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Article

From Pilot Projects to Transformative Infrastructures, Exploring Market Receptivity for Permeable Pavement in The Netherlands

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Abstract: Climate change and changing land use challenge the livability and flood safety of Dutch cities. One option cities have to become more climate-proof is to increase infiltration of stormwater into soil through permeable pavement and thus reduce discharge of stormwater into sewer systems. To analyze the market receptivity for permeable pavements in the Netherlands, this article focuses on the perception of end-users towards key transition factors in the infrastructure transformation processes. Market receptivity was studied on two levels: (1) on the system level, by analyzing 20 key factors in the Dutch urban water sector that enable wider application of permeable pavements; and (2) on the technology level, by analyzing 12 key factors that explain why decision makers select permeable pavements or not. Results show that trust between cooperating partners was perceived as the system level key factor that needs to be improved most to facilitate the wider uptake of permeable pavements. Additionally, the association of end-users with permeable pavement, particularly their willingness to apply these technologies and their understanding of what kinds of benefits these technologies could bring, was regarded the most important receptivity attribute. On the technology level, the reliability of permeable pavement was regarded as the most important end-user consideration for selecting this technology.

Keywords: SUDS; sponge city; permeable pavement; transformative infrastructures; stormwater infiltration resilience; urban water; market receptivity

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1. Introduction

Climate change and changing land use challenge the livability and flood safety of Dutch cities [1]. The urgency and necessity of mitigating climate change is demonstrated by the 2015 Paris Climate Agreement, in which most of the world's nations agreed to take the required measures to keep the world well below an average temperature rise of 2 °C. At the same time, adaptation to climate change is crucial, as the impact of climate change is already becoming critical, particularly in densely populated urban areas. In the Netherlands, the Delta Plan on Spatial Adaptation was established as a joint plan by municipalities, water boards, provinces, and the national government to make the Netherlands climate-proof and water-resilient [2]. The Delta Plan will accelerate and intensify strategies and measures to reduce flooding, heat stress, and droughts, and to reduce climate impacts through spatial planning measures. The goal is to make the Netherlands climate-proof and water-robust no later than 2050. From 2020 onward, all municipalities must take climate change into account for urban development and redevelopment projects in order to make their cities climate-proof by 2030 [2].

1.1. Stormwater Infiltration, Sponge Cities, and Transformative Infrastructures

One of the options cities have to become more climate-proof is to increase infiltration of stormwater into soil through permeable pavement and thus reduce discharge of stormwater to sewer systems. Permeable pavements are technical systems that are part of the wider category of sustainable urban drainage systems (SUDS) [3,4]. The ambition to apply these kinds of systems on an urban scale rather than on a pilot scale has led to the introduction of urban concepts such as "water sensitive cities" [5] and "sponge cities" [6]. The sponge city concept aims to preserve the natural water balance in urban areas [6]. The main characteristics of a sponge city are the capacities to infiltrate, absorb, store, purify, drain, and manage stormwater. In addition to these technical capacities, sponge cities should have the institutional capacity to mainstream urban flood management into urban planning and urban design practice, including implementation, maintenance, and adaptation of local urban water infrastructure systems [7]. While the concept of sponge cities has gained momentum among urban policy makers in China, the concept probably has another geographical origin, as earlier references are found in Vietnam and India [7]. Some of the concept's guiding principles can even be traced back to ancient urban civilizations [6].

In this article, the concept of transformation is used as an analytical lens to study the desired transition from permeable pavement pilot projects to transformative infrastructures. Sustainable urban transformations can be characterized by sustainable places, the sustainable transition of the urban development regime, and the sustainable transition of related societal sectors such as water, energy, and transportation [8]. The concept of transformation has been applied effectively in transition studies in the urban water sector [9–11]. A transformed infrastructure system has fundamentally different system characteristics than the system it evolved from [11]. Transformative capacity is a system's capacity to transform itself in face of expected catastrophic developments such as human-induced climate change impacts [12]. The urgency of transformative infrastructures lies in the inadequacy of current centralized capital-intensive urban infrastructures to adapt to and anticipate rapid social and environmental change [13,14]. Transformative infrastructures aim to deliver co-benefits across infrastructure sectors, between infrastructure and the environment, and between infrastructure and inclusive social development, as well as to increase spatial benefits. They have the potential to shift organizations that implement them towards more sustainable development trajectories [15].

