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Quantifying the impact on stormwater management of an innovative ceramic permeable pavement solution

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Abstract

Stormwater management in cities has traditionally been based on centralized systems, evacuating runoff as quickly as possible through drainage networks that collect and convey the runoff to the final point of treatment or the receiving water body. In recent years, a different approach focused on the use of Sustainable Urban Drainage Systems (SUDS) represents a paradigm shift, promoting a decentralized management as close to the runoff source as possible. Among these techniques, permeable pavements represent an effective solution for reducing runoff and providing pollutant treatment. This contribution describes the results obtained from an innovative ceramic permeable pavement developed as part of the LIFE CERSUDS project in the city of Benicàssim (Spain). This pavement, composed by modules built from ceramic tiles in stock, allows water infiltration, runoff treatment and water reuse as part of a SUDS built in 2018 and monitored from September 2018 to September 2019. The purpose of the research was to demonstrate the hydraulic performance of the proposed solution through monitoring of runoff quantity and quality variables. Monitoring data analysis have shown positive results, reducing peak runoff rates and the volume of water which is conducted downstream. From the hydrological point of view, the system capacity shown a 100% runoff management for events up to 15-25 mm of precipitation. This is a very significant threshold since these values represent, respectively, the 81% and 91% percentiles for the study area. System performance was confirmed in terms of runoff management and water infiltration. This demonstration case study represents a reference example of urban retrofitting actions which integrate social, economic and environmental aspects.

Keywords

Stormwater management, sustainable drainage systems, permeable pavement, ceramic tiles

Highlights

- An innovative SUDS solution for permeable pavements is described and analysed.
- The use of a ceramic permeable pavement has demonstrated the benefits of reducing impervious urban surfaces to control urban runoff at source.
- Recommendations for monitoring this type of SUDS techniques are provided.

1. Introduction

About 90% of all natural disasters are water-related. Over the period 1995–2015, floods accounted for 43% of all documented natural disasters, affecting 2.3 billion people, killing 157,000 and causing US$662 billion in damage (EM-DAT 2015). The nature of disastrous floods has also changed in recent years, with flash floods, acute riverine and coastal flooding increasingly frequent. In addition, urbanization has significantly increased flood runoffs and the runoff volume conveyed to the receiving water bodies has also increased (Ahiablame and Shakya 2016). Moreover, stormwater management in cities has traditionally been based on centralized systems, evacuating runoff as quickly as possible through drainage networks that collect and convey the runoff to the final point of treatment or the receiving water body.

Apart from the problem of managing runoff volumes, there is a need for alleviating water quality problems related to urban drainage, mainly regarding diffuse pollution (D'Arcy and Frost 2001) resulting from the introduction of pollutants to water bodies (e.g. suspended solids, organic matter with high biochemical oxygen demand, dissolved nutrients, heavy metals, hydrocarbons or pathogens (Scholz and Grabowiecki 2007).

Furthermore, actors involved in stormwater management should face additional challenges such as climate change, adapting urban drainage infrastructure to higher precipitation extremes and more frequent drought episodes and heat waves, resulting in new urban environments affected by extreme weather events (Zhou 2014).

In recent years, a different approach has arisen, the so-called sustainable urban drainage management, considering urban drainage as an opportunity and not a problem (e.g. providing ecosystem services, reduction of pollutants, water reuse, increased biodiversity, and improved microclimate). This new approach is based on the use of Sustainable Urban

Drainage Systems (hereafter SUDS), also known as Best Management Practices (BMPs) or Low Impact Development (LID) techniques (terminology mainly used in the United States). In this paper, the term SUDS is used referring to a range of technologies and techniques used to drain stormwater/surface water in a manner that is more sustainable than conventional solutions, based on the philosophy of replicating as closely as possible the natural, pre-development drainage of a urban environment (Fletcher et al. 2015). This paradigm shift promotes a decentralized management (Wang et al. 2018) as close to the runoff source as possible (Chang et al. 2018).

The scientific community has gradually recognized SUDS to be adequate techniques of modern, efficient and sustainable stormwater management. In addition, SUDS have gained growing public interest and acceptance in recent years, as a result of its positive effects on water quality and quantity management as well as multiple benefits perceived in the urban landscape, including biodiversity, local climate regulation, recreation and aesthetics, among other ecosystem services (Scholz et al. 2013).

