INTEGRATING PLUVIAL FLOOD MITIGATION MEASURES AND SYSTEMS FOR HEATING AND COOLING IN THE URBAN WATER SYSTEM

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ABSTRACT

Heavy precipitation results in high pressure on the urban water system. This leads to pluvial flooding and overflowing of the sewer system into the surface water. In order the mitigate the impact of these events, separate sewer systems and water storage facilities are implemented in cities. Surplus water overflowing from surface water or sewer system can be stored in a reservoir for a period of time and later slowly discharged back into the water system via pumping or infiltration. In most cases, the water is not harvested for reuse. However, rainwater has a high potential for reuse. Evaporation and aquathermia are two types of the use of water in systems to cool and heat buildings. Both offer a potential application for the reuse of harvested rainwater. This research paper aims to illustrate the position of rainwater storage and harvesting in the urban water system and investigates the possibility of reusing the harvested rainwater in systems cooling or heating buildings.

KEYWORDS: Pluvial Flood Mitigation, Urban Water System, Rainwater Storage, Rainwater Harvesting, Climate Systems, Evaporative Cooling, Aquathermia, Thermal Energy Storage

I. INTRODUCTION

Extreme weather events due to climate change in combination with urbanisation and soil sealing lead to high pressure on the urban water system. The current urban water system is unable to deal with increased rainfall, resulting in pluvial flooding and overflowing of the sewer system into the surface water (Hooimeijer, 2011). The urban water system needs to be improved in order to mitigate the impact of heavy precipitation in cities. Separate sewer systems and water storage facilities are examples of measures implemented by municipalities to deal with pluvial flooding (Hooimeijer et al., 2019). In schematisations of the urban water system, these measures are not visualized. Illustrating the position of these measures in the urban water system and their connection to other elements in the water system gives insight in possibilities to further integrate them into the urban water system. Another theme missing in the scheme of the urban water system is the utilization of water for heating and cooling buildings. Water functions as a thermal energy transporter (Kollo & Laanearu, 2015) and is therefore deployed as a medium to heat and cool. In common climate systems, water is used to transport heat or cold through a building via pipes, however, water can be deployed in alternative ways. Two characteristics of water are useful in climate control: evaporation and thermal mass.

The image below a schematisation of the urban water system based on schematisations of the by Ruger de Graaf (2009) and by Jules van Hoof (2021). Red comments highlight the missing elements to be investigated and positioned in this paper.

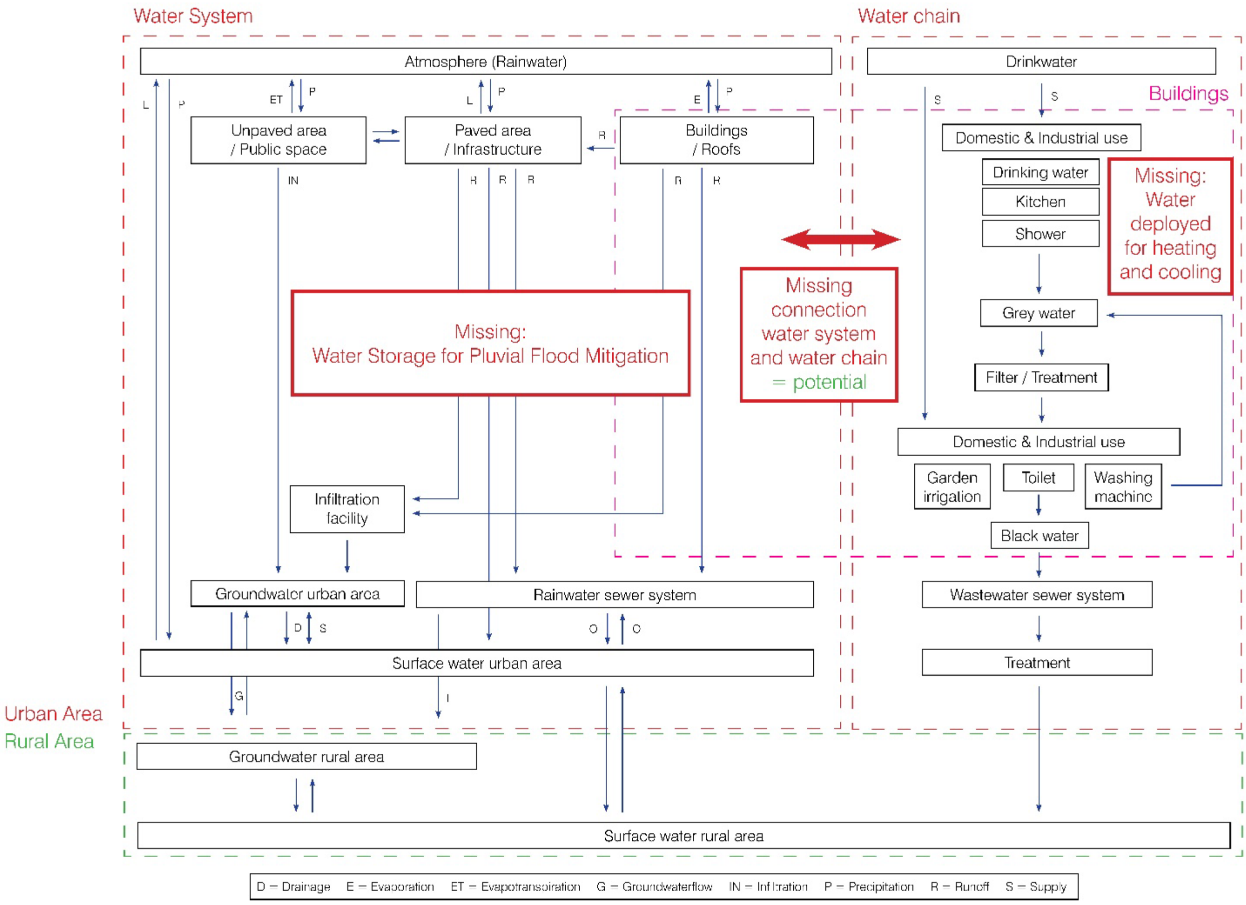

Figure 1: Schematisation of the urban water system and research themes (Hartmann, 2023).

The aim for this research is to look at the possibility of harvesting the stored rainwater and reusing it for heating and cooling, to create a more circular urban water system which is more resistant to extreme weather events and has a lower demand for potable water. The main question leading this research is: *Could rainwater harvested from storage facilities to mitigate urban pluvial flooding be re-used in a building, specifically for heating and cooling?*

1.1. Method

The result of this research is the creation of a stronger connection between the natural water system and the artificial water chain within the urban water system by integrating measures for water storage and -harvesting and techniques for the utilization of water for heating and cooling in the urban water system. This could lead to a more circular urban water system where the built environment is more resistant to pluvial flooding and the demand for potable water for heating and cooling is reduced.

To answer the main research question, the conducted research can be roughly split up in two parts. Rainwater storage and harvesting for urban pluvial flood mitigation and (rain) water for heating and cooling. The two themes overlap when harvested rainwater is reused for heating and cooling. The image below illustrates the connection between the research topics.