1.2. Permeable Pavements and Barriers to Their Wider Implementation

Permeable pavements are an infrastructure option that cities have available for the transition to transformative infrastructures. Permeable pavements have been used in the Netherlands for approximately 25 years to infiltrate stormwater runoff and assist with recharging groundwater in low-permeability soils [3]. When appropriately designed, constructed, and maintained, these systems can contribute to reducing urban flooding, mitigating the urban heat island effect, and reducing the effects of droughts through replenishment of groundwater [3]. Over the past 25 years, various types of permeable pavements have been implemented in municipalities in the Netherlands in order to increase infiltration capacity in urban areas and reduce stormwater discharge to surface water systems.

Despite the potential of permeable pavements to contribute to transformative infrastructures in urban areas, the actual widespread adoption of this technology on an urban scale remains limited. In the Netherlands, an increasing number of small and medium enterprises (SMEs) have launched different systems in the market. With often promising initial results, these adaptation measures seemed at first to be a very suitable solution for urban pluvial flooding. There are locations where the results are satisfactory, but in many cases, after several years, the infiltration capacity decreases due to clogging and pollution [16–18]. As a result, the willingness of municipalities to apply permeable pavements at a larger scale seems to remain limited. There is a lack of knowledge about the effectiveness of various permeable pavement systems; how the functioning of these systems is influenced by local circumstances such as soil type, vegetation, and traffic intensity; how maintenance can influence the long-term effectiveness of these systems; and what the life cycle costs and benefits of these systems are [19]. This lack of knowledge could be an important obstacle for the wider application and breakthrough of these systems, particularly because the reliability of novel technologies has been identified as the most important factor for urban water decision makers and policy makers regarding whether to apply a certain technology or not [20].

1.3. Research Context: The Sponge City Project

Urban living labs are spaces for sustainability experimentation. They are sites in cities where stakeholders can design, test, and learn from socio-technical innovations in real time. They are potentially capable of contributing to sustainability transitions beyond the living lab scale [21]. This article reports about a study that was executed in the context of a living lab: the Green Village TU Delft, the Netherlands. Within the Green Village is the Water Street (NL: Waterstraat), where entrepreneurs can test and demonstrate their water innovations in practice.

To address the slow implementation of permeable pavements in the Netherlands, the Sponge City Project (NL: Infiltrerende Stad) was established in the research context of the Water Street [22]. The project consortium consisted of universities of applied science, government agencies, and SMEs.

The main research objective in the project was building insights to move from permeable pavement pilot projects to transformative infrastructures. This objective requires that the technology of permeable pavements is applied at sufficient scale and, moreover, that stakeholders involved in urban (re)development processes are sufficiently equipped to design, implement, and maintain these technical measures during the life cycle of these infrastructures. For water innovations such as permeable pavements to have a system-wide impact on the city level, they need to be applied at an appropriate scale and speed. This scale should be relevant, and not only symbolic, in relation to the magnitude and severity of the urban climate change impacts and urban growth processes to which they aim to respond [23].

1.3.1. Classification of Permeable Systems

To develop a joint understanding in the Sponge City Project of the wide variety of permeable pavement systems, a generic model of different functionalities was made in close cooperation with the project consortium. This model enables the classification of permeable pavements [24]. The classification consisted of an overview of different working principles available in existing permeable systems in terms of permeability, infiltration, storage, and depletion of rainstorm water. This classification was also used to develop an infographic to explain the working principles of permeable systems to a wider audience. A review of technical background documents of permeable systems and interviews with the suppliers of these systems showed that permeable systems are usually a configuration of one or more of the following working principles, shown in Figure 1, with two examples in Figure 2, and further explained below.

1. Porous pavement: A range of different porous pavements is used around the world to treat stormwater runoff, including porous concrete pavers and porous asphalt used on highways and parking lots.
2. Permeable pavement: To infiltrate water from the street surface to the underlying aggregate layer and soil, various types of permeable pavements exist. Examples include concrete pavers with wide joints or apertures, generally referred to as permeable concrete interlocking pavers. Concrete and plastic grid pavers are also often used in some parts of Europe and other countries; the design and function of these systems are similar to those of permeable concrete interlocking pavers. Stormwater can infiltrate through the openings and gaps in these pavers, which are usually filled with gravel or topsoil planted with grass.