Examples of references found in the literature are, for example, the manual published by CIRIA in the UK (Woods-Ballard et al. 2007) and other design guidelines published in the US or Canada (SEMCOG 2008; TRCA and CVC 2010). These guidelines describe a number of different SUDS techniques that are oriented to provide a decentralized storm water management: green roofs, porous pavements, or bioretention areas, among others.

Although there exist some recommendations regarding SUDS design and maintenance, and research works concerning their design and analysis (Zubelzu et al. 2019), there is a need for providing adequate monitoring and analyses of new solutions that differ from common SUDS configurations.

An innovative permeable pavement solution was proposed as part of the LIFE CERSUDS project in the period 2016-2019. The main objective of this paper is to describe and analyse the system performance of this SUDS solution, based on the use of an innovative ceramic permeable pavement. This paper provides answers to the following key research question: "How does the proposed SUDS system perform in terms of runoff quantity and quality management over the course of the analysed monitoring period?"

Therefore, this paper describes: (1) the key aspects of the proposed SUDS system, and (2) the analysis of results obtained from the monitoring period.

Permeable pavements are those surfaces which, while being trafficable for both pedestrians and vehicles, allow for the filtration of water thus allowing for infiltration, groundwater recharge or water reuse (Woods-Ballard et al. 2007). This SUDS typology has been widely used and researched over the past years. Different types of surface materials can be used in permeable pavement systems, including grass, blocks or porous materials such as porous asphalt and concrete (Scholz and Grabowiecki 2007). In particular, porous concrete is widely used due to its multifunctional nature (Elizondo-Martínez et al. 2020), enabling water infiltration, providing sound reduction and mitigation of urban heat-island effect, among other benefits

Main publications addressing the subject of permeable pavements are concentrated in Europe, and more specifically in the UK. The leading institutions are the universities of Coventry (England) and Abertay-Dundee (Scotland). Among all the CIRIA different publications, "The SUDS manual" includes a specific chapter on permeable pavements (Woods-Ballard et al. 2007).

The amount of publications, experiences and recommendations on this subject has also increased in Spain. In 2008, the Centre for the Study and Experimentation on Civil Works

(CEDEX) published the “Technical Guide on Sewage Networks and Urban Drainage” in 2007 (CEDEX 2007), and the monograph “Rainwater management: Implications in the design of urban drainage and sewage systems”, as a complementary material, including the use of permeable pavements and other SUDS in general.

A review of sustainable drainage practices in Spain, specially focused on permeable pavements, shown examples of their implementation at different locations (Castro-Fresno et al. 2013; Gomez-Ullate et al. 2011). In addition, there are several examples of research projects including the implementation of permeable pavements in Spanish cities. In 2010, the AQUAVAL project (LIFE 08ENV/E/000099 AQUAVAL) comprised the execution of permeable pavements, as well as the monitoring and follow-up of the SUDS implemented for quality and quantity control of urban runoff.

Studies have shown these techniques to be especially effective for urban stormwater reduction and quality improvement. In fact, Spain highlights for being one of the reference countries in number of contributions to permeable pavements used as source control in SUDS (Elizondo-Martínez et al. 2020; Jato-Espino et al. 2016)

The efficiency of permeable systems in runoff quantity management has been analysed in recent years. As stated by (Gimenez-Maranges, Breuste, and Hof 2020), examples of permeable pavements in Granada (Spain) (Rodríguez-Rojas et al. 2018) totally absorbed rainfall during highly regular precipitation events and a simulation of permeable pavements in an urban catchment in Espoo (Finland) suggested an average runoff reduction of 40%-50% (Jato-Espino et al. 2016). In addition, the work conducted in Jato-Espino et al. (2016) also highlighted an average volume reduction at the outlet of the study catchment of 40%–50% for permeable pavement solutions. In particular, studies in the south of Spain shown the great potential of permeable pavements for reducing the volume of rainwater collected in the sewer system (Rodríguez-Rojas et al. 2018), with volumetric efficiencies over 80%.

The efficiency of permeable systems in water quality treatment has also been studied and demonstrated in recent years. Examples in the literature show pollutant reduction rates close to 90% for, e.g., total petroleum hydrocarbons and total suspended solid parameters (Castro-Fresno et al. 2013).

However, their widespread implementation is not yet accomplished, despite available publications around this particular matter in the last two decades. In addition, monitoring of real applications is time-consuming and highly-dependent on weather conditions, and consequently, not conducted in general.