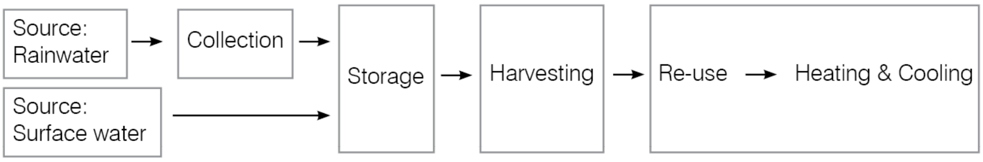

Figure 2. Overview of research topics (Hartmann, 2023).

Sub-questions on the different research topics help to structure the research. For each question, qualitative research is conducted by analysing literature and case studies.

First, the urban water system is analysed to understand the issues and the position of buildings in the system. This is necessary to later find the position of storage, harvesting and reuse measures within the urban water system and in relation to buildings.

The second step is to study literature and examples of measures for water storage for pluvial flood mitigation in order to summarize the concepts and place them into the urban water system. This is described in chapter three to answer the first sub-question: *How can surplus rainwater be stored in buildings and/or urban areas to mitigate pluvial flooding and what position do these measures take in the urban water system?*

To create a connection between the natural water system and the water chain, water could be harvested for reuse in the built environment. Most water storage facilities slowly release the water back into the water system when the pressure is lower again. However, all this excess water has the potential to be harvested. This leads to the following sub-question, explored in chapter three: *How can rainwater stored for pluvial flood mitigation be harvested and reused?*

The harvested water has to be brought back into the water system to be reused. The cycle of extraction, treatment, usage and transport of water for industry and household is considered the water chain. The water chain does not only include domestic water use from the tap or toilet, but also the use of water for heating and cooling the building. Systems for evaporative cooling and aquathermia could offer an application for the reuse harvested rainwater in the building system. This leads to the next sub-question for this research: *What techniques deploy water to heat or cool a building?* And subsequent: *Could harvested rainwater be used in these systems?* The findings are described in chapter four and five.

The integration of the studied concepts in the urban water system illustrates the potential to connect the themes and find out whether rainwater harvested from storage facilities to mitigate urban pluvial flooding be re-used in a building, specifically for heating and cooling. To conclude the research, the research question is answered, and an edited urban water system scheme is presented showing how pluvial flood mitigation measures and climate systems can be integrated in the urban water system.

II. The Urban Water System

Within Dutch water management, we acknowledge that the urban water system (UWS) is a hybrid system consisting of the natural water system and the water chain. The water system describes the natural cycle of rainwater, surface water and groundwater. The water chain is the artificial cycle of drinking water and sewer water of human utilization. However, in the Netherlands, the water system is not completely natural, because of artificial pumping of polders (Hooimeijer et al., 2019). The natural water system and artificial water chain are often connected via a combined sewer system. In a combined sewer system, wastewater and rainwater are discharged via the same sewer system. This system causes problems in times of increased rainfall. Heavy precipitation causes high pressure on the water system, which can lead to overflowing sewers discharging their surplus into the surface water. In the case of a combined sewer system, the discharged water is a mix between rain- and wastewater, with the latter polluting the surface water quality (Hooimeijer, 2011). At the same time, relatively clean rainwater is mixed with polluted sewer water and transported to the water treatment plant. To avoid these problems, separate sewer systems are becoming more common, especially in cities dealing with water nuisance due to pluvial flooding. In a separate sewer system, wastewater from households and industry is discharged with a sewer system separate from rainwater. This way, in the case of heavy precipitation and high pressure on the sewer system, only rainwater is directly discharged to the surface water, therefore minimizing pollution. Furthermore, the rainwater is not necessarily brought to the water treatment plant with the polluted sewer water. Separating the rainwater and wastewater sewer opens the potential for harvesting and reuse of the rainwater. If rainwater is harvested and reused in households and industry, this creates a new connection between water chain and water system within the urban water system. This is a measure to move towards a more circular urban water system and an opportunity to lower the demand for drink water.

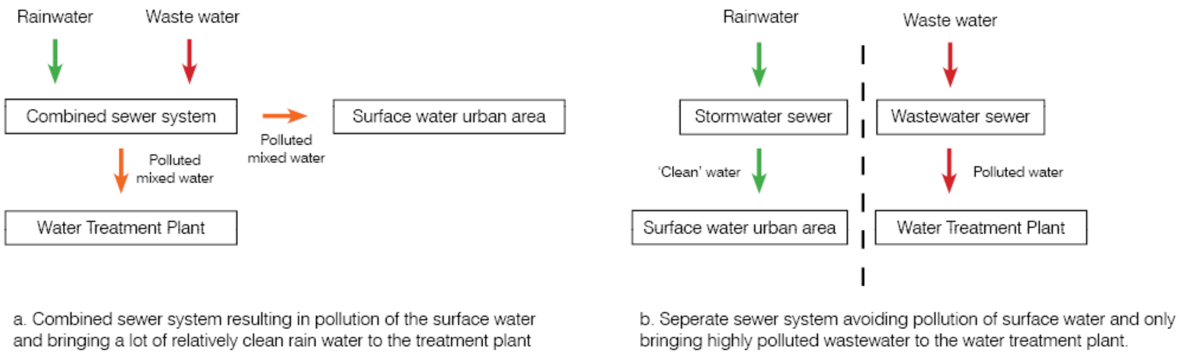

Figure 3. Combined vs. separate sewer system (Hartmann, 2023).

Buildings take up a prominent position in the urban water system since they are part of both the water chain and the water system. A large part of the water chain is located within buildings. Drinking water for households and industry is transported to buildings to be utilized and wastewater is disposed from buildings via the wastewater system. Parallel to this, buildings play a role in the water system, catching rainwater on the roofs and leading it towards the sewer system or infiltration facility via runoff. Rethinking the ways in which water is used in buildings can have an impact on the demand for drinking water, and changing the way we deal with water collected on roofs can influence the pressure on the stormwater sewer to avoid urban pluvial flooding.

III. Urban Pluvial Flood Mitigation

3.1. Rainwater Storage

To mitigate the impact of heavy precipitation, the pressure on the water system has to be lowered to avoid overflowing of the sewer system. A solution is storing rainwater for a period of time to delay the discharge to the water system until the pressure is lower (Hofman et al., 2014 and Mackenzie, 2010). Water storage refers to temporarily holding drained water from extreme precipitation events (Vergroesen et al., 2013). This way, storage measures contribute to the prevention of pluvial flooding (Voskamp & Van de Ven, 2015). In research for Deltares, Vergroesen et al. (2013) give a large overview of water storage measures categorized in four main categories: underground storage/delay, above ground storage/delay, underground infiltration and above ground infiltration/delay. A distinction is made by the storage method. In order to position the different types of measures in the urban water system, it is more useful to make a slightly different distinction, not only by where it is stored, but in combination with where it is collected.

This can be done using the layers described in the 'System Exploration Environment and Subsurface (SEES) by Hooimeijer and Maring (2013). This overview describes six functional layers of the physical domain: people, metabolism, buildings, public space, infrastructure and subsurface. Water does not have a set place within these layers but is a system that runs throughout the city (Hooimeijer & Maring, 2013). Therefore, we can use this overview of layers to categorize water storage methods by in which layers the rainwater is collected and stored: via buildings, public space, or infrastructure. The image below shows examples of measures that fall under these categories. This categorization with layers can be linked with the schematization of the urban water system by Rutger de Graaf (2009). These schemes describe how precipitation falls on roofs, the paved area, and the unpaved area (and directly to urban surface water) (De Graaf, 2009). Roofs are part of the buildings layer, the unpaved area is part of the public space and the paved area is part of the infrastructure.

