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Review

Overview of the (Smart) Stormwater Management around the Baltic Sea

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Abstract: In this review paper, we investigate the management of the quality of stormwater in the Baltic Sea region. Current stormwater management practices, standards, and legislation do not accurately depict stormwater quality, resulting in an underestimation of its environmental impact. The digitalization and harmonization of stormwater management through the implementation of e-monitoring (online or continuous monitoring) allow for the collection of data. This data can be used to improve stormwater quality and quantity management, thereby reducing the environmental harm induced by anthropogenic activities. Based on the literature review, supporting tables and matrices are proposed to assist decision-makers and other interested parties in developing and implementing "smart" stormwater management solutions. In this article, we demonstrate that such systems can enhance stormwater management and system performance by leveraging data-driven operation and maintenance. Another advantage of the approach is that it contributes to a healthier urban environment and ecosystem well-being.

Keywords: urban stormwater management; water quality; smart cities; green infrastructure; e-monitoring; surrogate parameters

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1. Introduction

Since the 1960s, the number of people living in cities has quadrupled, from 1 billion to over 4 billion. By 2050, it is expected that cities will house more than two-thirds of the world's population [1]. As a result of this rapid urbanization, cities have been forced to convert areas that used to be green and permeable into grey, impervious ones. Together with the effects of climate change, sealing up the surfaces leads to a significant shift in the water cycle. At worst, this shift could cause urban streams to degrade (urban stream syndrome), increase the frequency and severity of floods, degrade the environment, damage infrastructure, and pose risks to public safety and the urban environment [2]. Increasingly frequent downstream floods transport pollutants from roads, lawns, and other built-up surfaces directly into the sea. This contributes to a load of pollutants, such as fertilizers, heavy metals, oil, microplastics, polyaromatic hydrocarbons (PAH), per- and polyfluoroalkyl compounds (PFAS), and microplastics, entering the surrounding waterbodies [3–5].

This problem is widespread throughout the Baltic Sea region, in which intensive agriculture and urbanization have had a negative impact on the water quality of receiving bodies. The Baltic Sea, one of the largest brackish waterbodies in the world, is gradually losing water quality as a result of the influx of these pollutants and the limited water exchange with the world's oceans caused by the shallow and narrow Danish Straits. The pollutant load that reaches the sea is influenced by both anthropogenic land-based activities and meteorological and hydrological factors, including increased precipitation and runoff from the land [6]. It has also been reported that many European cities and regions are susceptible to a variety of climate-related threats, such as floods and droughts [7–11].

Northern Europe and the Baltic Sea region are expecting significant increases in the intensity and duration of precipitation [9–11]. The Tallinn Water Utility has already observed a 30% increase in precipitation intensity through its long-term observations in Estonia, and it is predicted that there will be further increases in the intensity of "normal" rainfall events. Between 1980 and 2013, in Europe, economic losses resulting from extreme weather totaled about 400 billion euros [10]. Extreme precipitation events have clearly had and will continue to have a negative impact on drainage system performance in the long run, resulting in more frequent flooding, increased soil and stream bank erosion, damage to downstream property and ecosystems, and further deterioration of the Baltic Sea water quality.

The traditional technological methods for stormwater management are being put to the test. Both separate and combined sewer systems are affected by this phenomenon, as increasing precipitation significantly alters hydraulic conditions, resulting in a higher frequency of flood events and the contamination of water bodies with pollutants and pathogens. To curb these effects, many cities around the Baltic Sea have begun replacing their existing combined sewer systems with separate systems. Currently, approximately 60% of cities have a combination of separate and combined sewer systems, 28% have only a separate sewer system, and 12% have a combined system [12]. Both the strategy of replacing combined sewer systems with separate sewer systems and that of enlarging the diameter of the pipes have several significant drawbacks. To begin with, the construction of a two-pipe system is expensive and frequently unaffordable for cities and municipalities with a history of chronic underfunding. According to the Organization for Economic Co-operation and Development (OECD), countries must increase their spending by at least 20% to meet European Union (EU) water standards. Additionally, it is estimated that there will be a combined funding gap of EUR 289 billion by 2030 [13]. Stormwater infrastructure is a long-term investment, and it is not easily replaced as the initial conditions change. Thus, as time goes on, the system will underperform or fail more frequently. This is exactly what is happening around Europe and the Baltic Sea, where the rapid change of climate, the progression of urbanization, and increasingly stringent regulatory requirements are putting the systems under stress. To cope with these quickly changing realities, rethinking stormwater management practices and increasing investments in stormwater infrastructure are necessary [14–16].

This issue has been addressed both globally and regionally. For example, during the IPCC COP27 conference, participating countries pledged to protect every human being with early warning systems over the next five years, as well as to allocate approximately 3.1 billion US dollars for the deployment of "transformative" technologies capable of combating climate change [17]. This funding also creates opportunities for urban stormwater management, as early warning systems can enable better data collection on stormwater quantity and quality. It can also aid in climate-proofing cities against extreme weather events [16,18,19]. On a regional level, HELCOM has been at the forefront of improving the Baltic Sea's status through the development of stormwater management recommendations and liaison with member countries. The organization has also emphasized the importance of accelerating the adoption of novel technological solutions for flood risk management, as well as pollution prevention and mitigation [20].

To drive change in stormwater management, researchers, engineers, and policymakers must be equipped with the right tools and be aware of the existing technologies and opportunities for managing both stormwater quality and quantity, particularly in a "smart" way. In this article, "smart" stormwater systems are defined as those that utilize the latest technologies and innovative design approaches to managing stormwater runoff in a more effective, efficient, and sustainable manner. This may entail the use of sensors, real-time monitoring, and predictive analysis to better understand and respond to changes in weather patterns, water flow, and water quality. These systems might be useful for reducing the amount of money spent on stormwater infrastructure, boosting climate resilience, increasing urban biodiversity, and generally making cities more aesthetically pleasing.

Some of these solutions are nature-based and provide some benefits on their own, such as reducing the environmental impact of stormwater systems, reducing the need for retrofitting the stormwater systems, providing ecosystem services, and protecting urban residents from flooding [21]. The inherent benefits of these systems can be enhanced further by combining them with "smart" solutions. Other solutions are primarily technological, but they, too, have the potential to reduce the volume of untreated stormwater and improve the quality of discharged stormwater. Examples of such solutions are online stormwater quality monitoring and sensor-based real-time control of separate sewer systems [22,23]. The latter is a topic that has grown in popularity as a result of the newly discovered value of water, the shift in perception of stormwater from a nuisance to a resource, the increased technological maturity of sensors, and the decreasing costs of information and communication technologies (ICT) [16].

Currently, urban stormwater management is shifting toward the development of a more resilient hybrid drainage system that combines grey infrastructure (e.g., pipes, tanks, etc.) and green infrastructure (e.g., nature-based solutions (NBS), low impact development (LID), and property-scale drainage and treatment facilities [22–24]. These hybrid infrastructures are monitored in real-time, and decisions are made based on the data collected. However, there are currently no universally applicable control, monitoring, or management strategies in place to ensure the proper operation of these hybrid urban drainage systems [25]. Most of the strategies that have been developed are based on modeling studies. However, to successfully adapt to the effects of climate change, reduce flooding and pollutant mobilization, and advance stormwater management systems, data collection efforts must be ramped up, and the transition from pilot-scale to full-scale technological solutions must be made [16].

Over the last 5 years, several review articles have been published on smart stormwater infrastructure. Eggimann et al. [26], for example, argued for using digitalization as a tool to improve the functionality of existing systems, while Li et al. [27] investigated the mechanisms and applications of green infrastructure for stormwater control and provided an overview of the performance of various green infrastructure solutions such as bioretention, green roofs, and permeable pavements around the world. The authors also noted the barriers to the implementation of green infrastructure, one of which is the availability of performance data, especially in the long term. Another key aspect noted was that there is a need for researchers to provide decision-makers with more effective and better green infrastructure implementation plans. Taguchi et al. [28] covered the performance of grey and green infrastructure and the conditions under which they perform best and alluded to possible unintended consequences in the social, ecological, or human health domains of utilizing these solutions. The authors emphasized that to avoid such issues, further investment in fundamental research and long-term performance monitoring and maintenance are required. Zhou et al. [29] composed a review on the benefits and disadvantages of state-of-the-art modeling approaches and decision-aid tools and argued the need for a more trans-disciplinary approach to green infrastructure design, as the complexity of the systems is often underestimated. The authors also took the view that the future of the approach is related to both high- and low-tech solutions, which are implemented in both a centralized and decentralized manner, as this is expected to provide the best balance between investment cost and performance efficiency. However, to achieve this, a design framework integrating various technical, social, environmental, economic, legal, and institutional aspects is still lacking. Erickson et al. [30] gave an overview of the maintenance of green infrastructure, noting that there is still a knowledge gap between performance and maintenance and that filling this gap requires more data. Webber et al. [31] evaluated the best stormwater management practices and created a framework to benchmark progress and highlight the next steps toward smart stormwater management. However, as this is still an up-and-coming approach, there are still various hurdles that must be overcome, such as the computational burden, silo approaches, technological maturity, existence of business cases, standardization of approaches, decision-makers, and the public's trust in the system. Some review papers focus on the outcomes and benefits of smart stormwater solutions [32–34]. In general, the authors concur that adopting smart stormwater management practices is crucial for the future. However, to achieve this goal, it is imperative to collect long-term data on the hydraulic and water quality performance of green infrastructure. This is necessary because the data serves as the foundation for incorporating effective stormwater management strategies.

The overarching goal of the present review article is to provide interested parties with a high-level overview of stormwater management's current state. The present review article distinguishes itself from the others by combining (some of) the previous authors' knowledge and synthesizing it into an output that can be used in real-world situations. To effectively facilitate the development and uptake of "smarter" and more resilient urban stormwater infrastructure, the authors have suggested a decision-support matrix for developing smarter stormwater infrastructures. This is relevant as currently the knowledge for developing hybrid stormwater infrastructure or enhancing the performance of green or grey infrastructure is scattered across various articles.

2. Materials and Methods

In this paper, the work of various authors is summarized and synthesized into tables, charts, and a decision-support matrix to help end-users, decision-makers, and other interested parties understand the current stormwater management issues, best practices, and the level of adoption of novel stormwater management solutions (e.g., monitoring and control of NBS).