Apart from its positive effects on reducing water runoffs, permeable pavements represent an opportunity to employ recycled or reused materials in urban retrofitting applications (Rahman et al. 2015), reducing the environmental impact of new actions and the corresponding carbon footprint.

Consequently, we need studies focused on characterizing the real performance of these techniques when incorporating new designs (e.g. the proposed solution in this paper) and the most appropriate configuration to communicate effectively the benefits in terms of stormwater quantity and quality management, then boosting their implementation. In such context, the LIFE CERSUDS project envisaged the execution of a demonstrator featuring an innovative solution based on the use of a ceramic permeable pavement, which is described and analysed in this paper.

To investigate the effectiveness of a new pavement solution, the ITC-AITE (Institute of Ceramic Technology), in collaboration with other entities, included the Polytechnic University of Valencia (UPV), developed the LIFE CERSUDS project in the period 2016

- 2019. The main goal of this project was first to establish the final design of a ceramic permeable pavement solution (Mira et al. 2012), and second, to demonstrate its performance in a real case. Demonstrating the effectiveness of the solution on reducing rainfall runoff is the initial, and necessary, step for its future replicability.

The LIFE CERSUDS project has demonstrated an innovative use for high quality ceramic material that was in stock and out of the market, and therefore had a low commercial value, in order to create a new Sustainable Urban Drainage System (SUDS), using ceramics as the main element for the construction of the pavement. Specifically, the innovative aspects that our work addresses respect to previous studies are: (a) the permeable pavement is made of ceramic permeable modules; (b) the permeable pavement is made of reused low commercial ceramic material, thus enhancing circular economy; and, (c) the system allows rainfall water harvesting and reuse.

Prior to the construction of the demonstrator, the project included several actions such as the characterization and quantification of ceramic tiles with low commercial value in each participating country (Spain, Italy and Portugal); the definition of the hydraulic, environmental and social objectives of the project, and the definition of the ceramic permeable system, being a novel and disruptive solution, with specific characteristics, requirements and specifications (CERSUDS 2019).

The LIFE CERSUDS project proposes an innovative ceramic permeable pavement using low commercial value ceramic pieces in stock (the estimated total amount is 5.2 million square meters of ceramic pieces in stock only in Spain). These pieces are cut in strips of a defined width, and then a set is assembled with a bonding agent to create a permeable module.

The proposed ceramic permeable modules were tested including aspect such as system permeability, impact resistance, transverse loads, shear strength, abrasion and frost resistance. The final configuration is a module consisting of 7 bonded ceramic strips, with a total dimension of 335x65x75 mm and a total weight of 3.3 kg (Fig.1). The modules were manufactured within the LIFE CERSUDS project and installed in a street of the city of Benicàssim in Castellón (Spain).

The present paper is structured as follows: section 1 presents the motivation for this research, the new permeable pavement solution and the project; section 2 describes the methodology and the solution; section 3 presents the main results; and, finally, section 4 summarizes the conclusions.

2. Materials and methods

Figure 2 shows a flowchart describing the research methodology followed for this study. Four stages can be distinguished: (i) design of the proposed solution; (ii) installation of monitoring equipment during system construction; (iii) performance monitoring, and (iv) performance analysis.

The design of the proposed solution was developed during the first year of the LIFE CERSUDS project by the consortium. In this stage, authors contributed to define the characteristics of lower layers of the system and the requirements of the monitoring equipment. The construction of the demonstrator took place during the second year of the project, including installation of monitoring equipment. Performance monitoring, in terms of runoff quantity and quality management, was conducted during the third and last year, including preliminary and final analyses of results.

Details on the demonstration case study, selected monitoring equipment, field measurements and conducted analyses are further described in this section.

2.1.The proposed SUDS system implemented at the demonstrator site

The study site is located in Benicàssim (Spain). Benicàssim is on the east coast of Spain (Fig.3a), in the core of a ceramic cluster which represents the 90% of Spanish ceramic tile production. The surrounding influence area was considered for potential replicability of the proposed solution and project outreach actions (Fig.3a, red circle).

Benicàssim has a mild Mediterranean climate. The average annual temperature is around 18.4 °C, with oscillations between 13.7 °C in winter and 22.9 °C in summer. In the period 1976 - 2016, average annual precipitation was close to 450 mm, with a strong seasonality. Registers show an average of 45 days of rain per year and all rainfall events with precipitation rates less than 142 mm. The 24-hour rainfall registers were less than 75 mm in 99% of cases. Heavy rainfall and storms are usually concentrated from September to November, with typically high, torrential intensities.

