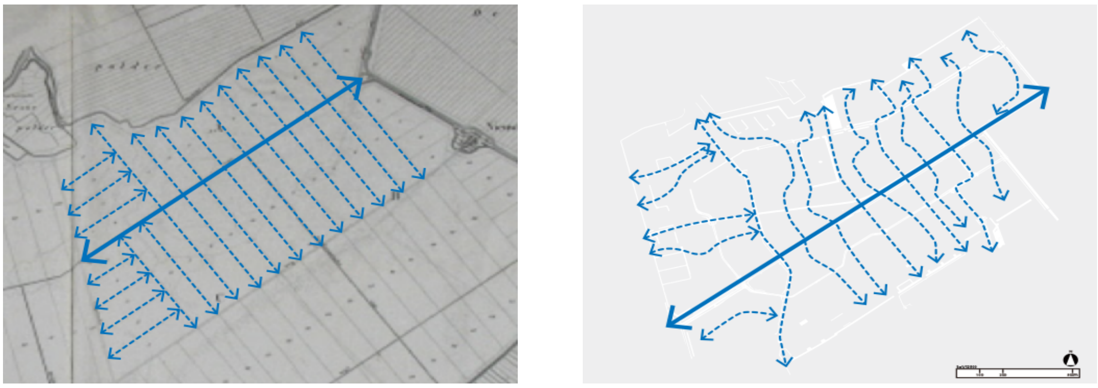
(a) Initial locations for green solutions

(b) Initial locations for grey solutions

Figure C.1: Initial locations for grey and green solutions

Step 4: Historical spatial structure - Urban Design

Researchers from urban design analyzed the historical spatial structure of Zevenkamp, as shown in Figure C.2a. This historical structure is recognized to have potential for making connections among spatial elements, as well as to show culture respect to the tradition of making polder cities. Therefore, historical structure needs to be applied on current spatial structure so that more spatial elements can be included. The spatial structure of Zevenkamp by applying the historical structure is then produced in Figure C.2b. Hence, the determination of locations for water measures should take this structure into account, and the final locations are expected to regenerate the missing parts in current structure.



(a) Spatial structure of Zevenkamp in 1869 (b) Applying historical structure to Zevenkamp

Figure C.2: Regenerating historical spatial structure in Zevenkamp

Step 5: Enhancing spatial hybridity - Urban Design

Initial proposed locations are analyzed to evaluate spatial hybridity by using the defined methodology, and some problems are found if they can be improved without compromising environmental requirements, spatial hybridity could be enhanced.

- Treatment facilities of DEWATS are placed in the basement and extra water will be discharged to open water through pipes. If DEWATS can be placed on the ground level, then red-blue or red-green connection may be legible.
- Harvested rainwater is assumed to be stored in the underground tank. If the tank can be placed on the ground level, then the harvesting system is more visible for people. Although there may not be new spatial connections generated, as stored rainwater will be reused back to domestic buildings, changing the visibility of this solution may provide opportunities to create connections in the future.
- Rain gardens are proposed to be installed in private gardens, usually in the backyard. This can enhance the red-green connection, but only at housing scale. Therefore, if rain gardens can be placed in the front yard, the connection will be visible for people walking in the street, thus the legible area could be larger.

Step 6: Engineering criteria - Water Management

To regenerate historical spatial structure and enhance spatial hybridity, researchers and students from the two disciplines had many discussions in order to finalize the locations.

Some engineering criteria are so fundamental that relocating some solutions should take the criteria into account. For instance, the area of reed bed is related with the population number, each person needs a certain area equivalent of reed bed. This means the total area of reed bed should always be calculated from the population. Moreover, installation of a reed bed system requires at least 200 m^2. The reed bed and wadi should have connections to open water in order to discharge extra water from the facilities. The safe distance of rain garden mentioned in Step 2 should be kept in mind to avoid rotting building foundation.

Step 7: Enhancing spatial hybridity - Urban Design

After discussions back and forth, some solutions are improved or relocated and then the spatial hybridity of the new layout is analyzed and evaluated.

- DEWATS is finally determined to locate at public green area in each neighbourhood. A small building, given the name of water housing, will be constructed at public green for treatment facilities. A water pond will be dug next to the water housing inspired by the pilot project in China, to store the extra water from DEWATS. In this case, wastewater from buildings will be treated in the water housing, and extra treated water will be discharged into water pond, thus the red-green connection can be formed. For neighbourhood where it is difficult to transform the public green to water housing, the DEWATS are still placed in the basement of the building.