This literature review addresses the following questions, with a special emphasis on the Baltic Sea region:

- How is stormwater managed in the region?
- What are the area's most pressing stormwater management issues?
- What is the level of adoption of novel stormwater management solutions in the area, such as green infrastructure or "smart" stormwater management solutions?
- How can smart stormwater management solutions be developed using a decision-support matrix?

To find relevant articles, the Scopus, Google Scholar, and ScienceDirect search engines were used. Smart stormwater management, water quality stormwater management, stormwater e-monitoring, stormwater quality control, and other keyword combinations were used to find the most relevant and recent studies and state-of-the-art in the field. This review article covers 178 scientific papers, including research and review articles and reports.

This review article provides interested parties with a high-level overview of the current state of stormwater management. The first section focuses on giving an overview of stormwater management in the Baltic Sea region, including major stormwater management issues, best practices, pollutant dynamics, and stormwater quality standards. The second half focuses on the efficacy of novel stormwater management solutions, such as nature-based solutions (NBS), as well as the feasibility of implementing cutting-edge e-monitoring solutions for stormwater management and the development of early warning systems for water quality to mitigate stormwater pollution. Finally, a decision-support matrix for determining the best "smart" solution for improving existing grey and green–blue infrastructure is presented. The paper concludes with a discussion section, which addresses knowledge gaps, future research needs, and the advantages and disadvantages of smart stormwater infrastructures (Figure 1).

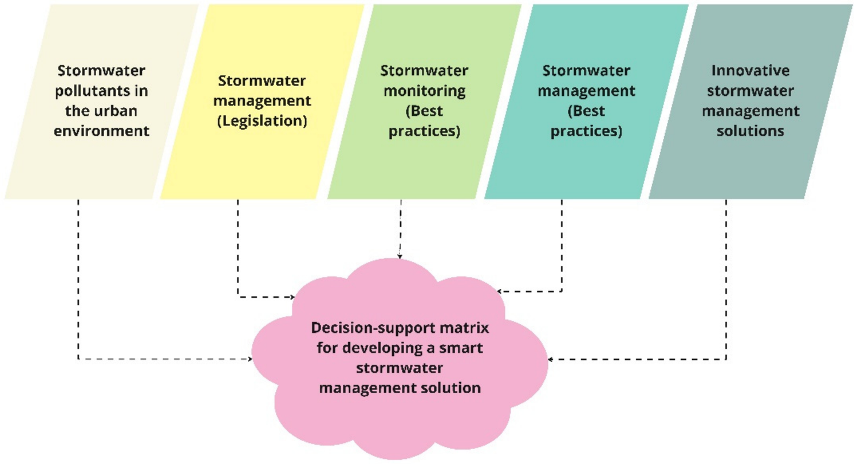

Figure 1. Structure of the review article.

3. Introduction to Stormwater Pollutants in the Urban Environment

3.1. Dynamics of Stormwater Quality

Pollutants in urban environments originate from a variety of sources and enter urban catchments via wet and dry deposition [35]. Based on the source, these pollutants are typically classified as either point-source or diffuse pollutants. The former can usually be traced back to a single source (for example, an industrial or wastewater treatment plant outfall), whereas the latter is usually unobservable on its own [36]. Non-point source pollutants accumulate on various surfaces, such as forests, roads, and buildings, during dry days and are washed away during rainfall events [37]. Strict regulations such as environmental quality standards have largely addressed point-source water pollution in the Western world, and the main remaining frontier of stormwater management is limiting non-point pollution. However, unlike point-source pollution control, there is no single responsible party to whom the high costs of stormwater management associated with diffuse pollutants can be directed [38]. Unconventional measures, such as green stormwater infrastructure, have been used to reduce the pollutant load associated with stormwater. This includes sustainable drainage systems (SUDs), water-sensitive urban design (WSUD), sponge cities, best management practices (BMPs), low-impact development (LID)), and enhanced green infrastructure (sophisticated stormwater control measures (SCMs)) [39–43].

The first step in implementing such green solutions is understanding the pollutant build-up and wash-off processes within the catchment. These are intricate processes influenced by hydrological, biogeochemical, and anthropogenic factors. Figure 2 depicts an example of the dynamics of pollutant transfer during a rainfall event in a catchment in Tallinn, Estonia. The sequence, in this case, was as follows: First, there was an increase in pollutant load, which lasted roughly until the peak of the storm, after which the pollutant load began to gradually decrease and then vanished completely. This is known as the “first flush”, and it occurs frequently in urban catchments [44]. Because the catchment contains easily mobilized contaminants, the “first flush”, or first pollution load wash-off, occurs frequently. The remaining pollution load, on the other hand, is caused by less mobile contaminants and is often referred to as the “middle flush” or “end flush” [45].

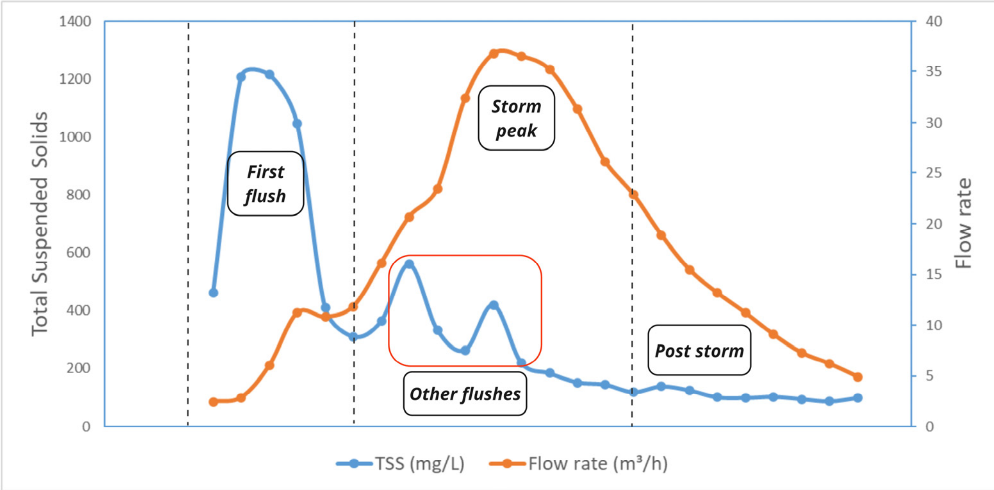

Figure 2. An example of the pollutant wash-off (TSS—Total Suspended Solids) based on a rainfall event in Tallinn. The other flushes of the rainfall event are represented by the red box.

Determining the fraction of pollutants mobilized is a highly complex matter that is dependent on several variables. These variables include pollutant re-suspension, aggregation, and re-deposition processes; temperature and photolytic conditions; the properties of the catchment (land cover; type of stormwater system); and the properties of the rainfall, such as intensity, duration, and depth [46].

As the environmental consequences of poor stormwater quality have become more widely recognized, there has been a global push for stormwater monitoring and management to shift toward more comprehensive stormwater monitoring that would include emerging pollutants (e.g., pesticides, microplastics, PAH, PFAS) in addition to the traditionally monitored parameters such as nutrients (phosphorus, nitrogen), heavy metals (Cu, Zn, Cd, Pb, Ni, Cr), pathogens, and oil products [5,47]. Microorganisms and substances (synthetic or naturally occurring) that are not routinely monitored but are expected to have negative environmental and human health effects are included in the category of emerging pollutants [47,48].

Even in a relatively small area of the European Union, such as the Baltic Sea, the countries have not standardized how stormwater quality is managed. This is largely because the existing water legislation, such as the Water Directive (2000/60/EC), the Floods Directive (2007/60/EC), the Groundwater Directive (2006/118/EC), the Urban Wastewater Directive (91/271/EEC), the Environmental Quality Standards Directive (2008/105/EC), and the Bathing Water Quality Directive (2006/7/EC), does not explicitly specify stormwater quality threshold values [49–53].

Several Baltic Sea states have self-imposed regulations at the national or local level through legislative (policy, permits, threshold values) or non-legislative (guidelines, standards) means (Table 1). Denmark, Lithuania, and Estonia are managing their stormwater quality through integrated environmental permits that establish either site-specific or national threshold limits [54–57]. Countries such as Finland, some regions of Sweden, Latvia, Poland, and Germany set stormwater quality requirements according to the environmental status of the receiving waterbody [58–65]. The latter approach is the typical approach, which is driven by the Water Framework Directive, but it requires extensive knowledge of local conditions and thus makes stormwater quality monitoring expensive and time-consuming.

Table 1. Water quality standards (WQS) in the Baltic Sea countries are in mg/L or % removal; for Sweden, superscript s refers to Stockholm and g to Gothenburg; elsewhere, c refers to combined sewers and s to separate sewers.

Quality Parameter	Estonia [1]	Sweden [2,3]	Germany [4]	Denmark [5]	Poland [6]	Lithuania [7]	Latvia [8]
BOD7	15				15 to 40	25 [s]/50 [c]	
BOD5							25 [s]
COD	125			30%	125 to 150		125 [s]/700 [c]
Total phosphorus	1	0.05 [s]/0.2 [g]		10%	5 to 7		1 [s]/9 [c]
Total nitrogen	45	1.25 [s]/2.5 [g]		10%	10 to 30		10 [s]/46 [c]
Total Suspended Solids	40	25 [g]/50 [s]	92%	60%	35 to 50 (100 [c])	30 [s]/50 [c]	35 [s]/450 [c]
Oil products	5	1 [s]/0.5 [g]	0.2 (80%)	80%	15 [c]	5 [s]/7 [c]	1 [s]/4 [c]
pH	6 to 9	6 to 9 [g]					
Monobasic phenol	0.1						0.1 [c]
Dibasic phenol	15						
Formaldehydes							0.5 [c]
Particle size (μm)			0.45 to 0.63				
Cl						1000 [c]	
SO_4						300 [c]	
PAH				90%			
Zn			0.5 (70%)	40%			0.30 [c]
Pb			0.025	65%			0.20 [c]
Cu			0.050 (80%)	60%			0.20 [c]
Cd			0.005				0.01 [c]
Cr							0.40 [c]
Ni							0.40 [c]
Hg							0.01 [c]
As							0.02 [c]

Note: [1] Estonian legislation [57]. [2] Swedish legislation (Stockholm) [60]. [3] Swedish legislation (Gothenburg) [61]. [4] German legislation [62]. [5] Danish legislation [54]. [6] Polish legislation [65]. [7] Lithuanian legislation [55]. [8] Latvian legislation [64].