The Sustainable Urban Drainage System (SUDS), developed within the LIFE CERSUDS project, has an area of approximately 3,000 m^2, and was built in a consolidated urban environment of light and pedestrian traffic located in a stretch of Sant Vicent street (Fig.3b),. Building the demonstrator in this space allowed for a very appropriate monitoring and evaluation aimed at proving that this permeable ceramic pavement can be an ideal solution for urban retrofitting actions as well as a reference for interventions in consolidated environments.

The demonstrator, executed between February and June 2018 (Fig.4), is 200 m long and has a variable width ranging from 10 m to 27 m and a 1.5% descending longitudinal slope. The demonstration site is located in a low-density residential area, characterized by several municipal sport facilities which make the street not only a frequent connection point between the beach and the city centre, but also an area linked to strategic public facilities.

The case study included the implementation of a sustainable drainage system along the street which allows water infiltration and collection, following international references for SUDS design (Woods-Ballard et al. 2007). The ceramic permeable pavement, in combination with selected materials for subbases, drainage cells and geotextiles, provides runoff treatment and reduction of water flows to the existing drainage network downstream (Fig.5). In addition, the system includes a rainwater harvesting tank, with a volume of approximately 10 m^3, aiming at reusing water for irrigation of gardens at the demonstration site.

With this solution, the proposed drainage system has evolved from being a conventional approach (consisting of a sealed surface featuring the collection of urban runoff by means of punctual gutters connected to a collector) to a new permeable solution which allows percolation of water to the ground, driving the excess water to the rainwater harvesting tank located under the bicycle lane and through the cells. The system acts as a collector, but delaying and reducing the contribution to the network during rainfall events.

The hydraulic design of the demonstrator has considered, in that order, the following specific objectives: (i) runoff reduction, (ii) increase in the proportion of permeable surfaces, (iii) runoff catching and filtering through the permeable pavement, (iv) use of the rainwater stored for irrigation, (v) infiltration, and (vi) reduction of peak flows reaching the collector downstream of the system.

2.2.Monitoring equipment

To monitor the quantity and quality of water managed by the demonstrator, runoff at two streets was analysed. Streets are denoted hereafter as A and B, respectively. Street A refers to the implemented SUDS system in Torre San Vicente street, and Street B to the conventional drainage system used for comparison purposes, located in Mossen Elies street (Fig.6). Street A was divided into two sections.

The purpose of monitoring two different sections (A1 and A2) is to collect runoff exceeding the capacity of the rainwater harvesting tank (Section A1) before flows downstream to the next section (Section A2), thus obtaining valuable information regarding managed volume by the storage facility. With such purpose, three chambers were built in the demonstrator for monitoring tasks (Fig.6): for monitoring the conventional system at Street B (HID1), downstream the harvesting tank (HID2), and at the final point of the demonstrator before connecting to the existing drainage network (HID3). In addition, two weather sensors for monitoring temperature and humidity were installed (AMB1 and AMB2) to evaluate the effect on urban microclimatic conditions in the demonstrator.

Each chamber included the installation of a portable automatic sampler (Fig.7), equipped with 24 bottles of 0.5 l and a data logger for the level probe. Flowmeters were used for analysing hydraulic characteristics of runoff in chambers HID1 and HID3, and a water level sensor at HID2.

In addition, a rain gauge (a compact all-in-one weather sensor for measurement of temperature, relative humidity, and precipitation, with 0.2 mm accuracy) was installed at the demonstration site.

2.3.Field measurements and sampling

Based on previous experiences (Andrés-Doménech et al. 2018), a monitoring period of 13 months have been set for analysing system performance in terms of runoff quantity and quality, between September 2018 and September 2019.

Flowmeters and water level sensors registered data for time intervals ranging from 1 to 3 min, depending on the monitoring point (with shorter time intervals for the conventional system to capture the rapid rainfall-runoff response). The rain gauge registered precipitation in one- minute time intervals.

The samplers include the ability to initiate up to different programs based on user-defined conditions, such as a water level or flow rate threshold. A small container was installed in each chamber to collect the first runoff of each section by the sampler. The frequency of sampling was defined to take 2 samples per point: the first sample is taken when the defined threshold is reached, to adequately capture the first flush; and the second sample is taken after 5 min, to cover the variability of the water quality. Samples should be collected in the first 48 hours after the event to be later processed.