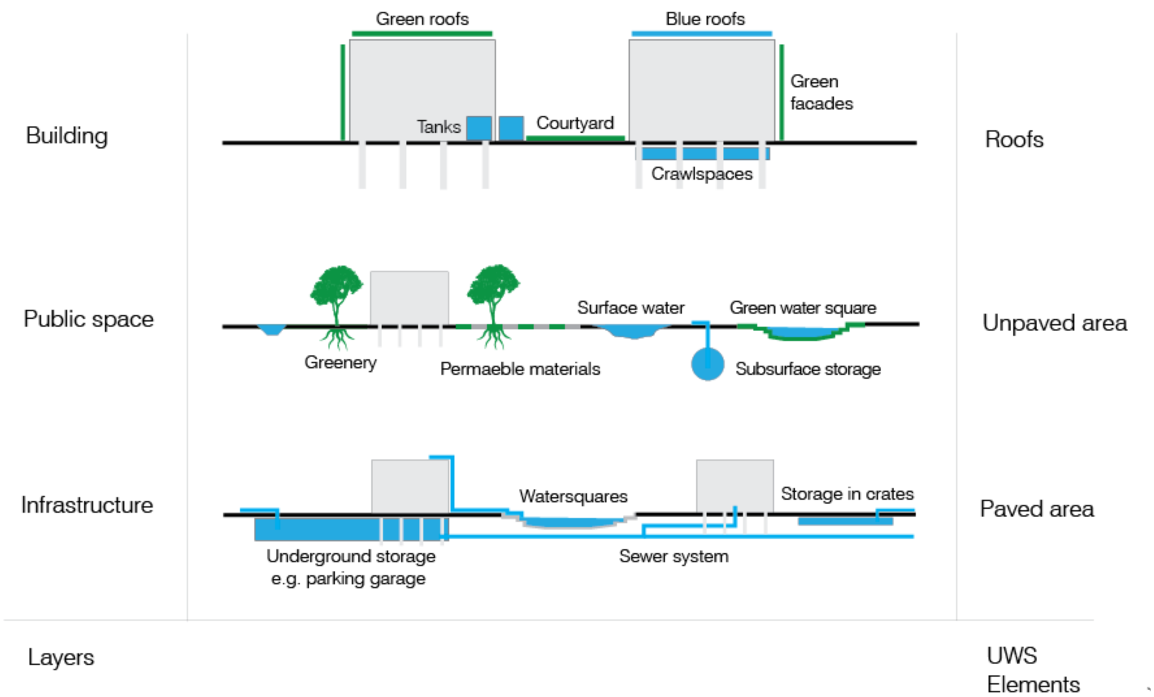

Figure 4: Types of Rainwater Storage. Categorization on left by layers, on right by elements of the UWS (Hartmann, 2023).

In the scheme by De Graaf (2009), after falling on roofs and paved or unpaved areas the rainwater moves towards the groundwater or urban surface water via runoff or infiltration (De Graaf, 2009). As mentioned, the purpose of water storage (for pluvial flood mitigation) is to delay this discharge further into the water system (Mackenzie, 2010). Most rainwater falling on unpaved areas infiltrates directly towards the groundwater. However, rainwater falling on paved areas or buildings runs off and can be brought to a storage facility, via direct runoff, the sewer system or urban surface water overflow. In the case of heavy rainfall, it sometimes occurs that the pressure on the sewer system or the surface water becomes too much, and the system overflows. This surplus water can be stored in the underground water storage, to avoid water nuisance and flooding. When the heavy rainfall is over and the pressure on the sewer system or water levels in surface water is low again, the water from the water storage is slowly released (often pumped back) into the system. Water from the storage can also be slowly infiltrated to the groundwater. Figure 5 illustrates the position of water storage in the urban water system, the dashed lines illustrate the delayed release of water back into the water system after storage. Reuse is presented as an alternative option to this.

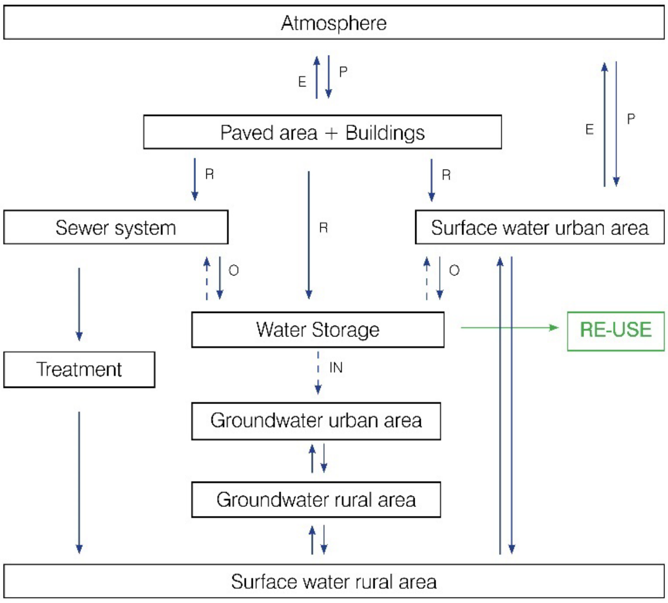

Figure 5: Urban Water Storage schematization (Hartmann, 2023).

Thus, to lower the impact of rainwater on the urban water system and avoid pluvial flooding, rainwater can be stored for a period of time. Rainwater is collected on roofs and paved areas and brought to the sewer system or urban surface water. When the pressure on the sewer system or urban surface water is too high, surplus water can overflow to water storage. When the pressure on the urban water system is lower again, the water is slowly discharged back to the sewer system or urban surface water or infiltrated towards the groundwater. To move towards a more circular system, re-use of stored rainwater is presented as an alternative.

3.2. Rainwater Harvesting

In most examples of water storage for pluvial flood mitigation, for example in the Watersquares and underground water storage in Rotterdam, the water is not re-used (Mackenzie, 2010). However, an important opportunity is missed here. Rainwater, especially when collected from roofs, is relatively clean (Mackenzie, 2010) and can therefore be reused: harvested. The term water harvesting is used when water is collected and stored with the purpose of providing water for later use (Hillel, 2005). Water storage measures can be utilized to harvest rainwater. Voskamp and Van de Ven (2014) describe examples of measures to reduce the impact of extreme weather events in urban areas that can be deployed for water harvesting. Instead of releasing the water back to ground- or surface water via infiltration or the sewer system, the stored rainwater can be treated and re-used as grey water. In this case it is important that the water in the storage is solely rainwater and not polluted overflow from a combined sewer system. This way, rainwater harvesting (RWH) can be an opportunity to create a connection between the urban water system and water chain and therefore move towards a more circular (urban) water system.