To systematize stormwater quality monitoring, it is critical to have a shared understanding of the methods for monitoring and evaluating the results. However, there is currently no common baseline for assessing the efficiency and impact of various stormwater management approaches and technical solutions [16]. This is also a hurdle for setting specific targets for assessing the effectiveness of mitigation actions, especially when progressing from an end-of-pipe assessment of stormwater quality (catchment scale) to the assessment of plot-scale interventions, such as nature-based solutions, and their effect on the whole catchment. The development of a standardized real-time stormwater monitoring system could allow for a more accurate assessment of pollutant concentrations and loads discharged into receiving waterbodies, as well as the efficiency of various nature-based interventions, while also guiding the implementation of smart stormwater infrastructure. However, to implement a monitoring system, the parameters that are simple to measure and carry the most information must be well established. This requires decision-makers to have knowledge and understanding of each of the substances to be measured and the representative monitoring devices, as well as the benefits and drawbacks of the existing stormwater monitoring methods.

3.2. Introduction to Stormwater Pollutants and Monitoring

3.2.1. Stormwater Pollutants

Densely populated urban areas contribute significant amounts of inorganic and organic pollutants (such as heavy metals and oil), whereas residential areas and green spaces contribute nutrients (e.g., phosphorus and nitrogen) [66]. These contaminants are washed off the ground and carried to the outfall as particulate matter (PM) (adsorbed form) or as a component of the water matrix (dissolved form) by stormwater runoff [67]. These contaminants may be broadly divided into physical and chemical parameters.

The physical parameters of stormwater, such as electrical conductivity (EC), turbidity, and temperature, are typically measured because they are a simple, quick, and inexpensive way to obtain information about the quality of the stormwater [68]. EC, for example, is related to the number of ions dissolved in the water [69]. It is an important parameter in the Baltic Sea region because, during the winter, cities use road salt (NaCl) as a de-icing agent, which leads to an increase in sodium and chlorine ions in snowmelt waters and, as a result, higher electrical conductivity [68]. Road salt in the snowmelt may cause changes in the physical and ecological characteristics of the soil and waterbodies, such as changes in the density gradient, stratification, and algal growth, which may reduce the soil permeability, increase surface runoff and erosion, and reduce the oxygen content of the receiving waterbody. Turbidity indicates the relative clarity of the water, and it is frequently correlated with total suspended solids and primary pollutants such as heavy metals and nutrients, making it yet another important physical parameter to consider when monitoring stormwater quality [70].

The chemical parameters commonly used to describe stormwater quality include dissolved oxygen (DO), pH, biological oxygen demand (BOD), chemical oxygen demand (COD), and total organic carbon (TOC). Each of these parameters provides unique information. For instance, the pH of the stormwater indicates its acidity, which is directly related to heavy metal speciation. A lower pH indicates the presence of dissolved metals, whereas a higher pH indicates the presence of heavy metals bound to particles [71]. The level of dissolved oxygen is affected by the temperature and flow regime of the water, as well as its biological and chemical activity. BOD and COD analyses provide information on the sample's biological and chemically available carbon (oxygen demand) [69]. These parameters are important because low oxygen content, a potential sign of deteriorating water quality, is frequently brought on by excessive organic matter input and native organic matter that has been supplemented by nutrient pollution [72]. According to [73,74], phosphorus (such as phosphate) and nitrogen species (such as ammonium and nitrate) derived from decomposing biomaterials, burning fossil fuels, and fertilizers are major contributors to nutrient pollution in urban areas. These species are crucial in causing eutrophication and the production of algal toxins in the waterbodies, which have an impact on the water quality and the aquatic ecosystem.

Another group of parameters that are monitored in stormwater are heavy metals. These contaminants are frequently described in conjunction with total suspended solids (TSS) because they bind and mobilize alongside them during rainfall events [75]. Although heavy metals are naturally occurring elements, anthropogenic activities such as industrial combustion of fossil fuels, road and vehicle abrasion, and corrosion of metallic structures all contribute to their presence in the urban environment [73,74]. Heavy metals are needed in trace concentrations for physical and biochemical functions, but their excess can cause acute or chronic toxicity [76,77]. Heavy metals such as cadmium, zinc, copper, lead, nickel, mercury, chromium, and arsenic are prioritized because they have been shown to accumulate in tissue over time and cause harm. If the levels of these elements are not controlled, they may disrupt cellular organelle function, cause acute or chronic toxicity, act as endocrine disruptors, or be carcinogenic to aquatic life forms [76].

Monitoring of organic contaminants has been an important activity since the early 2000s, when the international community signed the Stockholm Convention on Persistent Organic Pollutants [78]. Organic substances (emerging contaminants) originating from anthropogenic activities, such as traffic and industrial activities [74], have been identified as priority substances to monitor due to their proclivity to accumulate in the tissue and induce endocrine disruptive and carcinogenic effects [79,80]. The most commonly monitored groups of organic substances in stormwater are polyaromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and persistent organic pollutants (POPs), but there are many other potentially hazardous substances, such as polyfluoroalkyl substances (PFAS), microplastics, etc. [5,79,80].

The preceding describes the pathways through which anthropogenic activities pollute stormwater and impact our environment, aquatic ecosystem, and human health (Figure 3). Therefore, pollutants must be monitored and controlled to avoid their inflow to waterbodies.

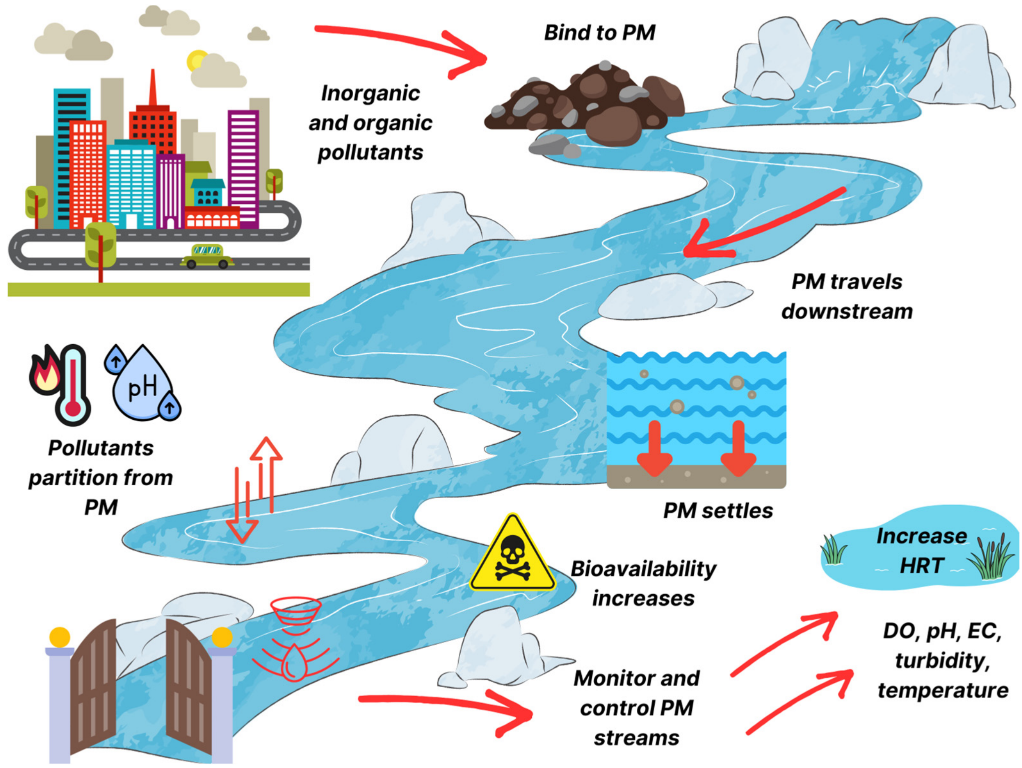

Figure 3. Stormwater pollutants, their monitoring, and their control.

3.2.2. Stormwater Quality Monitoring

Stormwater quality is frequently assessed using monitoring programs, which collect data for scientific, operational, legal, political, and environmental purposes [81]. These programs call for the collection of "high quality" data that is accurate, reliable, and timely to analyze sources and sinks of pollutants, event loads, flow trends, and the potential consequences in the waterbodies [82,83]. However, due to limitations such as inconsistent stormwater flow, the sampling period, monitoring goals, legal requirements, cost, and logistical considerations, the method commonly used to achieve these goals—a single sample taken as a grab sample or a sample taken with an automatic sampler—may be insufficient [84].

Grab sampling, traditional sampling, and discrete sampling are all terms used interchangeably to describe a sample taken at a specific point and time and considered to be representative of the entire pollutant flow. The benefits of grab sampling include its low cost and flexibility, as it requires no expensive equipment, electricity, or specialized technical knowledge, and the sample can be collected at any site deemed representative. It is particularly useful for measuring pollutants that degrade rapidly as they move away from the source of pollution. However, it is difficult to ensure consistent sample collection patterns because it is difficult to arrive at the sampling point prior to the occurrence of the first flush. As this approach is intended to collect information on stormwater quality at a single point in time, the method does not allow the easy detection of minimum and maximum pollutant concentrations or capture trends. A significant number of samples would need to be gathered and examined to accomplish this, which could be prohibitively expensive for many municipalities. However, multiple grab samples can also be combined to form a composite sample, which is useful for determining event mean concentrations (EMC) and is a sample representative of a whole storm event [85–90].

In many places around the world, local governments and industries must demonstrate that the water quality at their outlets meets the requirements by taking a grab sample after a set period, which could be monthly, quarterly, or yearly. However, as demonstrated in the preceding paragraph, collecting a representative grab sample is tricky. The collection of a representative sample has a limited window of opportunity, and fitting into this is associated with logistical and procedural challenges. If these are not met, the result is differences in the representativeness of samples. To address these concerns, sampling may be outsourced to an accredited environmental laboratory; however, even in this case, the timing of the sample collection is dependent on the route and schedule of the specialist assigned to this task.