3. Permeable pavement by street drains: To discharge an excess of storm water to the subsurface layers of permeable systems, street drains can be applied. These street drains are comparable to street drains from sewerage systems, but in this case they are connected to available storage in the sub base aggregate of the street. Street drains can be connected with a drainpipe that distributes the water equally into the storage space.
4. Storage in bedding/sub base aggregate: Various systems are available to store water in the bedding or the sub base aggregate of the street. Examples include porous aggregate materials, plastic cradles, or hollow concrete blocks. Geofabric textiles can be applied under the storage to prevent groundwater seepage from flowing into the storage space.
5. Discharge over weir: Storage systems are often equipped with a weir to discharge the water once the storage has been filled with water. This overflow can be connected to various other systems, such as the surface water system, a sewerage system, or systems for active groundwater infiltration.
6. Drainage pipe: Drainage pipes are applied to empty the system. Drainage pipes are usually connected to the surface water, but can also be connected to sewerage systems or systems for active groundwater infiltration.
7. Infiltration: A passive way to empty the system is infiltration to the underlying soil.

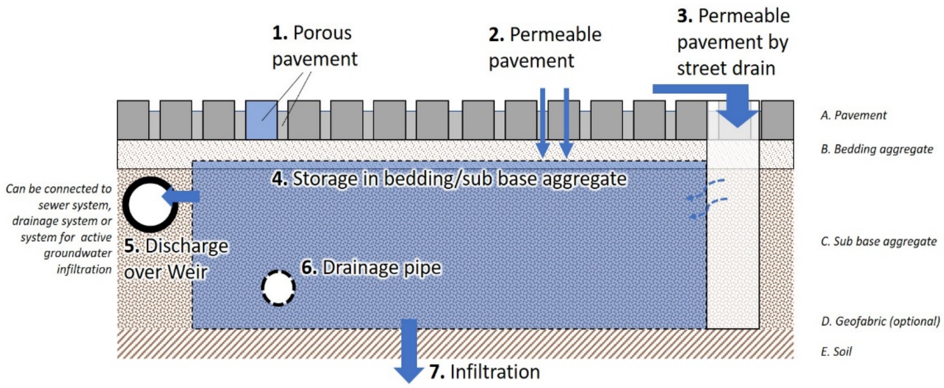

Figure 1. Classification of working principles in permeable systems.

(**a**) (**b**)

Figure 2. Examples of permeable systems that were full-scale tested at the Urban Living Lab Green Village TU, Delft, the Netherlands: (**a**) Bufferblock system, (**b**) Urban Rainshell.

1.3.2. Long-Term Functioning of Permeable Systems

The long-term functioning and effectiveness of maintenance of permeable pavements was addressed in the Sponge City Project by executing over 100 full-scale tests in a real-life setting in the Netherlands using full-scale infiltration testing methodology [16,18]. The infiltration capacity of the studied systems was well above the Dutch and international target values for infiltration. The tests also provided insights on the effectiveness of maintenance. Analysis of 17 cases indicated that on average, the infiltration capacity of permeable pavements increased 380% after carrying out maintenance [25].

1.3.3. Societal Costs and Benefits of Permeable Systems

Comparing the investment costs, operational costs, and adequacy of permeable pavements to those of conventional technologies was done by a societal cost–benefit analysis with a number of exemplar neighborhoods representative for the wide variety of locations with permeable pavement installations that were studied by the Sponge City Project [26]. The outcome [26] showed that permeable pavements can be a cost-effective alternative for the minimization of flood risk in urban environments if they are correctly designed. A comparison of various management and maintenance strategies also indicated that thorough management and maintenance pays off: extending the systems' lifespan results in a reduction of construction costs that outweighs the annual additional costs of maintenance.

1.4. Study Focus: Market Receptivity for Permeable Pavements

This article describes one of the main research topics in the Sponge City Project: market receptivity for the wider adoption of permeable pavements. To analyze this, the article focuses on the perception of end-users towards key transition factors in infrastructure transformation processes. In these processes, the awareness, willingness, and capacities of individuals and organizations that are expected to adopt new technologies, as well as the processes that influence the preferences of these end-users, are essential factors [11]. The theoretical model of receptivity [27] originates from technology transfer policy studies and can assist in understanding which conditions should be met to achieve technical and social system impact. Jeffrey and Seaton [27] defined receptivity as "the extent to which there exists not only a willingness (or disposition) but also an ability (or capability) in different constituencies (individuals, communities, organizations, agencies, etc.) to absorb, accept and utilize innovation options". The receptivity framework has been applied and operationalized successfully in earlier research to investigate the transformative capacity of the Dutch water sector [28].