One of the few examples where rainwater storage for flood mitigation and rainwater harvesting are combined is the Urban Waterbuffer (UWB) of Sparta, in Spangen, Rotterdam. Water running off from the paved area around the Sparta stadium and water collected from the field via a drainage system (A in figure 6) is stored temporarily in a water reservoir made of crates below the Johan Cruyff court (B in figure 6). This mitigates water nuisance in the neighbourhood in periods of heavy rainfall. The rainwater passes a planter which functions as a biofilter (C in figure 6). After this, the water is infiltrated towards a deep underground water storage in the sand layer of the ground (D in figure 6). The stored water can be pumped up again in dryer periods to irrigate the field of the Sparta stadium (E in figure 6). This way, no potable has to be 'wasted' for this purpose (Zuurbier & Van Dooren, 2019). This Waterbuffer project is a good example of mitigating the impact of heavy rainfall while at the same time reusing the water to create a more circular water system.

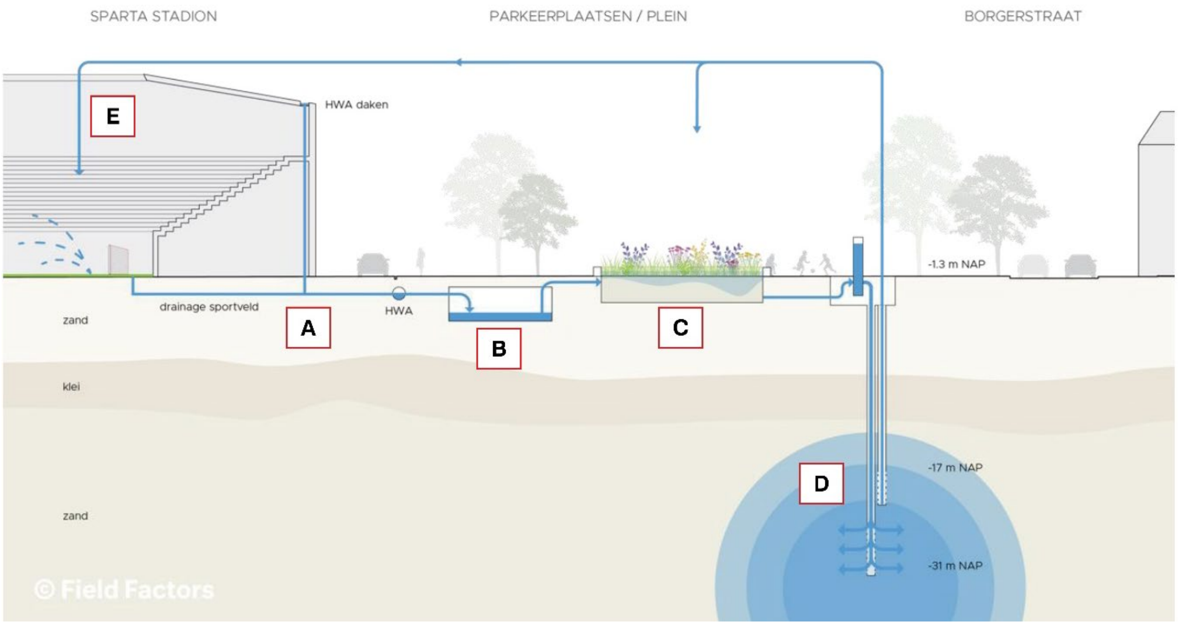

Figure 6. Watersystem UWB Spangen (Fieldfactors via Zuurbier & Van Dooren, 2019).

To harvest rainwater for reuse, it is important that the runoff rainwater is brought to a storage facility via a separate rainwater sewer system, to ensure the relatively clean rainwater is not polluted with wastewater. Instead of releasing the stored water back to ground- or surface water via infiltration or the sewer system, the rainwater should be treated and brought back into the water chain as a supply source for functions that do not require drink water. Utilizing rainwater as an alternative water supply can lower the demand for drink water. Figure 7 visualizes measures for rainwater collection, storage and harvesting to enable re-use.

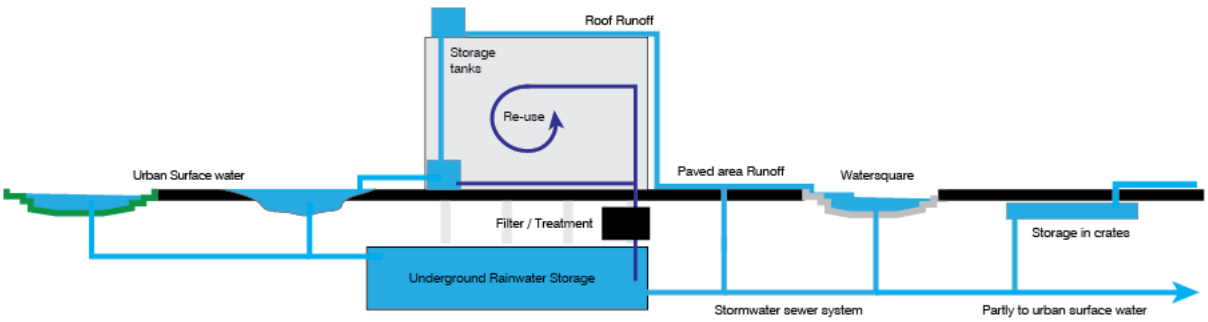

Figure 7. Surplus rainwater harvesting overview (Hartmann, 2023).

IV. THE WATER CHAIN AND CLIMATE SYSTEMS

4.1. Water Chain and Climate Systems

To understand the potential of reusing harvested rainwater in buildings, it is important to understand the artificial water chain. The water chain consists of three levels of water quality: potable water, grey water (all domestic wastewater flows except flows from toilets) and black water (toilet wastewater and sometimes kitchen wastewater flows) (Abu Ghunmi, 2009). Rainwater harvesting for domestic grey water use is becoming more common, to lower the demand for potable water. Rainwater harvesting for domestic grey water use is only one example of how rainwater can be reused. According to Kollo and Leaanearu, “Storage tanks offer several possibilities to exploit natural water more diversely” (2015, p. 213). They suggest harvesting rainwater not only for domestic use, but also for providing comfortable climate conditions in urban areas and buildings (Kallo and Leannearu, 2015). This indicates deploying rainwater in cooling and heating systems. The component of the climatic systems for heating and cooling using water is usually not included when describing the water chain of a building. The water in these systems does not need to be as clean as potable water, and after use, the water remains grey water instead of black water, so it could be reused again. This is an opportunity to reuse harvested rainwater.

Water functions as a thermal energy transporter (Kollo & Laanearu, 2015) and is therefore deployed as a medium to heat and cool buildings. In common climate systems, water is used to transport heat or cold through a building via pipes, however, water can be deployed in alternative ways. Two characteristics of water are useful in climate control: evaporation and thermal mass. Both characteristics are used since ancient times to help cool and heat buildings and innovative developments aim to use these characteristics in more efficient systems (De Joanna, 2016).