Automatic samplers are frequently used to overcome this logistical challenge. The approach entails installing sampling devices that collect samples based on predefined criteria, such as flow rate or velocity, water level, time, and water quality parameters (measured by sensors). The behavior of pollutants build-up, rainfall, and other physical, chemical, or biological processes within the catchment is still highly stochastic, making it challenging to compare different samples, even though the automatic sampler enables more consistent sampling criteria. However, the sampling approach is also primarily helpful in situations with variable flow conditions because programming the device enables the sample to be collected only when a specified criterion is satisfied, allowing for comparison of the collected samples. The problem with such an approach, however, is that the sampling equipment and its maintenance are relatively expensive and inflexible. The equipment needs a source of electricity, a sheltered space, and timely maintenance to ensure that samples do not become contaminated. Moreover, it is not particularly useful for determining some specific parameters, such as pH, dissolved oxygen, particle size distribution, fecal indicator bacteria, oil, and grease. The collection of some other samples, such as organic pollutants and heavy metals, is also complicated as the samples require preservation [83,85,87–90].

Another, less well-known way of investigating stormwater is passive sampling. This is a set of extraction methods that allows for the long-term monitoring of various environmental pollutants with a single sample collection. The method is based on the mass transport phenomenon caused by the chemical potential difference between analytes in a given environmental compartment and the collection medium inside a dosimeter. The method allows for a reduction in the number of samples required while also cutting the costs associated with sample handling and preparation. It is especially useful when working with trace-level compounds and allows for the investigation of a wide range of analytes in both short and long timeframes. However, this approach does not provide information on concentration fluctuations, so its main selling point is contaminant load estimation [86,90,91].

In general, for "high quality" data acquisition using sustainable methods, it is critical to minimize the sources of error. It is possible to achieve this by developing an effective monitoring strategy, selecting appropriate sampling tools, periods, and procedures, and performing appropriate data quality control and data analysis [84,92]. In an ideal world, these procedures would be conducted automatically, but in reality, they are frequently conducted manually, necessitate a great deal of specific knowledge, take a long time to complete and verify, and do not provide quick information on stormwater quality [92].

Monitoring the quality of stormwater is complicated by the stochastic nature of the stormwater and the uncertainties associated with characterizing it. In stormwater measurements, five major sources of sampling variance exist, with two related to sample heterogeneity (analyte concentration and distributional heterogeneity) and three related to the sampling procedure itself (type of sample, sample size, and manner of sampling) [93]. The heterogeneity of stormwater samples is primarily caused by the characteristics of the locality (e.g., land use, topography, anthropogenic activities), as well as a variety of physical, chemical, and biological processes. The stochasticity of pollutant build-up and wash-off processes, as well as rainfall and watershed hydrology, makes predicting changes even more difficult [94]. As a result, adequate data is required to reduce the degree of uncertainty when estimating various hydrological processes, especially processes associated with stormwater quality and quantity [95].

Some of the uncertainty can be mitigated through systematic planning and implementation. This includes selecting appropriate measurement equipment, ensuring proper maintenance, selecting representative sampling sites, standardizing the sampling and measurement technique, establishing proper data quality control routines, and being aware of the limitations of various analytical and statistical methods for interpreting water quality and quantity data [95–97].

Even if all these potential sources of error are considered and mitigated, the aforementioned sampling approaches are all in-situ and require manual pick-up and delivery of the samples to the laboratory. Additionally, once in the laboratory, the analysis of the samples may take days, which creates a significant gap between the reception of the information about the quality of water and the implementation of the intervention (if it is still needed). Thus, the majority of today's stormwater quality monitoring techniques are retroactive, making them unsuitable for implementing real-time interventions.

It is clear that new methods for collecting information on stormwater quality are required, as the existing ones do not allow problems to be tackled head-on. A multi-tier stormwater monitoring strategy based on e-monitoring might be one of the solutions for overcoming this problem (Figure 4).

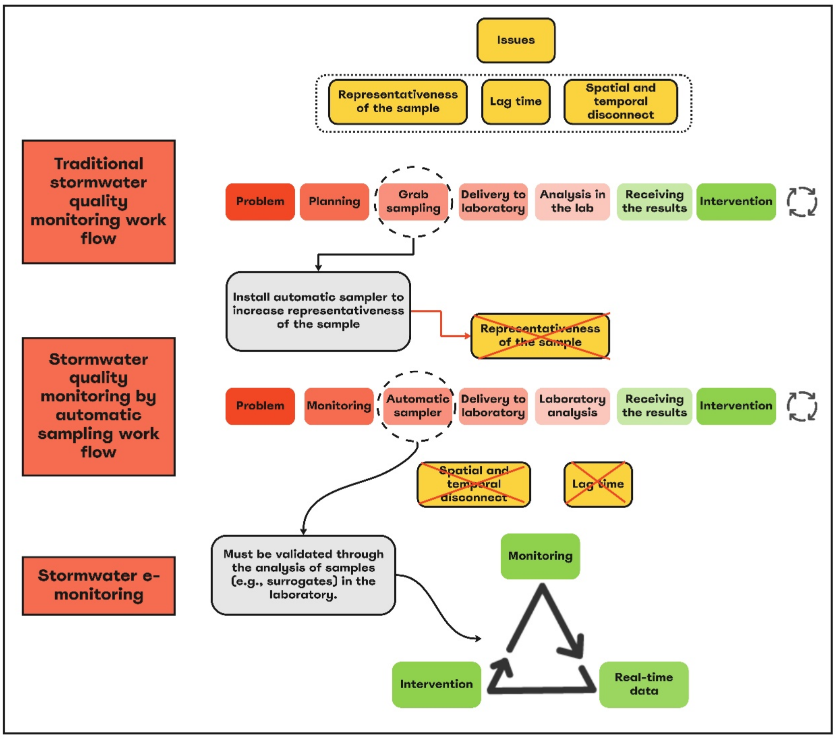

Figure 4. Stormwater sampling strategies are represented schematically, from traditional stormwater sampling (**top**) to e-monitoring (**bottom**).

E-monitoring (known also as continuous monitoring, real-time monitoring, or on-line monitoring) has been tested and implemented with increasing frequency in the last decade. It is an in-situ monitoring approach in which a system comprised of telemetry, sensors/sondes, data storage, analysis, and representation is installed and used to collect high-frequency data on water quality [98]. The approach is already being applied in wastewater treatment plants and water treatment plants, and more recent advances in information and communication technologies (ICT) and off-grid power technologies have made it an appealing alternative to "traditional" stormwater monitoring, which relies heavily on representativeness of the grab samples. Establishing an e-monitoring system to collect data in real-time using sensors has enormous potential to open up new ways to manage stormwater by providing high-resolution (in space and time) information on stormwater quality and allowing for the development of new interventions to improve stormwater quality [98–101]. As the former roadblocks, such as cost, data storage, battery capacity, data transmission, and sensor accuracy, are removed over time, the solution is expected to become more and more viable [102–104].

To unlink e-monitoring from laboratory measurements, surrogate parameters are regularly used. Surrogate parameters are water quality parameters that are linked to laboratory-based measurements via a variety of analytical and statistical methods [105–107]. As the approach is also dependent (at least initially) on laboratory-based sample analysis, the uncertainties of traditional stormwater monitoring and e-monitoring overlap significantly. However, the main advantage of e-monitoring is that it fills the gap that traditional grab sampling is incapable of filling (or finds expensive to fill): providing minimum and maximum values. After calibration, the e-monitoring systems are no longer constrained by the uncertainties of traditional stormwater monitoring but rather by the uncertainties arising from the data collected by the sensors and the representativeness of the monitoring location [108]. Thus, e-monitoring promises to help overcome various challenges of stormwater quality assessment while also promising to contribute to improved data quality control, model application, and calibration by assisting various data-related constraints of water quality models (Figure 5) [109–111].

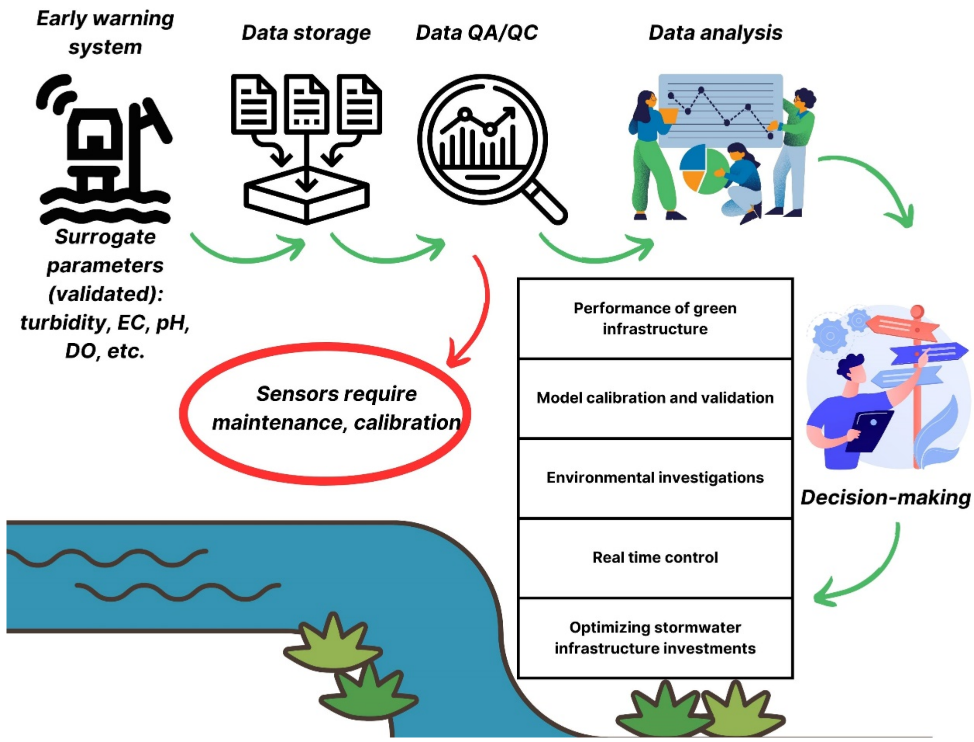

Figure 5. Potential benefit of e-monitoring (early warning systems).