Reduction of runoff volume, reduction of peak flows and reduction of drinking water consumption for irrigation processes were analysed as key indicators of runoff quantity management in the system.

2.4.Biochemical analysis

Samples for analysis of water quantity and quality indicators were collected during the monitoring period. Results regarding electrical conductivity (UNE-EN-27888:1994), pH (ASTM D1293), dissolved oxygen (UNE-EN-ISO 5814), Total Suspended Solids (TSS, UNE-EN-872), Total Phosphorus (TP, UNE-EN ISO 11885) and total metals (PB, Zn, Cu, Ni, SM 3111), turbidity (UNE-EN-ISO 7027), Total Nitrogen (TN, UNE-EN 12260), 5- and 20-day Biochemical Oxygen Demand (BOD_5, BOD_{20}, SM 5210B D), Chemical Oxygen Demand (COD, ISO 15705), oils (SM 5520C), hydrocarbons (SM 5520C), volatile suspended solids (VSS, UNE-EN ISO 15169), E. Coli and helminth eggs were obtained in eight rain events.

3. Results and discussion

3.1.Rainfall and runoff flow characterization

Results regarding recorded rainfall events and volumetric balances are included.

3.1.1. Recorded rainfall events

Table 1 shows the key monitoring results of the quantity variables in the demonstrator, including rainfall rates per event, the volume precipitated in the entire demonstrator area, the volume recorded by the sampler located in HID3 (final point of the system), and the hydraulic performance of the system (last column), that is, the proportion of the precipitated water completely managed by the system (water retained or infiltrated and not reaching the downstream drainage network). Thirty-five events were recorded during the monitoring period, taking into account events with precipitation greater than 1 mm. The average daily rainfall record within the monitoring period is 11.4 mm, with a maximum daily record of 48.8 mm, which occurred on 18 October 2018. This value, according to the statistical analysis of the reference station (Castellón - Almazora station), corresponds to the 97% percentile, that is, precipitation that is only exceeded in 3% of the rainy days.

Records show that the monitoring period has been a dry period. From October 2018 to September 2019 (hydrological year), 367.4 mm were registered. The accumulated average annual rainfall in the reference rainfall station is 446.7 mm per year. Concerning rainy days, from September 2018 to August 2019, thirty-one events were recorded; from October 2018 to September 2019, the amount was 32 days. The annual average obtained from the analysis of the aforementioned series is 45 days of rain per year.

Table 1. Key hydraulic performance results for the monitoring period.

Event ID	Date (dd/mm/yyyy)	Daily rainfall in demonstration area (mm)	Precipitated volume in demonstration area (m³)	Volume recorded at the outlet of the system (m³)	Demonstrator hydraulic performance (%)
01	15/09/2018	8.2	27.06	0.00	100%
02	**18/09/2018**	**22.2**	**73.26**	**16.42**	**78%**
03	26/09/2018	1.2	3.96	0.00	100%
04	14/10/2018	17.4	57.42	0.00	100%
05	**18/10/2018**	**48.8**	**161.04**	**119.36**	**26%**
06	**19/10/2018**	**38.4**	**126.72**	**8.58**	**93%**
07	27/10/2018	11.6	38.28	0.00	100%
08	30/10/2018	7.4	24.42	0.00	100%
09	31/10/2018	11.8	38.94	0.00	100%
10	09/11/2018	13.4	44.22	0.00	100%
11	16/11/2018	21.0	69.30	0.00	100%
12	17/11/2018	6.0	19.80	0.00	100%
13	**18/11/2018**	**22.2**	**73.26**	**3.89**	**95%**
14	**19/11/2018**	**14.4**	**47.52**	**0.98**	**98%**
15	23/11/2018	2.0	6.60	0.00	100%
16	13/12/2018	3.8	12.54	0.00	100%
17	19/03/2019	5.0	16.50	0.00	100%
18	31/03/2019	5.4	17.82	0.00	100%
19	02/04/2019	3.6	11.88	0.00	100%
20	08/04/2019	1.4	4.62	0.00	100%
21	18/04/2019	28.6	94.38	0.00	100%
22	22/04/2019	2.2	7.26	0.00	100%
23	03/05/2019	1.6	5.28	0.00	100%
24	21/05/2019	1.8	5.94	0.00	100%
25	24/05/2019	8.6	28.38	0.00	100%
26	07/07/2019	4.6	15.18	0.00	100%
27	08/07/2019	6.2	20.46	0.00	100%
28	14/07/2019	3.6	11.88	0.00	100%
29	20/08/2019	3.0	9.90	(*)	(*)
30	21/08/2019	1.2	3.96	(*)	(*)
31	27/08/2019	14.8	48.84	(*)	(*)
32	02/09/2019	4.6	15.18	0.00	100%
33	**11/09/2019**	**37.0**	**122.10**	**66.74**	**45%**
34	12/09/2019	1.2	3.96	0.00	100%
35	13/09/2019	14.8	48.84	0.00	100%