- The underground storage tank of rainwater harvesting system is decided to be on the ground level. This will increase the visibility of rainwater harvesting system. Collected rainwater can be used for irrigating plants in private gardens, and thus the red-green connection is created. The shape of storage tank may be designed in the future, for instance, it could be in the shape of a box so that it can function as a water fence with some plants on it. This design idea is proposed by the urban designers, and more studies could be carried out on this subject.
- Some rain gardens are relocated in the front yard of the building so that people can see and experience in the streets. The safety distance (8 m) applied for initial locations is shortened, but still is kept 3 meters away from buildings [53]. For applications in the future, the safe distance needs further investigation.

In addition, the relocation also considers trying to regenerate the historical spatial structure as much as possible. Finally, all the locations are finalized and it is shown in Figure 5.1.

Summary

Collaborative design phase is an essential step in this project. As the realization of closed city needs to finalize the solutions and their locations, the involvement of urban design would solidify this decision-making process and contribute to sustainability of both urban development and urban water systems. By the back-and-forth discussions and reflections, this phase offers the opportunity for both disciplines to exchange the knowledge and get better understanding of each other. This would be the cornerstone for inspiring the integrated water resources management, to show the way of how different disciplines/stakeholders can cooperate and communicate.

D

Water quantity involved in each sphere of future visions

Table D.1: Water distribution to each sphere in Mechanical Zevenkamp

From	**To**	**Amount [m^3]**
Technosphere	Technosphere	411000
Technosphere	Techno-Geo	928000
Geosphere	Techno-Geo	736000
Biosphere	Bio-Geo	833000
Bio-Geo	Geosphere	441000
Geosphere	Bio-Geo	54000
Bio-Geo	Bioshpere	114000

Table D.2: Water distribution to each sphere in Green Zevenkamp

From	**To**	**Amount [m^3]**
Technosphere	Techno-Geo	105000
Technosphere	T-B-G	316000
T-B-G	Technosphere	187000
Techno-Bio	Technosphere	53000
Techno-Bio	T-B-G	278000
T-B-G	Techno-Bio	139000
T-B-G	Techno-Geo	274000
T-B-G	Geosphere	11000
T-B-G	Bio-Geo	11000
Bio-Geo	T-B-G	7400
Geosphere	Techno-Geo	757000
Biosphere	Bio-Geo	715000
Bio-Geo	Geosphere	367000
Geosphere	Bio-Geo	46000
Bio-Geo	Bioshpere	115000

Table D.3: Water distribution to each sphere in mixed vision 1

From	**To**	**Amount [m^3]**
Technosphere	Technosphere	226000
Technosphere	Techno-Geo	476000
Technosphere	T-B-G	45000
Technosphere	Techno-Bio	185000
T-B-G	Technosphere	52000
Techno-Bio	Technosphere	53000
T-B-G	Geosphere	5000
T-B-G	Bio-Geo	5000
Bio-Geo	T-B-G	5000
Geosphere	Techno-Geo	757000
Biosphere	Bio-Geo	715000
Bio-Geo	Geosphere	367000
Geosphere	Bio-Geo	50000
Bio-Geo	Bioshpere	114000

Table D.4: Water distribution to each sphere in mixed vision 2

From	**To**	**Amount [m^3]**
Technosphere	Technosphere	132000
Technosphere	Techno-Geo	476000
Technosphere	T-B-G	190000
Technosphere	Techno-Bio	89000
T-B-G	Technosphere	124000
Techno-Bio	Technosphere	53000
Techno-Bio	T-B-G	149000
T-B-G	Techno-Bio	75000
T-B-G	Techno-Geo	147000
T-B-G	Geosphere	8000
T-B-G	Bio-Geo	8000
Bio-Geo	T-B-G	8000
Geosphere	Techno-Geo	770000
Biosphere	Bio-Geo	744000
Bio-Geo	Geosphere	376000
Geosphere	Bio-Geo	50000
Bio-Geo	Bioshpere	114000

Table D.5: Water distribution to each sphere in mixed vision 3

From	**To**	**Amount [m^3]**
Technosphere	Technosphere	45000
Technosphere	Techno-Geo	476000
Technosphere	T-B-G	316000
T-B-G	Technosphere	187000
Techno-Bio	Technosphere	53000
Techno-Bio	T-B-G	278000
T-B-G	Techno-Bio	139000
T-B-G	Techno-Geo	274000
T-B-G	Geosphere	11000
T-B-G	Bio-Geo	11000
Bio-Geo	T-B-G	7400
Geosphere	Techno-Geo	757000
Biosphere	Bio-Geo	715000
Bio-Geo	Geosphere	367000
Geosphere	Bio-Geo	50000
Bio-Geo	Bioshpere	114000