To implement e-monitoring devices for stormwater quality and management, it is preferable to monitor as few parameters as possible, and the devices chosen should have the following characteristics: (i) low associated maintenance costs; (ii) capable of withstanding extreme weather conditions [111,112]. This limits the application of sensors because many of them are unsuitable for long-term in situ studies due to their inability to operate independently for extended periods without sample preparation or re-calibration [113]. Furthermore, stormwater systems are harsh environments, so maintenance costs may be prohibitively expensive in comparison to other benefits [16]. The main feature of e-monitoring systems is not their accuracy as such, but rather their ability to gather descriptive data about the in situ fluctuations of pollutants and to produce early warning signals.

Electrical conductivity (EC), turbidity, pH, temperature, and dissolved oxygen are some of the robust surrogate parameters that can be used in e-monitoring and implemented for early warnings. For example, EC is a surrogate for total dissolved solids, and this relationship was useful for investigating road salt application on roads [110,114]. The relationship of EC with heavy metals has been used to inspect the affinity of the metals to be found in the dissolved phase (together with temperature and pH) [115]. The relationship between turbidity and total suspended solids has been of particular interest to many authors, as the parameter may represent the mobilization of sediments and particle-bound heavy metals and other trace elements. Such relationships, however, are event- and location-specific [114–119]. Often the relationship between turbidity and nutrients, more specifically phosphorus, is investigated, but less frequently also the relationship with pathogens [120–123]. Aside from using parameters as surrogates for other contaminants, it is also possible to use e-monitoring of parameters such as pH, temperature, and dissolved oxygen to collect background information. Long-term temperature data, for example, may shed more light on the solubility of heavy metals as well as the progression of photosynthesis in aquatic plants and its relationship to general toxicity and oxygen levels. Temperature can also be used to detect new pollution from illegal household sewage or industries [117,124]. Similar to temperature, pH also affects the solubility of metals, and sudden rises or falls in pH could be signs of pollution [110,114,115]. Many other surrogate relationships have been investigated and regression equations derived [40,109,110,117–122]. However, these relationships are frequently location- or case-specific, and to use them, they must be validated locally. The implementation of e-monitoring is a prerequisite for water quality-based control of stormwater systems. A brief overview of possible surrogates for stormwater quality investigation is given in Table 2.

Table 2. List of commonly used e-monitoring surrogate parameters.

Surrogate Parameter	Relationship
Electrical conductivity (correlation)	Total dissolved solids (TDS), heavy metals (dissolved), nutrients (total nitrogen).
Turbidity (correlation)	Total suspended solids (TSS), heavy metals (particle-bound), nutrients (total phosphorus), pathogens.
Temperature	Affects the solubility of heavy metals and the photosynthesis of aquatic plants (general toxicity, oxygen levels). This may indicate fresh pollution (e.g., illegal household sewage inflows and industrial discharges).
pH	May be used to detect pollution. A sharp increase/decrease in pH may indicate an effect of pollution. The pH is related to the solubility of metals.
Dissolved oxygen	A rapid decrease in dissolved oxygen may indicate pollution (e.g., an oil spill). Low DO indicates that something is consuming the oxygen—either chemical processes or biological processes (e.g., decomposition of organic matter, respiration).
UV–Vis spectroscopy (absorbance and fluorescence-based surrogate)	Nitrate, DOC, turbidity, TSS

4. Technological Solutions for Stormwater Management

4.1. Introduction to Stormwater Management Solutions

Urban stormwater infrastructure has not changed much since its inception in nineteenth-century Europe. In many places, the primary method of dealing with stormwater is to quickly transfer it to nearby waterbodies, and the majority of stormwater management occurs in a silo, separated from other technical services in a centralized and technocratic manner [125,126]. Due to land constraints in cities, grey infrastructure, such as an underground pipeline network, was developed as a compact solution for protecting the property and health of urban residents [41]. However, as time passed, many issues concerning the solution's design began to surface. By the 1970s, it was clear that the current stormwater management approach is too short-sighted and harmful to city finances and the environment, owing primarily to increasing urbanization and urban sprawl. The systems were clearly incapable of handling the increased stormwater volumes caused by the increase in impervious surfaces, and refurbishing such systems solely through technical means would incur an ever-increasing cost for digging deeper and placing larger diameter pipes, as well as maintaining them. Furthermore, such systems have been found to reduce aquifer recharge, alter the natural water cycle, and increase the transfer of pollutants to nearby waterbodies [125,127].

In response to these issues, various stormwater management practices and technologies known as "green infrastructure" have been developed [41]. The technology works by detaining, retaining, and/or treating stormwater and is effective in limiting the introduction of pollutants into the waterbody and reducing peak flows. A hybrid strategy that connects green and grey infrastructure and aims to retain as much water as possible in the urban environment has recently been put forward as the “Sponge City” concept. The system mainly functions by promoting infiltration and slowing discharge. Such an approach provides an opportunity to avoid overburdening the sewer systems and retaining the most polluted portion of runoff water, while also limiting the costs associated with the construction of new and larger diameter pipes [126].

Detention basins, infiltration basins, swales, trenches, permeable pavements, detention roofs, and other technical solutions have been used to achieve the goal of “slowing the flow”. However, there are currently insufficient effective evaluation methods and pilots in operation to assess the co-performance of green and green–grey infrastructure. Therefore, it can be difficult to gather enough pertinent data to convince stakeholders of the significance of such systems [125–127]. To close this gap, it is crucial to develop technologies and management strategies that can monitor stormwater quality to lessen the impact of stormwater systems on the environment.

4.2. Enhancing Green and Grey Stormwater Infrastructure with Smart Solutions

Traditional stormwater management is centralized and not adaptable enough to deal with the changing and challenging realities brought about by climate change and urbanization. This has initiated a shift toward more widespread use of green-grey infrastructure (hybrid stormwater infrastructure). Such systems are designed to incorporate the best of what green and grey have to offer, providing decentralization, climate and hydrological resilience, and sustainability through flexibility and adaptability [127]. These systems are valued for their ability to retain, delay, and filter stormwater while also assisting in overcoming space and cost constraints, providing aesthetically pleasing landscapes, and improving treatment efficiency [128,129].

However, the majority of today’s hybrid stormwater systems are neither “smart” nor “dynamic”, as there is no way to gain a continuous overview of the processes occurring within the system, nor is it possible to control the performance of these systems. As a result, the next logical step in the evolution of urban stormwater systems is to follow the trend of digitalization that is already underway in many other industries. The addition or retrofitting of sensors and control devices to hybrid stormwater systems allows real-time control and optimization of the system’s operation (Figure 6) [130,131].

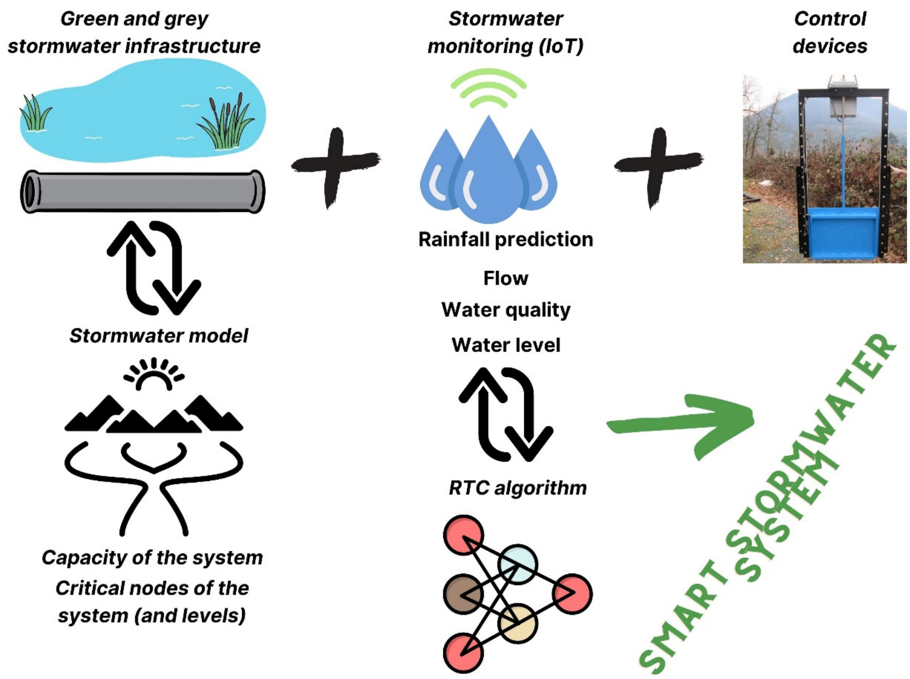

Figure 6. From static infrastructure to dynamic, smart stormwater infrastructure.

It should be noted that what we will refer to as enhanced stormwater infrastructure is also known as hybrid infrastructure. As a result, it provides the opportunity for cost-effective infrastructure investment and valuable space conservation, all while reducing flooding and maximizing the removal of pollutants from the watershed [130,131].

The effect of deploying various smart solutions for enhancing hybrid stormwater infrastructure has been simulated over the years. However, only recently have practical applications been developed and tested [130]. The following paragraphs will give some examples of making various green infrastructures smarter.

4.2.1. Bioretention Cell

The United States Environmental Protection Agency (US EPA) defines bioretention cells, also known as bioretention basins, bioretention ponds, or rain gardens, as small, shallow, sunken areas of planting that collect stormwater runoff from roofs, streets, and sidewalks [131]. To reduce peak runoff and flooding, as well as non-point source pollution, the solution employs physical (sedimentation, filtration, and adsorption), chemical, and biological treatment mechanisms (photosynthesis, respiration, and denitrification) and replenishes groundwater resources through infiltration [132,133]. Bioretention cells are a viable solution in a variety of situations, as their size and structure can be tailored to the specific needs of the target location [134]. Despite significant differences in implementation, bioretention systems have certain common features such as vegetation [135–138], engineered filter media [135,139,140], depression with temporary ponding volume [135], and hydraulic controls [135,139].