4.2. Evaporative Cooling

Evaporative cooling is a process where heat is transferred from air to water. The water absorbs the heat from air to evaporate, decreasing the temperature of the passing air (Camargo, 2008). This principle is deployed since ancient times by introducing stagnant, or even more efficiently, moving water into the environment (De Joanna, 2016). Examples are fountains and ponds in the Alhambra in Spain (Jimenez Alcala, 1999). Two main types of evaporative coolers can be distinguished: direct or indirect evaporative coolers. In direct evaporative coolers (DEC), water and air are in direct contact, therefore the humidity of the air increases. In indirect evaporative coolers (IEC), a material separates the fluids to avoid humidity change of the air. A combined system is also possible (Amer et al., 2015). This traditional technique uses relatively little energy compared to other cooling systems, and therefore innovative systems are being developed to make it more efficient and easier or to integrate in buildings (De Joanna, 2016).
Two interesting innovative examples using evaporation to create a more comfortable climate in a building are the British Pavilion for the 1992 Expo in Seville and the Hotel Breeze in Amsterdam. The ‘Water Wall’ of the British Pavilion lets water run down a glass façade, to cool the façade surface and the air, that way preventing heating up of the interior (GRIMSHAW, 2010). Hotel Breeze uses the Earth, Wind & Fire concept by Ben Bronsema (Bronsema, 2013) and has a ‘Climate Cascade’ where water runs down to clean and cool down the outside air which then is transported to the rooms via the ventilation system (SmartCircular, 2019).

Figure 8. Water Wall, British Pavilion for the 1992 Expo in Seville (GRIMSHAW).

4.3. Aquathermia

Aquathermia is thermal energy from water: extraction, storage, and distribution of heat and cold from a water source to heat and cool buildings sustainably. The three main types of aquathermia use different types of water: surface water, wastewater and drinking water (Kruit et al., 2018). The most interesting type is Surface Water Thermal Energy (SWTE), since according to a report by CE Delft and Deltares, SWTE could cover “more than 40% of the total future heat requirement in the built environment per year” (Kruit et al., 2018 p. 3). Heat is extracted from the surface water in summer, in winter a heat exchanger releases the heat to a heat pump to heat the building. The opposite can be done using winter cold to cool in the summer. This system is often combined with seasonal heat and cold storage in the ground, for example with an Aquifer Thermal Energy Storage (ATES) system. These systems deploy groundwater to transport thermal energy from and to an underground aquifer, where heat and cold is stored (Cabeza et al., 2015).

Architect and academic Matyas Gutai deploys aquathermia in an innovative way with his ‘Water Filled Glass’. These WFG-systems consist of two layers of glass with a layer of water in between, connected to a storage tank. The water can circulate through the system. In summer, the water absorbs the heat from the sunlight and transports it to the storage tank, acting as a buffer to keep the interior cool. In winter, the stored heat can be transported through the system to heat the building (Gutai, 2021). The concept has high potential because of its energy-efficiency in combination with high aesthetic value. The earlier mentioned British Pavilion by Grimshaw utilises the thermal mass of water in a less complex way, with a wall made of water tanks functioning as a buffer to prevent the building from heating up too much (GRIMSHAW, 2010).

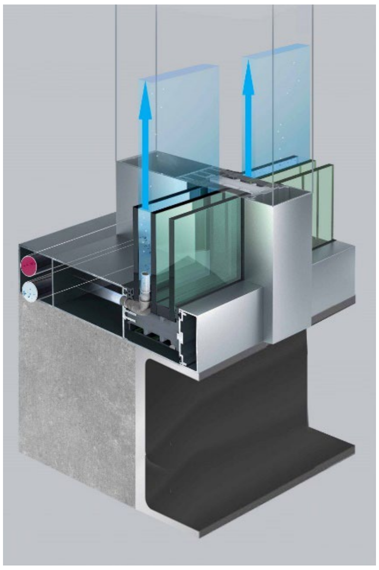

Figure 9 & 10. Water Filled Glass and Water House 2.0 at Feng Chia University in Taiwan by Matyas Gutai (2021).

V. Rainwater in Climate Systems

To integrate these heating and cooling systems in a circular urban water system, it is interesting to look at possibilities of using harvested rainwater instead of potable water for systems for evaporation or aquathermia.

5.1. Evaporative Cooling

Different examples demonstrate that harvested rainwater can be the source for evaporative cooling systems. A demonstration project by the Technical University of Denmark presents positive results implementing evaporative cooling with harvested rainwater for a school in Århus, Denmark. Rainwater is collected from the roof with existing gutters and conveyed to an underground storage tank. From here it is pumped through a filter to a smaller tank connected to the cooling system. This smaller water tank is supplied with UV disinfection "to eliminate possible bacterial contamination" (Hviid et al., 2020, p. 3). Via an Adiabatic Indirect Evaporative Cooling system, the rainwater cools the air providing a comfortable indoor climate in the classrooms (Hviid et al., 2020). Another example is the Passive Cooling Water Wall (PCWW) for the SEGi University Tower in Petaling Jaya, Malaysia. The system uses harvested rainwater collected at the roof of the building to run down between two layers of a glass façade. The façade allows sunlight to enter the building without heating up the interior, because the water removes the heat built up between the glass layers (Venkiteswaran et al., 2017).

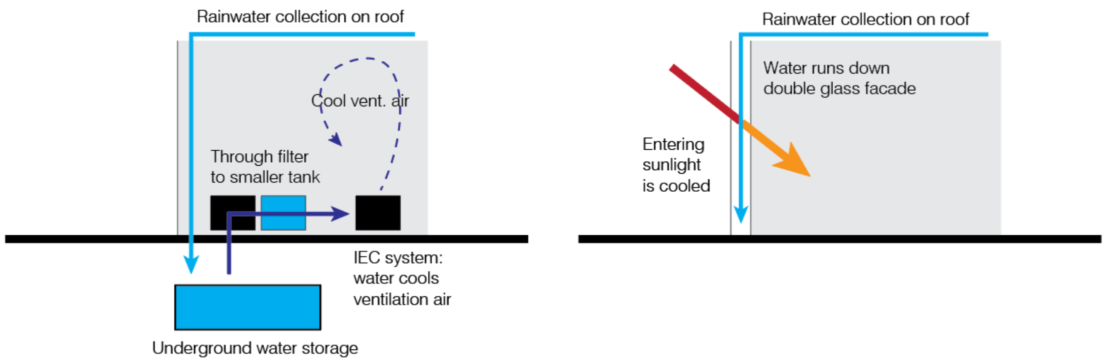

Figure 11. Simplified visualisation of evaporative cooling concepts for a school in Denmark on (left, Hviid et al., 2020) and the Passive Cooling Water Wall in Malaysia (right, Venkiteswaran et al., 2017) (Hartmann, 2023).

5.2. Aquathermia

The use of specifically rainwater as a source for aquathermia is less developed and studied in literature. However, some research suggests there might lie potential in combining rainwater storage and harvesting and aquathermia systems. In Urban Water Journal it is stated: "Hot water production from stormwater is feasible in the case of a building that has a large catchment area, where flood risk is an important issue and more-or-less stable hot water consumption exists. There is great potential for the application of the integrated stormwater system for thermal energy extraction in urban areas" (Kollo & Laanearu, 2015, p. 221). French researcher Jean-Baptiste Bouvenot studies a 'hybrid geothermal rainwater tank': a passive and low-tech concept which can be deployed in both urban or rural areas and can contribute to dealing with climate change and lack of natural resources. Rainwater is collected from a roof or drainage system and stored in a rainwater tank (RWT) above- or underground to relieve the sewer system and at same time supply grey water supply. More importantly, it functions as thermal storage and can be "thermally activated by the immersion of a heat exchanger" (Bouvenot, 2021, p. 2) to preheat or precool fresh air entering a building via the ventilation system (Bouvenot, 2021).