2. Materials and Methods

The Dutch market for permeable pavements developed by SMEs mainly consists of municipalities. Market receptivity was studied on two levels: (1) on the system level, to analyze the key factors in the Dutch urban water sector that enable wider application of permeable pavements; and (2) on the technology level, to analyze the main considerations of decision makers regarding why they select permeable pavements or not.

2.1. The Receptivity Framework

The receptivity framework was applied to analyze the professional perception on change in urban water management. For mainstreaming of new professional practices and alternative technological options, four attributes are required according to the receptivity framework [27]:

- Awareness: being aware that a problem exists, and that alternative options are available.
- Association: associating these options with the stakeholders' own agenda and objectives.
- Acquisition: being able to acquire, implement, operate, and maintain the alternative options.
- Application: having sufficient legal and financial incentives to apply the alternative options.

A developed operationalization of the receptivity framework for 20 key factors (Table 1) on the system level [28] and 12 key factors (Table 2) on the technology level [20] was used in this study to analyze market receptivity for permeable pavements.

Table 1. The 20 system level key factors that were tested in this survey, classified according to the receptivity framework.

Awareness	**Acquisition**
1. Available knowledge of the local urban water system	11. Trust between cooperating partners in projects
2. Water management knowledge of other stakeholders	12. Experience in connecting water management and spatial planning
3. Reliable scientific knowledge about the urban water system	13. Availability of networks and organizational arrangements for stakeholder cooperation
4. Knowledge of technical innovations in urban water management	14. Quality of design skills in project teams
5. Juridical and administrative knowledge in urban water management	15. Quality of negotiation skills in project teams
Association	**Application**
6. Enthusiasm and perseverance of individuals	16. Financial incentives and subsidy schemes from national government
7. Support and commitment of elected officials	17. Accountability frameworks for stakeholders in urban water management
8. Involvement of citizens	18. Flexible interpretation of legal frameworks
9. Supportive organizational culture	19. Commercial viability of technical innovations
10. Availability of a national overarching vision	20. Binding targets for water quantity and water quality

Table 2. The 12 technology level key factors that were tested in this survey, classified according to the receptivity framework.

Social	**Economic**	**Ecological**	**Technical**
1. Effects on spatial planning	5. Investment costs	8. Environmental impacts	9. Inadequacy of conventional technology
2. Acceptability to citizens	6. Operational costs		10. Organizational experience with innovative technologies
3. Effects on public relations	7. Availability of financial incentives and subsidy schemes		11. Expected implementation timeframe
4. Public health impacts			12. Reliability of technology

2.2. Data Collection and Analysis

To study market receptivity on the two levels, two identical workshops were organized in which a cumulative number of 34 experts participated (n = 34). These experts included entrepreneurs, researchers, consultants, and policy makers, all in the field of permeable pavements. The first workshop was organized as part of the Sponge City Project [29]; the second workshop was organized as part of a symposium of the Community of Practice—Permeable Pavement [30]. In both workshops, participants were asked to indicate: (1) which factors at the system level, in their view, deserve the most and least priority to be improved to achieve the overall objective of accelerating the application of permeable pavement; and (2) which factors at the technology level determine whether or not decision makers may select permeable pavements as a technical solution. During the workshops, the participants could allot positive and negative points to the key factors. A cumulative 65 votes were cast in both workshops. The aggregated results of both workshops are presented in the results section. To statistically compare the scores of the different factors, the Z-score was used [31]. The Z-score assumes a normal distribution of the data. In statistics, the Z-score (also referred to as the "standard score") is obtained by subtracting the data population mean from an individual raw score and then dividing the difference by the standard deviation. The advantage of using this method is that it preserves extremes while the overall dataset is normalized. The spread of values is also captured by the Z-score method.