In general, such systems have been shown to have a high pollutant reduction efficiency. Studies have shown (e.g., [133]) that a rain garden reduces TSS concentrations by 85% on average, COD by 91%, both TN and TP by 74%, and copper and cadmium by up to 98%. In addition, runoff can be reduced by up to 96%, but this is highly dependent on local climatic conditions, system design, and maintenance frequency. The groundwater level, hydraulic conductivity of the surrounding area, and the filling and clogging rates (dependent on the number of particles entering the system) are all key factors to consider, as they can introduce significant variability in the solution's performance [133]. In general, such systems are thought to perform well during light and moderate rain events (5–10 mm), but their performance suffers significantly during heavier rain events [133].

Both prolonged ponding and drought hurt the plants and microorganisms responsible for the system's chemical and biological treatment aspects, reducing the system's ability to remove pollutants. To improve the performance, hydraulic control devices have been implemented to control the flow [33,34,141,142]. These devices are needed to regulate the system's inflow and outflow rates, as well as to prevent overflow or bypass in the event of an extreme event. Without such control structures, water volumes exceeding the bioretention system's maximum capacity could damage the system and carry pollutants downstream through erosion. Flow control is also beneficial in preventing long-term ponding or drought in the system, which can be fatal to vegetation [139]. The key benefits of dynamic controls include maximizing system performance during small and medium rainfall events, preparing systems for larger rainfall events and thus limiting the adverse effects of overflows, and further improving pollutant removal by increasing the system's hydraulic retention time. It also increases the ability to promote both aerobic and anaerobic conditions and thus perform both nitrification and denitrification [142].

4.2.2. Wetlands

Wetland systems that include a pond or submerged area [143] are beneficial for large catchments (more than 10 ha) and have the potential to provide a variety of benefits, such as the creation of new habitats in urban areas, increased biodiversity, wildlife refuge, reduced flood frequency, and improved water quality [144]. Wetlands naturally occur near flood-prone water sources and where watersheds meet large bodies of water [145]. Wetlands, such as sedimentation ponds or bioretention cells, perform sedimentation, but they can also control water flow and quality due to the presence of plants, algae, and microorganisms that convert nutrients into biomass. Heavy metals can be absorbed and accumulated by certain plants, and certain organic materials can be broken down by other organisms [146]. Water pH, temperature, and hydrological conditions all influence how well wetlands perform because they affect how quickly plants, algae, and microorganisms grow and litter decompose. The majority of pollutants can be removed by wetlands, but litter, nitrogen, biological oxygen demand (BOD), and oil are particularly difficult [147–149].

The water quality treatment efficiency of wetlands varies in different studies, resulting in a semi-rural wetland TSS removal efficiency of approximately 93%, TP removal efficiency of 77%, TN removal efficiency of 52%, and heavy metal removal efficiency ranging between 56–88% (different heavy metals) [143]. Another study in five wetlands discovered that the TSS removal efficiency was between 25–83%, the TP removal efficiency was 6–66%, the TN removal efficiency was 5–47%, and the heavy metal removal efficiency was 2–70% (different heavy metals) [144]. The large disparity in results was due to poor design and uneven pollutant loads but also because lower concentrations of pollutants are more difficult to remove than higher concentrations, thus lower efficiencies may be observed [143,144]. Maintenance is critical to ensuring that the wetlands function as intended; however, planning for the removal of sediments and litter, as well as cutting reeds and weeds, is difficult. Altering the environmental and operational conditions, such as adding thermal insulation, controlling the flow regime, providing additional carbon, recirculating the water, adding biomass, and others, may further improve the performance of constructed wetlands [150]. However, such an approach will drive up the life-cycle costs of wetlands.

4.2.3. Stormwater Ponds

Stormwater ponds, also known as "basins", collect rainwater that has "runoff" the nearby landscape of rooftops, roads, and lawns. Stormwater is temporarily held in the basin before being slowly released into a nearby water body. Stormwater detention basins reduce the rate at which runoff enters our natural waterways while simultaneously buffering temperature. Thus, the stormwater ponds prevent downstream erosion and flooding. The majority of detention basins also capture runoff pollutants such as nutrients, metals, and sediments; however, the efficiency of this capture is dependent on the hydraulic retention time [151,152]. The main vectors through which stormwater ponds treat water are sedimentation, flotation, infiltration, adsorption, and various biological processes. A typical detention basin has at least one primary outlet, such as an orifice, weir, or riser, to pass the regulated flow from the basin and one emergency overflow for heavy rainfall events [142,151]. Typically, the detention basins are built to control floods, thus providing few water quality benefits; however, some design strategies (such as the implementation of wet and dry sections) do allow improved pollutant removal [142]. Dynamic flow control can reduce the peak flow [152–154] and increase the TSS removal efficiency from 46% to between 70% and 90%, depending on volumetric capacity [155,156]. A control device can avoid short-circuiting-related low pollutant removal efficiencies by increasing TSS removal by 51% (39% to 90%), ammonia nitrogen removal by 74% (10% to 84%), and zinc removal by 24% (20% to 42%) [157]. A water quality-based control (TSS control), for example, may reduce the likelihood of system failure by 18.7–38.7% while also reducing suspended solids by 11.4–18.9%. Instead of TSS measurements, it has been suggested that if the associated costs or measurement uncertainties are prohibitively expensive, one can simply control the hydraulic retention time, which yields comparable water quality improvement results [158]. Most catchments are large and thus comprise multiple types of green infrastructure; however, most research focuses only on the performance of a single or, at best, a train of NBS. To attain certainty about the performance of the NBS, more studies focusing on scaling must be conducted; however, as this is based on modeling, it requires large amounts of input data that are currently not available for many sites [159]. If left uncontrolled, stormwater ponds are problematic, especially in catchments where multiple stormwater management solutions exist. The simultaneous release of water may erode streambanks and cause downstream floods.

4.2.4. Green Roof and Rainwater Harvesting

A green roof is typically made up of a waterproof membrane, a drainage layer, and a light soil mixture containing plants that absorb and temporarily store rainwater. The water stored during rainfall events is returned to the atmosphere via evapotranspiration. Green roofs are advantageous because they provide aesthetic appeal as well as thermal insulation for buildings, while also sequestering carbon and reducing the urban heat island effect and peak runoff [34,142,160]. However, green roofs do not come without their challenges—for example, they are ineffective at retaining solutes and particulate matter, and their efficiency is highly dependent on the amount and distribution of rainfall, the thickness of the soil substrate, water storage capacity, slope, vegetation, the previous dry period, and local climate. Additionally, their capacity to retain heavy metals varies, and during heavy rainfall events, they may become net contributors to them [160]. Despite performance-related issues, green roofs combined with a rainwater harvestings system, such as a storage unit, pond, water tank, or rain barrel, can be a useful tool for reducing peak flows and addressing water resource scarcity, which is a prominent issue in various parts of the world [34,160]. The utility of rainwater harvesting systems is highest as long as consumption and supply go hand in hand. However, if there is more rainfall than the consumers are capable of consuming, overflows may occur, which lead to downstream floods. To grapple with this issue, sufficient freeboard must be maintained at all times. This may be achieved through dynamic control of harvesting systems based on real-time data on operational conditions such as soil moisture, water level, and precipitation [142,161–165]. Harvesting-based technologies can be further utilized for improving the water quality, namely for reducing the urban stream syndrome. However, such an approach would require investments in long-term hydrologic and water quality monitoring of the interventions [166]. The combination of rain barrels in conjunction with porous pavement may decrease the runoff and TP and TN concentrations by 2–12% [167].

4.2.5. Permeable Pavement

According to the United States Geological Survey (USGS), permeable pavement is a porous urban surface that collects rainwater and surface runoff, stores it in a reservoir, and then gradually releases it into the ground or drains it through a drain tile [168]. The solution is mostly applied to parking lots, low-traffic roads, sidewalks, and driveways. It is considered beneficial as it helps restore a more natural hydrologic balance and lowers peak flow and runoff volume. The solution may lessen the concentration of pollutants using the physical, chemical, or biological treatment and lower the temperature of urban runoff, which will lessen the strain and negative effects on the receiving waterbodies. Another important benefit of permeable pavements is their capacity to reduce the need to apply road salt during the winter months [168]. Permeable pavements, other nature-based solutions, have the limitation of performing well during light and moderate rainfall events but overflowing during heavy rainfall events. They can also become clogged by debris and sediments and have an adverse effect on the infiltration performance and the quality of the infiltrated water. This means that there is still concern about the long-term performance of such solutions, especially in areas where the winter months are harsh and require sanding and/or salting of roadways [169]. Investigations on the performance of permeable pavements in cold climate environments have revealed that the permeable pavement's peak outflow rates may be 91% lower than could be expected from asphalt runoff on average, and attenuation occurred during all seasons. Rainfall events with precipitation of less than 7 mm were captured, even in the case of low-permeability soils [169,170]. Experiences with increasing the hydraulic retention time (from 32 h to 15 days) for water quality benefits and peak flow reduction were revealed to be possible and feasible for permeable pavement systems, as 50% of peak flows were reduced throughout the study period [170].

Investigation of the clogging dynamics indicated that the progression of clogging and scheduling maintenance for the owners depend on the impact of varying rainfall characteristics, the ratio of the contributing drainage area, land use of the drainage area, and pavement section evaporation [171]. Piezometers and pressure transducers integrated into permeable pavement provide enough information to set up a real-time, remote monitoring system, allowing maintenance to be scheduled. The solution is most suitable for soils with large hydraulic conductivity [172]. Alternatively, temperature sensors (e.g., thermistors, thermocouples, etc.) can be utilized for determining the presence or absence as well as the location of the moisture change. These sensors were assumed to change more slowly at clogged locations (compared to locations without clogging) [173]. Infiltration trenches and vegetative swales are sometimes combined with permeable pavements for pre-treatment. However, this solution is only feasible in areas where the subsoils are highly permeable and the groundwater table and bedrock are located below the bottom of the system. As both solutions are prone to clogging, pre-treatment with a sedimentation pond could increase the systems' longevity [34,172].