(*) No data records available due to low battery levels.

Table 1 includes rainfall rates per event, the volume precipitated in the entire demonstrator area, the volume recorded by the sampler located in HID3 (final point of the system), and the last column shows the hydraulic performance of the system, that is, the proportion of the precipitated water completely managed by the SUDS (that is, water retain or infiltrated and not reaching the downstream drainage network).

It can be observed that output flow has been recorded only 6 times in the system (events numbered with ID 2, 5, 6, 13, 14 and 33). These events correspond to 4 rain episodes: 18 Sep 2018, 18-19 Oct 2018, 18-19 November 2018, and 11 Sep 2019. These data show the very high reduction of the system in the frequency of exceeding output flow downstream.

It should be noted that two episodes, with a very appreciable and similar magnitude, presented a different behaviour in the system: on 18 Apr 2019 with 28.6 mm there is no output flow, however on 12 Sep 2019 with 37.0 mm there is an output record in HID3. The reasons why similar episodes do not generate the same system response are basically two:

- During the episodes of September and November 2018, significant rainfall intensities were recorded, with the precipitation significantly concentrated in short periods of time. This exceeds the system capacity and results in output flows downstream.
- On the contrary, the event in April 2019 occurred after a very long dry period, with low or insignificant rains, which increases the system capacity to retain and infiltrate water. However, the event in September 2019 occurred two weeks after an event of not negligible magnitude (on 27 Aug 2019 with 48.84 mm).

Therefore, it can be deduced that, depending on the initial humidity state of the system, it has a capacity for complete management of rainfall episodes up to 15-25 mm. From the hydrological point of view, this is a very significant threshold since these values represent, respectively, the 81% and 91% percentiles of the reference rain gauge series (Castellón - Almazora station). The results confirmed the appropriate system performance in terms of managing runoff quantity, where high precipitation rates are needed for collecting output flows downstream the system.

3.1.2. Volumetric balance

Figure 9 shows a volumetric balance of the system for the period from September 2018 to August 2019. Four components are defined within the balance. Components denoted as (1) are measured and deducted directly from monitoring. Components type (2) are deduced from the study of irrigation demand and the rainfall harvesting tank capacity conducted during the design stage of the project. Component (3) is deducted from the balance and corresponds to the flow that returns into the natural hydrological cycle, either by evapotranspiration or by infiltration into the subsoil. Finally, component type (4) represents water filtered by the system.

Results show that the system has a large volumetric capacity for runoff management, since 86% of the precipitated water can be used, directly from the tank or as a return to the natural hydrological cycle. The results are aligned with other examples found in the literature (Rodríguez-Rojas et al. 2018), even higher than the 40%–50% of average volume reduction obtained in other studies as mentioned in the introduction (Jato-Espino et al., 2016).

3.1.3. Comparison with conventional drainage system

The comparative analysis of events between monitoring points in Street A (demonstrator, monitoring point HID3) and B (conventional drainage system, monitoring point HID1) allows to analyse the hydraulic performance of the system in terms of kinetics. However, there have been very few events for which comparison is possible since HID3 did capture output flows. However, when occurred, results observed are conclusive.

Runoff flow rates in Street A were compared with those in Street B for three events. Outflow rates with the new pavement solution are lower than those with the conventional drainage system. Figure 9 shows the hyetograph and hydrograph for the rainfall event registered on 18 Oct 2018 as an example, for which the time interval from the beginning of the rainfall event to the first output flow into the downstream system was 50 min.

As shown in Table 2, the time interval from the beginning of the rainfall event to the first output flow at the monitoring point is clearly larger at the demonstrator compared with the response of the conventional system.

Table 2. Maximum runoff rates in monitoring points HID1 and HID3.