3. Results

The system level results (Supplementary Materials) provided insights into which of the 20 key factors are considered to require improvement to increase market receptivity (Figure 3). Of the studied key factors, trust between cooperating partners in projects was regarded as the single most important factor in urban water management to enable wider application of permeable pavements. Enthusiasm and perseverance of individuals, support and commitment of elected officials, and available knowledge about the local urban water system were also considered priority factors for improvement.

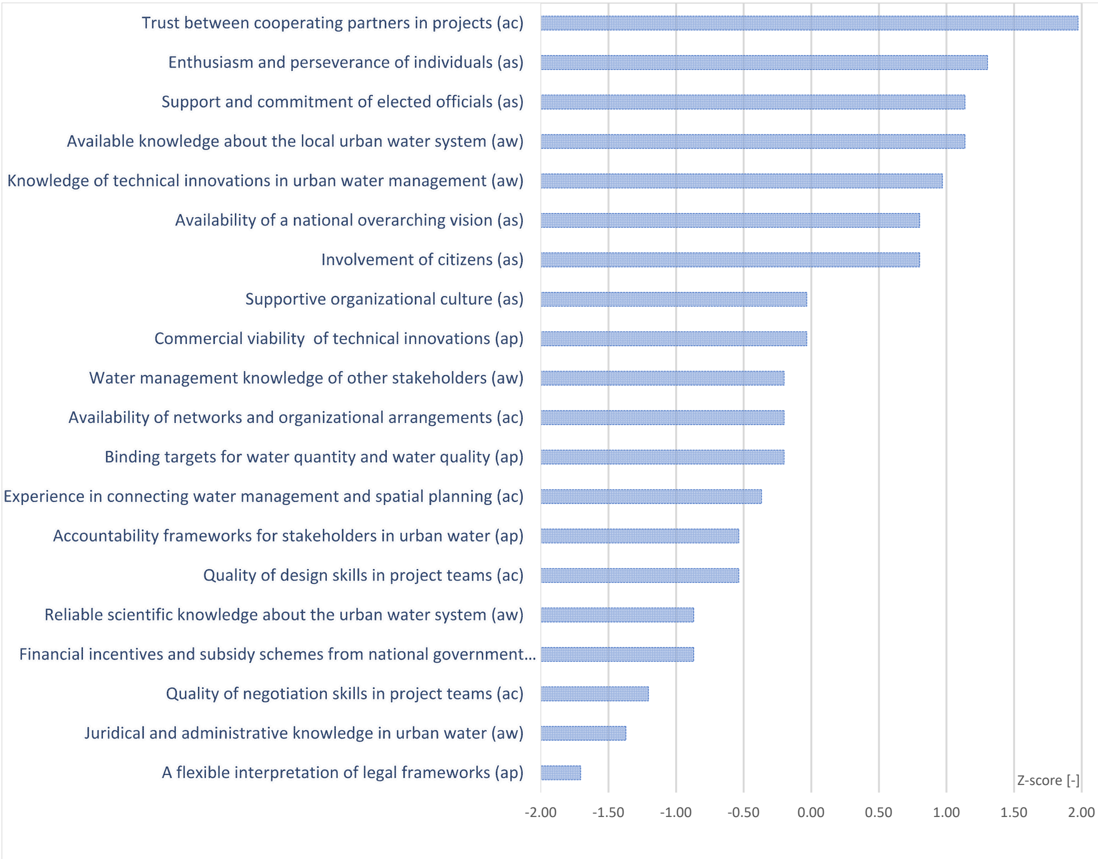

Figure 3. Results on system level: Z-score of key factors specified per receptivity attribute: aw = awareness, as = association, ac = acquisition, ap = application. Higher scores indicate more perceived priority; lower scores indicate less perceived priority.

The results also provide insights into which of the four receptivity attributes was considered to require most priority. The majority (4/5) of the "Association" factors were considered priority factors for improvement to facilitate the transition to transformative infrastructures. All "Application" factors, on the other hand, have a negative Z-score and were not considered a priority. "Awareness" and "Acquisition" were in between. Therefore, the results provide an indication that specifically the willingness of decision makers and their understanding of what benefits this technology might bring to them should be strengthened.

The technology level results (Supplementary Materials) provided insights into which of the 12 key factors most determine whether or not end-users will apply permeable pavement technology (Figure 4). The reliability of the technology was the single most important perceived key factor for decision makers to select permeable pavements. Environmental impacts were the second most important key factor, followed by operational costs. The availability of financial incentives and subsidies was considered least important.