4.2.6. Alternative Technologies

For several decades, systems and concepts for collecting data on water quality have been under development, with significant progress being made. An environmental instrumentation and software company, In-situ, for example, has conducted a case study to determine cost-effective monitoring strategies that revealed that continuous monitoring makes it possible to identify potential sources of pollutants and solve the problem rather than simply providing data, as is the case with individual samples [174]. Another case study conducted in Australia as part of the Mind4stormwater project aimed to develop and evaluate the application of various low-cost sensors for stormwater control measures, optimizing performance relative to operating conditions, and performing system maintenance [175,176]. Many of these devices are currently under development, and they serve as the foundation for monitoring stormwater quantity and quality, which is also an important component of smart city development. Recently, the EU Interreg Central Baltic region funded the CleanStormWater project, which identified and implemented technologies that could provide a cost-effective way of monitoring stormwater quality in urban settings. Four Baltic Sea countries Estonia, Finland, Latvia, and Sweden joined together in this effort and built pilots to test the solutions. All of these countries have made substantial investments in infrastructure, digitization, and the development of e-monitoring systems for both water quality and quantity [177].

The above examples represent only a subset of the existing solutions and theoretical concepts that have been developed around the world. In cities around the Baltic Sea, the use of such state-of-the-art approaches for monitoring or managing the performance of nature-based solutions is still limited. However, as demonstrated by the examples above, insufficient integration of grey and green infrastructure results in a significant loss of performance. To begin with, this is because the system's topography dominates the performance of the grey infrastructure, and ponding occurs in the system's lowest points during heavy rainfall, so it is possible to optimize and redesign the system to channel the water flows and thus economize on the required investments in rebuilding a new stormwater system [164,165]. Second, the performance of various green solutions (vegetative swales, infiltration trenches, stormwater ponds, and so on) varies greatly due to the rainfall characteristics (intensity and duration) and the drainage capacity of the underlying soils (driven by soil moisture content and groundwater level). Smart solutions such as weather forecasting, data collected through sensors, and a control device can be used to interactively regulate the quality and quantity of stormwater. Third, different algorithms have been developed to improve the performance of hybrid (green-grey) infrastructures in terms of water quality, flood protection performance, or both, but all of them have their advantages and disadvantages. However, currently, there is a lack of a high-level strategic vision or guidance that would lead the decision-making process toward one of the available approaches or guide the development of alternative approaches. The benefits of various nature-based solutions were presented in a GrowGreen project deliverable [178]. The overview was improved to better visually represent the strengths of the various solutions and to encourage their improvement and testing for feasibility (Figure 7).

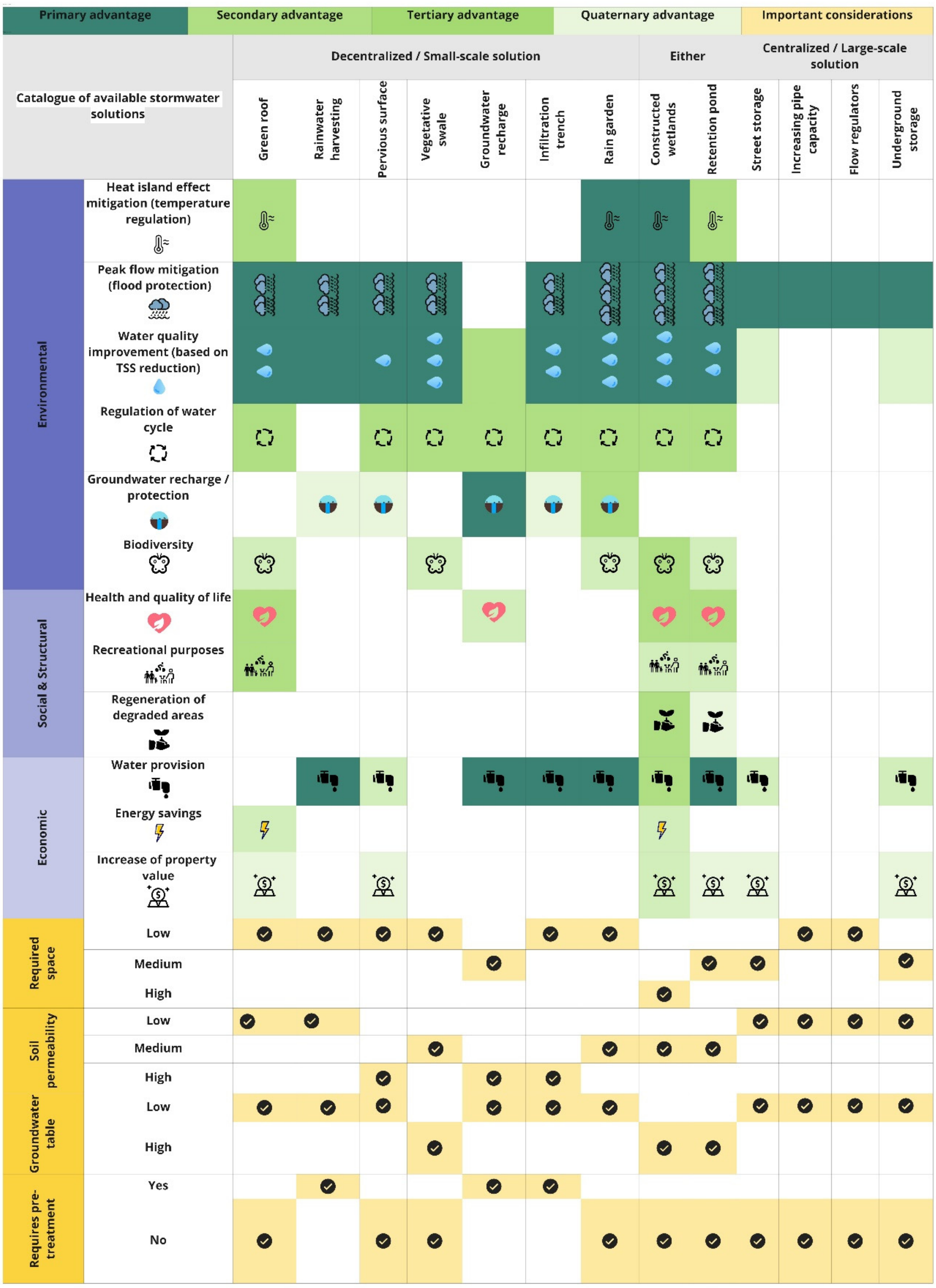

Figure 7. Stormwater solutions and benefits.

5. Outlook for Stormwater Management

This review has summarized the current state of stormwater management in the countries of the Baltic region, as well as the challenges in stormwater quality monitoring strategies. Urbanization and land use have a significant impact on stormwater quality by flushing pollutants from roads, construction areas, parking lots, lawns, and so on. Climate change, on the other hand, may result in long dry or wet periods, and increased rainfall intensity can have a direct impact on the quantity of stormwater. Concerning its quality, several stakeholders must work together to develop appropriate technological solutions and monitoring systems to protect waterbodies.

This review article distinguishes itself from others by being the first of its kind (to our knowledge) to gather the advantages of green infrastructure and the technological prerequisites for enhancing and integrating them into a real-world output: a decision-support matrix for developing stormwater solutions. The most relevant previous review articles [26] have either covered the fundamental processes by which a green infrastructure improves flood protection and provides benefits for water quality [27], developed frameworks for implementing green infrastructures [28,29], or highlighted the advantages of enhanced infrastructures [33–35]. However, none of these reviews have addressed the issue holistically, from legislation to implementation, nor have they included the requirement to monitor the system's efficiency through e-monitoring. This article argues that e-monitoring of green solutions is necessary to facilitate research on using the data gathered to streamline the maintenance of green infrastructures, which system managers frequently overlook due to a lack of experience or knowledge. Furthermore, e-monitoring can provide decision-makers and the scientific community with accurate information on the performance of the solutions.

Additionally, "smart" stormwater solutions have been developed to improve e-monitoring solutions for stormwater quality management and to evaluate the efficiency of the treatment. Figure 8 depicts the smart solutions developed and referred to by various researchers. Sensors and measurement devices, flow control devices, weather stations, and telemetry and data management systems are some of the hardware categories that are commonly found on the market and used to enhance stormwater solutions. This diagram provides an overview of these hardware and software categories. However, it also emphasizes the importance of developing algorithms that improve the usefulness or effectiveness of the system, whether the system is concerned with data processing, developing an objective function, or controls.

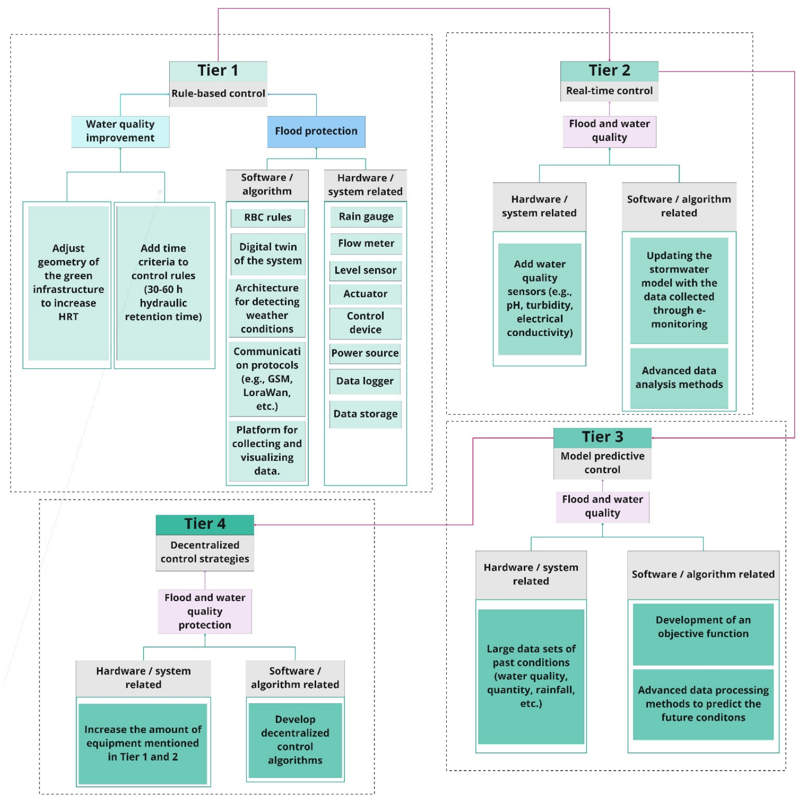

Figure 8. Common steps for enhancing stormwater systems.