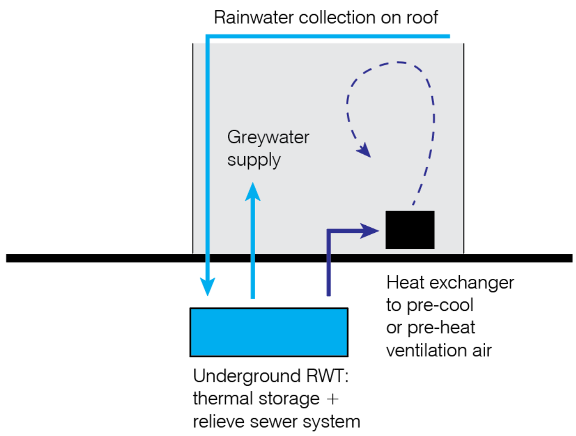

Figure 12. Simplified visualisation of 'hybrid geothermal rainwater tank', concept by Bouvenot (2021) (Hartmann, 2023).

Although not widely applied yet, several case studies suggest that harvested rainwater could be deployed instead of drinking water for concepts of evaporative cooling and aquathermia. For systems using rainwater for cooling or preheating ventilation air, it is advisable to disinfect the water before use.

Within aquathermia there are already concepts deploying surface water or wastewater as an alternative to drinking water. Harvested rainwater has the potential to be used for this application, especially for thermal energy storage.

VI. DISCUSSION

The combination of integrating flood mitigation and climate systems into the urban water system, could help creating a more circular urban water system and even move towards a 'Closed City'. This proposal was presented in 2005 and is defined as "a city that does not have adverse effects on its surroundings, such as water depletion or emission of pollution" (Hooimeijer et al., 2019, p. 4). In this situation the water system is able to respond to water shortages and floods. Improving the water storage capability and sewer systems are important elements to achieve this. Furthermore, focus lies on deploying recycled rainwater and treated wastewater as alternative resources (Hooimeijer et al., 2019). The aim of this research paper is in line with the concept of the Closed City. The described measures for water storage contribute to an urban water system that is better able to respond to extreme precipitation to avoid pluvial flooding. By harvesting rainwater from these storage facilities and reusing it in buildings, the rainwater is deployed as an alternative resource. In addition, collecting, storing and harvesting rainwater separate from wastewater helps to avoid pollution of surface water and spoiling the relatively clean rainwater. Deploying recycled rainwater for heating and cooling buildings by evaporation or aquathermia offers a new potential for the reuse of rainwater, integrating another element of the built environment into the urban water system. Therefore, the combination of concepts described in this paper can contribute to a Closed City, in combination with other measures.

Switching to alternative, local water sources like rainwater could improve resilience in dry periods. Instead of depending on a single source, a 'closed city' using multiple sources like rainfall and recycled grey water make it possible to restore quicker from dry periods. This system helps to prevent the impact of climate change, however, other factors might disturb the system. For example, locally collected water is more vulnerable to pollution of the water system by inhabitants (De Graaf et al., 2007). As mentioned in chapter five, it is important to carefully disinfect collected rainwater or reused water in these decentralized systems. The 'closed city' is difficult to implement in existing urban areas, because of the high investments and high lifetime of existing centralized water supply systems. However, researchers from TU Delft suggest small scale local water supply experiment as an opportunity to move more towards decentralized infrastructure (De Graaf et al., 2007). Implementing the findings in this paper could be an interesting experiment to see how using harvested rainwater as supply for heating and cooling systems can lower the regular water demand and make a building function more independently.

VII. CONCLUSIONS

The main question leading this research was: could rainwater harvested from storage facilities to mitigate urban pluvial flooding be re-used in a building, specifically for heating and cooling? The aim for this research was to integrate both themes in the urban water system and to see if they can be connected.

Measures for urban pluvial flood mitigation have been investigated and their position in the urban water system has been found. The measures can be categorized by where the water is collected: via unpaved areas (public space) paved areas (infrastructure) and buildings. Storing surplus rainwater reduces the pressure on the sewer system to avoid water nuisance due to pluvial flooding. Most implemented typologies for water storage slowly discharge the water back into the water system via pumping or infiltration when the pressure on the water system is low again. Instead of releasing the stored rainwater into the surface- or groundwater, it is possible to harvest the water and reuse it in the water chain. Reusing harvested rainwater reduces the amount of potable water supply required and less potable water is 'wasted' for purposes where it is not specifically necessary. It is important that the water for reuse is not polluted with wastewater in a combined sewer system, and it is wise to filter or treat the water before reuse.

Evaporative cooling and heating and cooling using aquathermia are techniques that deploy the characteristics of water to cool or heat a building in a more sustainable way. For evaporative cooling, several studies prove that harvested rainwater can be used instead of potable water. Less research has been conducted on deploying rainwater for thermal energy extraction or thermal energy storage. However, some case studies present the potential of using rainwater for these purposes in the same way surface water is deployed. It can be concluded that these systems for heating and cooling with water offer a new purpose for reuse of harvested rainwater in buildings.

The concepts described come together in buildings, because those are part of the water chain as well as the water system, and can therefore play a role in strengthening the connection between these two parts of the urban water system. Buildings can be utilized to collect and store surplus rainwater as well as utilize the harvested rainwater for the elements of the water chain located within the building, including systems for heating and cooling. The combination of integrating water storage, harvesting and reuse for heating and cooling into the urban water system contributes to an urban water system that is more resistant to heavy weather events, because of water storage measures, and at the same time lowers the demand for potable water by reusing this rainwater.

It is important to start thinking about the position of buildings and building parts in the Urban Water System and how those could have a positive impact on this system. Designing with water is threefold, the building needs to offer a place to collect water, a place to store water, and have options to reuse the rainwater within the building. When these three components are integrated in a building, optimal interaction with the Urban Water System is possible.

Revisiting figure 4, Types of Rainwater Storage, we can see how every element in the 'building' layer can be part of the Urban Water System and contribute to rainwater management and climate control. For example, roofs of buildings cover a large surface area and should therefore be deployed for rainwater collection and rainwater retention. Instead of letting this water run-off to the sewer system, it can be stored in other parts of the building and directly be reused. Façades can be used for collecting rainwater as well and offer great potential for using rainwater for climate control. Rainwater running down a façade can help cool the direct environment through evaporation. On both roofs and façades, water elements can be deployed as a buffer against solar heat. Crawlspaces, courtyards and tanks can serve as water storage for rainwater to be reused in the building. The stable temperature of the water in these storage areas can be deployed for cooling and heating systems.

These examples offer inspiration for rethinking the relationship between buildings and water. New buildings and even renovations of existing buildings should create a place for water in several parts of the building. The emphasis lies on not only on collecting and storing rainwater for the sake of lowering the pressure on the sewer system, but at the same time utilizing the characteristics of the water for the benefit of the building and its environment.

Figure 13 on the next page illustrates how pluvial flood mitigation systems and climate systems can be integrated in the urban water system with an edited schematisation of the Urban Water System including storage measures for urban pluvial flood mitigation, rainwater harvesting and climate systems deploying water for cooling and heating.

(In appendix I, the implementation of the concepts presented in this research paper in the final design are summarized).