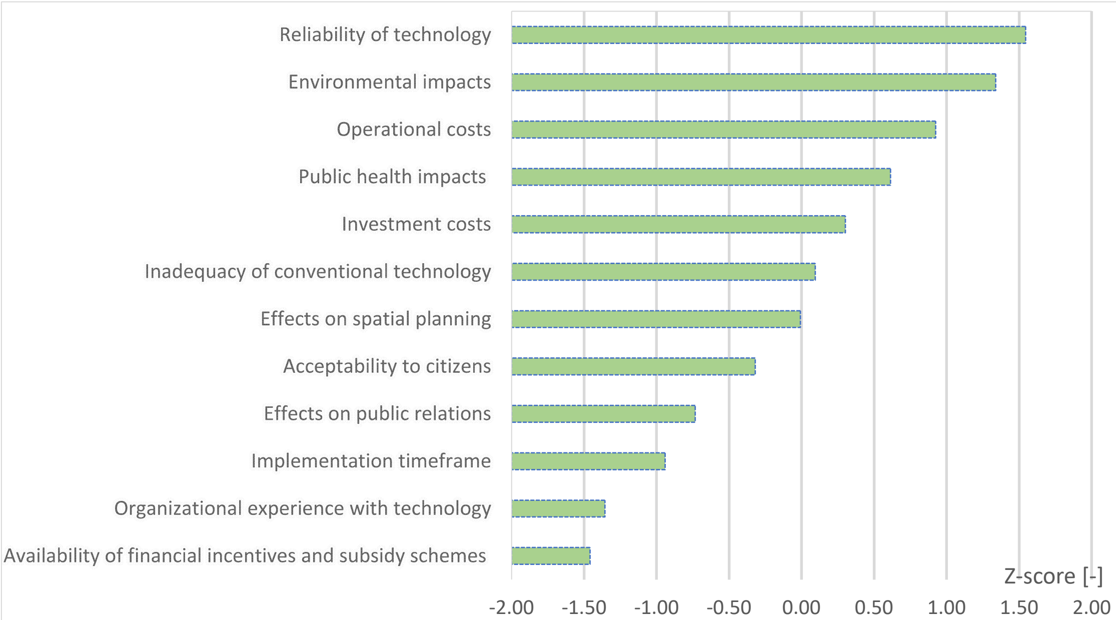

Figure 4. Results on technology level: Z-score of key considerations for selecting permeable pavements. Higher scores indicate a higher perceived importance; lower scores indicate lower importance.

4. Discussion

The study results in this article indicate that on the system level, trust between cooperating partners in projects was the most prioritized key factor for the transition from permeable pavement pilot projects to transformative infrastructures. On the technology level, the reliability of permeable systems was perceived as the most important key factor for end-users to select these technologies. Reliability includes technical functioning after installation, but also after a few years, when pollution and clogging may have reduced infiltration capacity

4.1. Comparison of Market Receptivity Results with Previous National Survey

To put the market receptivity results of this study in perspective, they were compared with the results of the 2009 Dutch national study into transition potential in urban water management [28]. This survey took place more than 10 years ago and was aimed at a broader collection of urban water innovations, whereas the current research was specifically aimed at permeable pavements. Despite these differences, it is remarkable that there were still three identical priority factors in the top five of both studies. These were: trust between cooperating partners in projects; support and commitment of elected officials; and available knowledge about the local urban water system. As these factors have appeared in this study again, the results of this project indicate that these factors still need to be addressed to facilitate the accelerated, wider application of permeable pavements.

Similarly, on the technology level, the results showed that three out of the five most important considerations were the same as in the national study from 2009 [20]: the reliability of technology, investment costs, and environmental impacts. Two factors perceived as important in this study were not identified as important in the 2009 national survey—operational costs and public health impacts. Operational costs, and in particular the theme of maintenance, have emerged as an important theme in the Dutch permeable pavements sector in recent years [32]. They were also discussed frequently in the Sponge City Project. It is therefore not surprising that the expert group participants considered this an important factor. Public health impacts and benefits in relation to permeable pavements, and in particular heat stress, have also emerged as a theme of rising importance in the last 10 years [33].