A four-tier system was developed to create an enhanced stormwater system (Figure 8). The first tier, known as "Rule-based control", is the easiest to achieve because it only requires the setting up, calibration, and validation of a digital twin of the current stormwater system (using, for example, Storm Water Management Model (SWMM)-based technology), identifying a few pertinent control parameters, and modeling the ideal limits for these parameters using scenarios, while taking into account the effects of urban development and climate change. To further customize these scenarios, time criteria based on the particle size distribution and the relevant hydraulic retention time can be added. To enhance the system even further, water quality (Tier 2) sensors can be added, and threshold values can be set as a control parameter. The actions taken thus far should lay the groundwork for the collection of a substantial amount of real-time data, which should include measurements of water quality as well as data on water level, flow, and precipitation. As the data and the system's digital twin become linked, scenarios for real-time control can be developed to improve the system's performance (by adjusting the threshold values). These scenarios must be validated through vulnerability and robustness checks, which could be based on different climate scenarios. Tier 3 adds a forecasting capability to the real-time control, requiring the development of an optimization algorithm based on an objective function and stormwater management scenarios. These scenarios must be subjected to additional control by making vulnerability and robustness checks, in which the impact of various unfavorable conditions is assessed. While the first three tiers deal with a single solution, Tier 4 deals with controlling a network of enhanced stormwater solutions. A good practice for developing a network of enhanced stormwater solutions is to divide the larger system into smaller systems based on some pre-defined characteristics (e.g., topography) and identify the most critical locations in the system (those most prone to flooding or those that provide the most benefits). Following these steps, a decentralized control algorithm should be designed to maximize the system's capacity and performance in terms of improving water quality.

The preceding figures (Figures 7 and 8) serve as inputs for the following matrix (Figure 9). This decision-support matrix was designed to aid municipalities, stakeholders, engineers, city planners, and other interested parties in the development of a "smart" stormwater system.

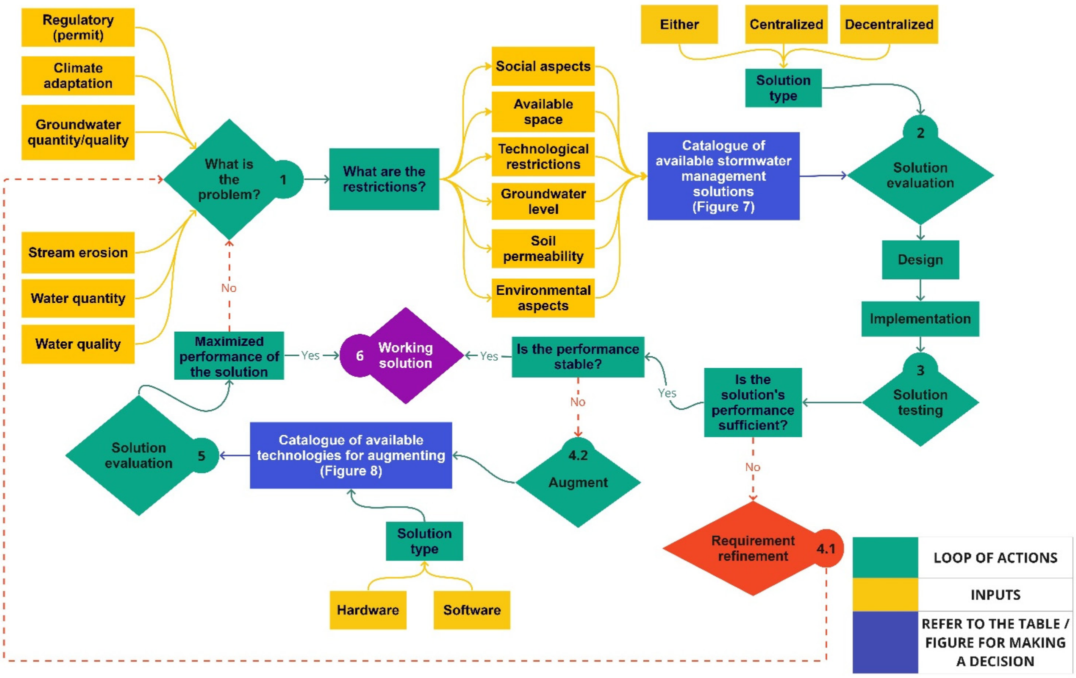

Figure 9. Decision-support matrix for developing a smart stormwater system.

The decision-support matrix (Figure 9) outlines six steps required to implement an appropriate stormwater management solution. In the first step (1), a “problem” needs to be defined, which could be related to flood protection, improving the water quality of the receiving waterbody, adhering to environmental permit requirements, increasing the quantity or quality of groundwater, or limiting erosion of the banks of the streams. Local factors such as soil characteristics or the groundwater level may then determine whether rainwater can be infiltrated. When land is limited, solutions with a smaller footprint may be preferred. This frequently results in the use of decentralized solutions rather than centralized ones. All of these restrictions, as well as the benefits of various stormwater management solutions, are covered in the “catalog of available stormwater solutions” (Figure 7). It is the user’s responsibility to define the most important criteria for their site and select the best technology to use.

For example, if pluvial flooding occurs frequently in the catchment and there are some water quality issues, infiltrating stormwater could be a viable solution. This assumes that the catchment area, for example, is in a suburban area with plenty of space or that the land belongs to the municipality and neither space nor cost is an issue. Furthermore, the soil at the site should be sandy with a low groundwater table. This means that if the user browses the list of solutions, a few options—both centralized and decentralized—will stand out. The “constructed wetland” option, on the other hand, would outperform the others because it aims to reduce flooding, improve water quality (by 90%), increase thermal comfort (by reducing the urban heat island effect), align the urban water cycle with the natural one, and add new recreational space to cities. Because the water in this wetland will be relatively clean after passing through it, it could be used for irrigation or artificial groundwater recharge in a dry climate.

Following the completion of the cost-benefit analysis of the systems, the user must deal with more practical issues (2), such as designing, constructing, and optimizing the solution for their site, as well as evaluating (3) the as-built performance. If the solution works as intended (e.g., treatment and flood reduction), it is time to assess the system’s stability under various weather and other working conditions. A workable solution has been discovered if the system provides a sufficient level of redundancy (6). If there are any issues with stability or performance, the entire system should be re-evaluated (4.1), and either a new green infrastructure should be installed or the functionality of the existing infrastructure should be improved (4.2).

When adding to the stormwater infrastructure, the user should consult the “catalog of available solutions for enhancing the stormwater infrastructure” (Figure 8). The user can select from several levels of complexity here. A simple rule-based control (Tier 1), which typically calls for the regulation of valves via actuators in accordance with a control parameter, such as the water level, or a more complex option, such as real-time control (Tier 2) or model predictive control (Tier 3), which aims to forecast future conditions or even decentralized controls that take into account both the capacity of a single unit and the system as a whole, are available (Tier 4). After determining the type of solution, the necessary research must be conducted to determine the optimal thresholds for the control nodes. Trial and error, engineering judgment, preliminary modeling of the stormwater system under various climate conditions and development scenarios, calibration, and validation with real-world measurements are all part of the research process. The performance of the solution is then evaluated again (5), and if the performance is adequate, a practical solution has been found (6). As regulations or on-site realities change, these systems can be improved further by being re-evaluated.

This decision-support matrix was developed concurrently with the report “Recommendations for Policy Developments at the EU Level for Digitalization in the Water Sector” [15], which revealed that the water sector is still in the early stages of digitalization and that no EU policies exist to encourage the adoption of digital stormwater management solutions. There is currently a lack of standardization of technology, monitoring, and interoperability in smart stormwater management solutions, and stormwater policies at the EU level are unclear or nonexistent. The availability and quality of stormwater data, which are related to the incentives for collecting them but are currently lacking due to the regulatory environment, are major barriers to the development of these standards. Stormwater quality e-monitoring device deployment on a large scale could at least close the data availability gap, and the accumulated data could eventually guide the creation of stricter regulations, early-warning systems, or the creation and maintenance of new stormwater management solutions. As the market encourages the use of these devices, it will follow suit and offer less expensive, more durable, and accurate solutions for monitoring efforts.

Based on this thorough literature review, the knowledge gaps in terms of future research needs and barriers that are holding back innovation are as follows:

- Implementation of smart technologies for more accurate assessment of the performance of stormwater treatment technologies, especially in real-time.
- Development of new, robust, and more cost-effective e-monitoring devices that could withstand harsh environmental conditions and could be implemented on a wide scale.
- Development of e-monitoring and stormwater system QA/QC and maintenance procedures based on the analysis of data that is collected in real-time.
- Standardizing the deployment and maintenance of enhanced (hybrid) stormwater treatment solutions.
- Developing a supportive framework (policy, governance, cost-benefit assessments, tendering, etc.) for wide-scale deployment of enhanced stormwater treatment solutions.
- Developing computationally less demanding (time-consuming) algorithms for model-based predictive control.
- Moving from the domain of modeling to the physical world (validating modeling results).
- Making it common practice to combine separate sewer systems with suitable green infrastructure to limit non-point pollution.

6. Conclusions

This research aimed to promote the adoption of efficient stormwater management practices for both quality and quantity in the Baltic Sea region. Additionally, it aimed to provide interested parties with a simple decision-support matrix for developing or improving stormwater management strategies in their catchment of interest. These objectives were met by:

- Providing an overview of the best practices for stormwater quality monitoring and suggesting how they could be improved through e-monitoring. To achieve this, we conducted a literature review of the benefits and drawbacks of different monitoring techniques and explored the possibility of using surrogate water quality parameters to enhance the monitoring service.
- Compiling the most recent legislation that pertains to stormwater management in the Baltic Sea region.
- Providing a review of the advantages to be gained by enhancing existing green infrastructure.
- Creating tables to provide data for a decision-support matrix, including a pictogram to assist in choosing the most appropriate green infrastructure and a multi-level system to select the required "tier" of smartness of the stormwater management system.

The decision-support matrix can be used to aid the development of smart infrastructures and e-monitoring solutions, which can provide critical data for knowledge-driven stormwater management. These systems can provide information for better decision-making, the deployment of early warning systems, the improvement of the efficiency of stormwater management facilities while also improving water quality and environmental status, and the reduction in the amount of investment required for refurbishing a stormwater system.

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