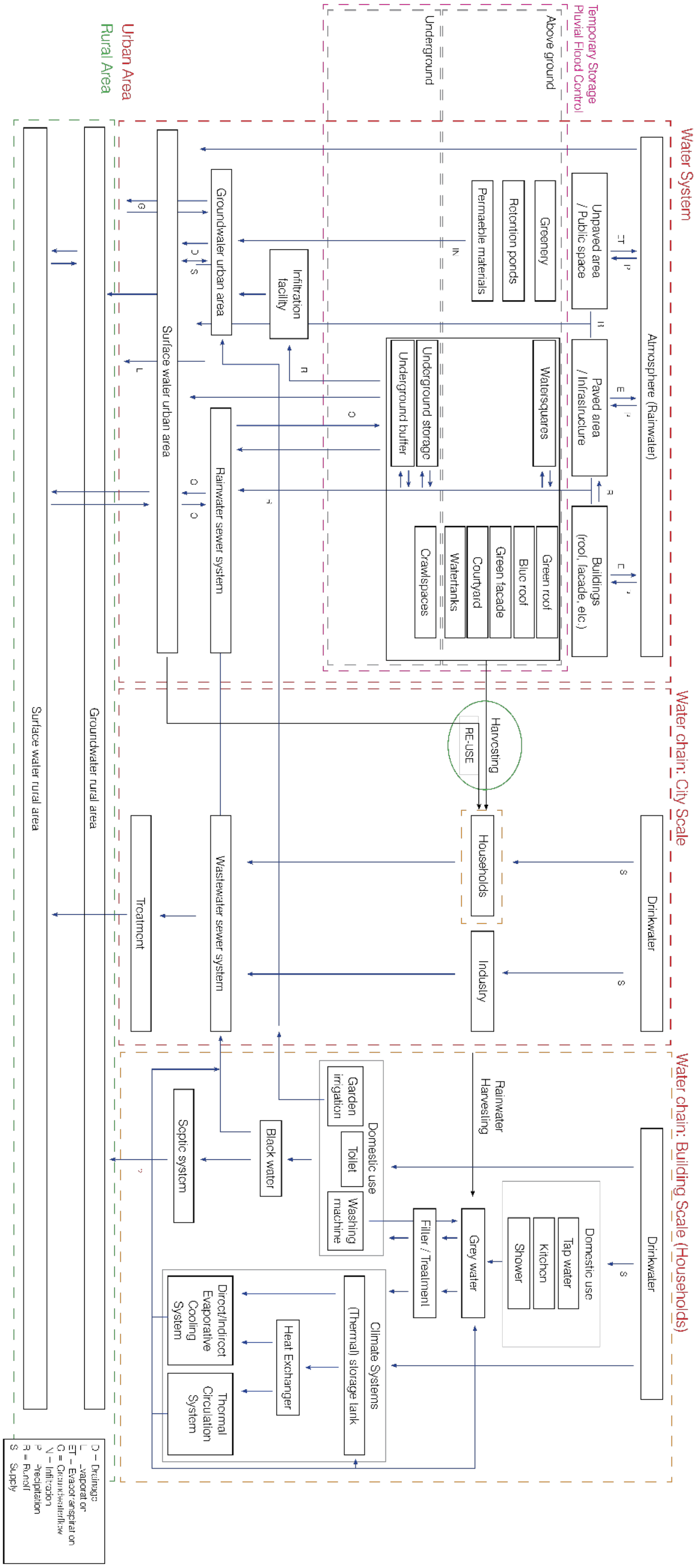

Figure 13. Edited schematisation of the Urban Water System including storage measures for urban pluvial flood mitigation, rainwater harvesting and climate systems deploying water for cooling and heating (Hartmann, 2023).

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FIGURE REFERENCES

Figure 1: Hartmann, N. (2023) Schematisation of the urban water system and research themes.

Figure 2. Hartmann, N. (2023) Overview of research topics.

Figure 3. Hartmann, N. (2023) Combined vs. separate sewer system.

Figure 4: Hartmann, N. (2023) Types of Rainwater Storage. Categorization on left by layers, on right by elements of the UWS.

Figure 5: Hartmann, N. (2023) Urban Water Storage schematization.

Figure 6. Fieldfactors via Zuurbier & Van Dooren (2019) Watersystem UWB Spangen.

Figure 7. Hartmann, N. (2023) Surplus rainwater harvesting overview.

Figure 8. GRIMSHAW. (1992) Water Wall, British Pavilion for the 1992 Expo in Seville.

Figure 9 & 10. Gutai, M. (2012) Water Filled Glass and Water House 2.0 at Feng Chia University in Taiwan by Matyas Gutai.

Figure 11. Hartmann, N. (2023) Simplified visualisation of evaporative cooling concepts for a school in Denmark on (left, Hviid et al., 2020) and the Passive Cooling Water Wall in Malaysia (right, Venkiteswaran et al., 2017)

Figure 12. Hartmann, N. (2023) Simplified visualisation of 'hybrid geothermal rainwater tank', concept by Bouvenot (2021).

Figure 13. Hartmann, N. (2023) Edited schematisation of the Urban Water System including storage measures for urban pluvial flood mitigation, rainwater harvesting and climate systems deploying water for cooling and heating.

Figure 14. Hartmann, N. (2023) Simplified visualisation of final design for the theatre of Gouda, including water interventions.

APPENDIX I RESEARCH & DESIGN

The final design project connected to this research paper showcases a symbiosis between the two themes of the project: water and theatre design. The findings from the research paper operate as guidelines to implement rainwater collection, storage and re-use measures in the design to create a building that is integrated in the Urban Water System. The design objective was to find design elements that have a positive influence on the urban water system as well as the climate, functionality, and character of the theatre. Finally, the design includes several interventions which have this layered purpose.

The three most important design interventions are the rainwater retention roof ponds, the rain curtain façade, and the water storage below the elevated building and terraces. With these measures, the building offers a place to collect water, a place to store water, and re-use purposes. Not only does each solution have a function in the water system, they also improve the exterior or interior climate and contribute to the spatial quality and aesthetic character of the building.

Water is collected on the roofs and in the roof ponds, the roof ponds function as water retention roofs, where water can be stored for a period of time to lower the pressure on the sewer system in heavy rainfall events. These roof ponds furthermore buffer the sunlight hitting the flat roofs, and offer a view on the water from higher parts of the building and through the skylights below the water. The building is elevated and collected rainwater can be stored underneath. Storing the water relieves the sewer system and the water can be reused for grey water purposes in the building. The stable temperature of the stored water is deployed to pre-cool or pre-heat ventilation air. The water storage places the complete theatre building on a 'stage', creating possibilities for urban life on its elevated terraces, slopes and stairs. Via rain curtains and rain chains surplus water is drained from the roof ponds down to the water storage. The rain curtains cool down the environment through evaporative cooling and stop the heat from the sun interior from heating up the interior. The rain curtains provide theatrical façades with the possibility to open and close in different places when needed, while at the same time showcasing the water dripping down from the roof. This way, the interventions are not only beneficial for the urban water system, but also serve the building and urban environment by improving the exterior and interior climate and have a role as aesthetic elements that shape the character of the building. The concepts are visualised in figure 14, on the next page.