4.2. The Sponge City Project as Research Context

The Sponge City Project provided an effective research context to execute this study on market receptivity because the network and expertise of permeable pavements were available in a collaborative Urban Living Lab setting. The project also enabled addressing the main outcomes of the market receptivity study to stakeholders in the Dutch permeable pavements network. In the project, one way that the key factor of trust between cooperating partners was addressed was by establishing cooperation among the entrepreneurs, researchers, and policy makers. They regularly met in consortium meetings, masterclasses, workshops, and expert groups. This enabled the development of a joint understanding of the many available permeable systems, which served as a common knowledge base and reference point during the project. The Sponge City Project provided insights that indicated that maintenance is effective to safeguard the technical functioning and reliability of permeable systems. Operational costs were also regarded as one of the three most important key factors for end-users. In the project, this was addressed through a societal cost–benefit analysis that showed that regular maintenance is an effective strategy and has a competitive cost–benefit level.

4.3. Next Research Steps: A Proposal for a "Theory of Change"

From the study results reported in this article, but also from the authors' experience in the Sponge City Project, the perception of end-users seems to be a strong overarching driver for the transition from pilot projects to transformative infrastructures. Both in the system level key factor of trust between cooperating partners, and in the technology level key factor of reliability of technology, end-user perception plays a dominant role. Therefore, the Theory of Change [34] was selected as a suitable framework to reflect on the research results and develop hypotheses for further research. According to [34], "Theories of Change are the ideas and beliefs people have—consciously or not—about why and how the world and people change. How people perceive and understand change and the world around them is infused by their underlying beliefs about life, human nature and society. They are deep drivers of people's behaviour and of the choices they make" The authors formulated a Theory of Change for how to scale up from individual permeable pavement projects to urban scale transformative infrastructures to implement the concept of the sponge city. This theory is illustrated in Figure 5 and explained below.

The transition from small scale pilot projects to transformative infrastructure requires two shifts. The first shift is from focusing on creating stakeholder awareness (informing) towards addressing full social system potential. This can be achieved by addressing the entire receptivity continuum, including the willingness and capacities of end-users to design, implement, and maintain permeable pavements. Executing a societal cost–benefit analysis over the entire life cycle of permeable pavements could potentially contribute to this. The second shift is from studying the technical functioning of permeable pavements at a relatively small scale towards investigating total system impact. In this project, the second shift was made by evaluating permeable pavements in real-life settings with full-scale testing, but also by testing and evaluating operation and maintenance strategies. Knowledge distribution, education, and training can also be effective strategies to contribute to transformative change beyond the scale of an Urban Living Lab [21]. Global sharing of best practices through partnerships and online knowledge platforms can contribute to increasing the scale and speed of climate-resilient transformations [35]. Monitoring of, learning from, and evaluation of innovative climate projects are needed to enable innovations to move from a niche-scale, project-based approach towards an inclusive process-based approach in which innovations become able and equipped to compete with large-scale, centralized, unsustainable infrastructures. Ideally, transformative infrastructures would become an integral part of every intervention in the urban environment. The authors propose two key factors that could play an essential role in this process. The first is replication and improvement of permeable systems. The second factor is mobilizing increased investments and scaling up. The assessment of total life cycle costs in this project and evaluation of system-wide impacts could provide input to develop solid business cases, which are needed to arrange the much larger required budgets to implement transformative infrastructure at an appropriate speed and scale to address the urgency and magnitude of the climate crisis that cities are currently facing.