The final design functions as an example and inspiration for other projects of rethinking water as a building element. Next to playing a role in the rainwater management, climate, functionality and aesthetic character of the building, the project aspires to create a bigger 'water awareness' for its users. It is not unimportant to realize the role of water in our surroundings. Instead of draining rainwater as soon as possible to invisible sewers, it is deployed as a decorative and playful element for people to enjoy. Making water and its movement through our built environment more visible can improve the relationship between humans and water. It should create awareness of the influence of water and start discussion on how we should live and deal with it now and in the future.

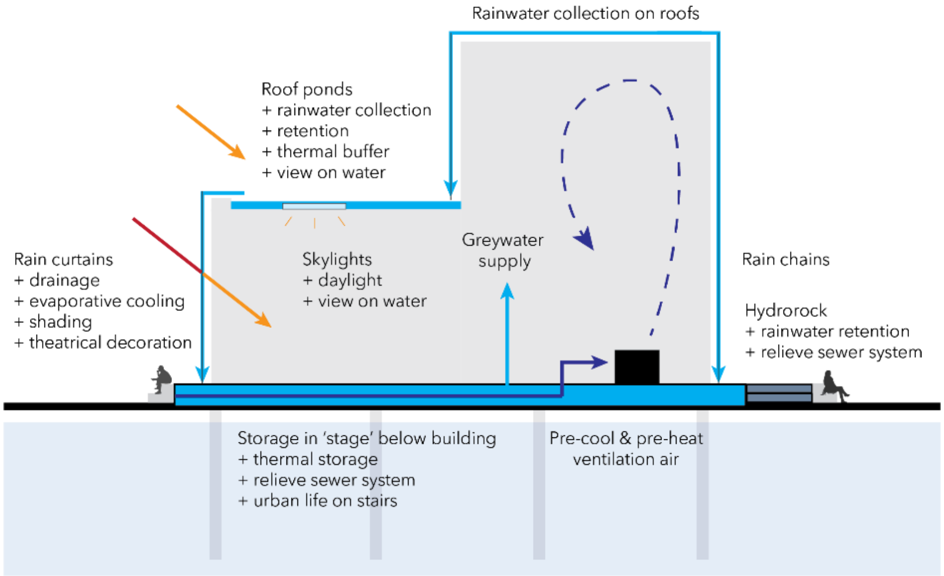
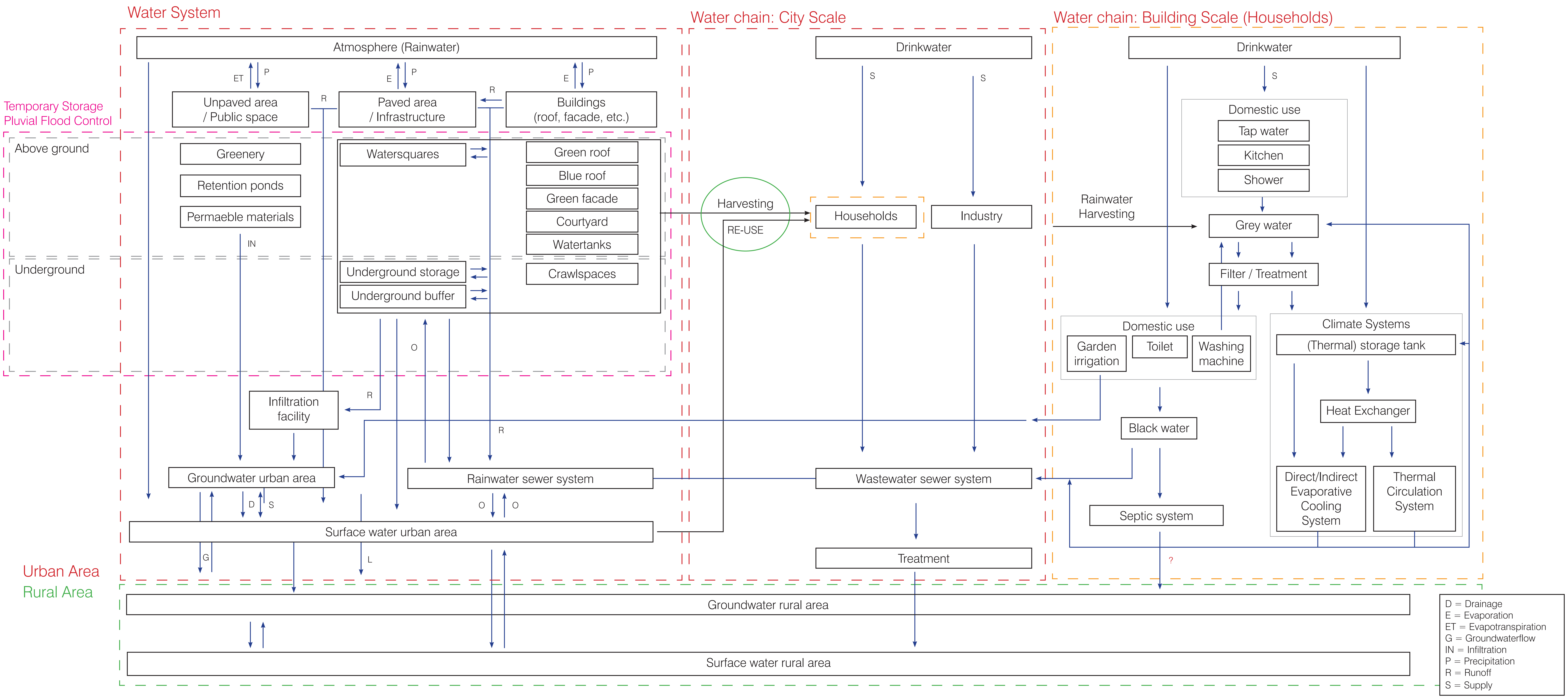


Figure 14. Simplified visualisation of final design for the theatre of Gouda, including water interventions. (Hartmann, 2023).

APPENDIX II EDITED SCHEMATISATION OF THE URBAN WATER SYSTEM

Large version: Edited schematisation of the Urban Water System including storage measures for urban pluvial flood mitigation, rainwater harvesting and climate systems deploying water for cooling and heating (Hartmann, 2023)


Water System
Water chain: City Scale
Water chain: Building Scale (Households)
Temporary Storage
Pluvial Flood Control
Atmosphere (Rainwater)
ET
P
E
P
E
P
Unpaved area / Public space
R
Paved area / Infrastructure
R
Buildings (roof, facade, etc.)
Above ground
Greenery
Retention ponds
Permaeble materials
Watersquares
Green roof
Blue roof
Green facade
Courtyard
Watertanks
Crawlspaces
IN
Underground
Underground storage
Underground buffer
O
R
Infiltration facility
R
Groundwater urban area
Rainwater sewer system
D
S
O
O
Surface water urban area
G
L
Drinkwater
S
S
Harvesting
RE-USE
Households
Industry
Wastewater sewer system
Treatment
Drinkwater
S
Domestic use
Tap water
Kitchen
Shower
Rainwater Harvesting
Grey water
Filter / Treatment
Domestic use
Garden irrigation
Toilet
Washing machine
Climate Systems
(Thermal) storage tank
Heat Exchanger
Black water
Direct/Indirect Evaporative Cooling System
Thermal Circulation System
Septic system
?
Urban Area
Rural Area
Groundwater rural area
Surface water rural area
D = Drainage
E = Evaporation
ET = Evapotranspiration
G = Groundwaterflow
IN = Infiltration
P = Precipitation
R = Runoff
S = Supply