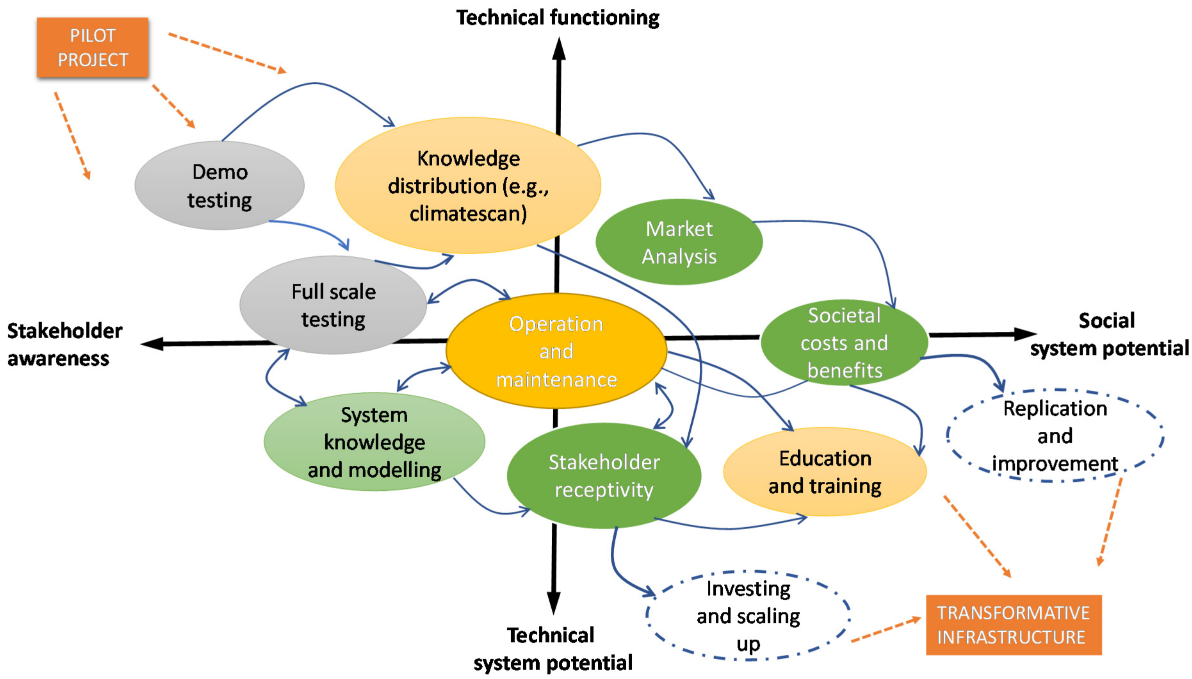

Figure 5. Overview of factors discussed in this article to move from pilot projects (left/top) to transformative infrastructure (right/bottom).

5. Conclusions

Climate change and changing land use challenge the livability and flood safety of Dutch cities. One option cities have to become more climate-proof is to increase infiltration of stormwater into the soil through permeable pavement and thus reduce discharge of stormwater into sewer systems. Permeable pavements have been used in the Netherlands for approximately 25 years to infiltrate stormwater runoff and to assist with recharging groundwater in low-permeability soils.

Transformative infrastructures aim to deliver co-benefits across infrastructure sectors, between infrastructure and the environment, and between infrastructure and inclusive social development, and to increase spatial benefits. They have the potential to shift the organizations that implement them towards more sustainable development trajectories. Despite the potential of permeable pavements to contribute to transformative infrastructures in urban areas, the actual widespread adoption of this technology on an urban scale remains limited.

To analyze market receptivity for permeable pavements, this article focuses on the perception of end-users towards key transition factors in infrastructure transformation processes. In these processes, the awareness, willingness, and capacities of individuals and organizations that are expected to adopt new technologies, as well as the processes that influence the preferences of these end-users, are essential factors. Market receptivity was studied on two levels: (1) on the system level, by analyzing 20 key factors in the Dutch urban water sector that enable wider application of permeable pavements; and (2) on the technology level, by analyzing 12 key factors that explain why decision makers select permeable pavements or not.

The market receptivity study results in this article showed that trust between cooperating partners was perceived as the system level key factor that needs to be improved most to facilitate the wider uptake of permeable pavements. Additionally, associations of end-users with permeable pavement, particularly their willingness to apply these technologies and their understanding of what kinds of benefits these technologies could bring, was regarded the most important receptivity attribute that needs to be addressed. On the technology level, the reliability of permeable pavement was regarded as the most important end-user consideration for selecting this technology or not.

Building on the results of the Sponge City Project, a Theory of Change was formulated that contains two required shifts. The first shift is from focusing on creating stakeholder awareness towards addressing the full social system potential. The second shift is from studying the technical functioning of permeable pavements at a relatively small scale towards investigating the total system impact. The authors propose two key factors as part of these two required shifts. The first key factor is replication and improvement of permeable systems. The second factor is mobilizing increased investments in permeable pavements and scaling up. These are expected to be key factors to implement transformative infrastructure at an appropriate speed and scale to address the urgency and magnitude of the climate crisis that cities are currently facing.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su13094925/s1. Raw data, the data analysis, photos of the workshop results (in Dutch) and an anonymized excel file with the workshop participants.

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