Event ID	Date (dd/mm/yyyy)	Daily rainfall in demonstration area (mm)	Time to first output flow at HID1	Time to first output flow at HID3	Accumulated rainfall at HID3 for first output flow (mm)
05-06	18-19/10/2018	48.8-38.4	10 min	50 min	13.4
13-14	16-19/11/2018	22.2-14.4	NA	48 h	40
33	11/09/2019	37	NA	14 h	15

(*) NA: Not available due to equipment failure during the event.

Concerning the event occurred from 15 to 19 November 2018, rainfall rates in the region reached accumulated amounts of significant relevance (e.g. up to 630 mm in La Safor, south of the province of Valencia). In Benicàssim, the accumulated precipitation was much lower, with registers of 64 mm for the whole episode (4 days) and a total of 21 mm on 16 Nov, with 14 of them in the time interval from 5:00 to 7:00. However, the system did not show output flows downstream until 48 hours later, when the accumulated precipitation was 40 mm.

Finally, the event occurred on 11 Sep 2019 represents a good example of how the internal pattern of the rainfall episode is crucial for the demonstrator's hydraulic performance. Figure 10 shows the hyetograph of this event and the output hydrograph as an example. Since the initial moment of the event at 1:00 am and until approximately 3pm, rainfall intensities were very low (15 mm accumulated in 14 hours) without output flows from the system. From 3pm, the intensity increased, registering 15.4 mm in 35 min, and resulting in the first output flows at the final point (HID3). In the next hour, the episode presented lower intensities and hydrograph at the final point shows a delay of one hour between the end of the event and the last output flows.

Therefore, with this event, two conclusions that have already been pointed out are checked: first, in case of moderate rainfall intensities, the system is capable of managing precipitations up to 15 mm; second, the system significantly delays response times in the downstream point.

3.2.Water quality characterization

Regarding runoff water quality during the monitored events, the concentrations of pollutants presented great variability when comparing the conventional and the SUDS system.

From the four rainfall events with output flows downstream the system, three were also monitored for water quality characterization. In general, concentration of pollutants registered during this first flush at HID1 is very high when compared with the concentration rate at HID3.

For instance, during the event on 18 Sep 2018, the concentration of TSS at the end of the permeable pavement system (HID 3) was 81% lower than in HID 1 (from 58 mg/l to 322 mg/l). It means that the strong negative impact of urban runoff over the water bodies can be significantly reduced. In fact, permeable pavement serves as "treatment facility", reducing TSS to values close, for example, to 35 mg/l, the discharge requirement for effluent from wastewater treatment plants (Directive 91/271/ ECC).

The same applies for organic matter. Considering all the events, mean efficiencies, in terms of COD concentrations, are around 90%, from 120 to 8 mg/l. Both results, TSS and COD, confirm that the organic matter in runoff is in particulate form, so it is easily retained in pavement. This fact itself would justify the implementation of this type of infrastructure at large scale but, at the same time, we should reminder the importance of a proper maintenance programme.

Two interesting results regarding organic matter are the relationships BOD_{20}/COD and BOD_5/BOD_{20}. BOD_{20}/COD ratios close to 1 indicate a very high biodegradability; as the value tends to 0, lower biodegradability. In this case, HID 1 has a ratio of 0.33, showing that organic matter collected in the streets has a low biodegradability. The BOD_5/BOD_{20} ratio is an indicator of how fast/slow is the biodegradation process: as the ratio tends to 1, faster is the reaction (as reference, for organic matter in urban sewage is around 0.68). In HID 1, the ratio is 0.47, showing a low reaction velocity. Both factors, low and slow biodegradability, explain that dissolved oxygen was always high, both in HID1 as in HID3, with more than 80% saturation and that pH was in normal values between 7 and 9 pH units.

Trace metals were always in all samples below the threshold detection value, i.e. lower than 0.1 mg/l. Removal efficiency of E.coli was high, from 5.1 in HID 1 to 3.1 $\log_{10}$ units in all other monitoring points within the system (HID 2-3-4). The pavement, acting as a filter, reduced pathogens making runoff more suitable for irrigation purpose. Finally, TN and TP concentrations, although not especially high, are also reduced from HID1 to HID3. More concretely, TP from 0.45 to 0.26 mg P/l and TN from 2.9 to 1.5 mg N/l.

Based on reported water quality analyses, it can be affirmed that the infrastructure performance in terms of pollutant treatment was satisfactory. On the one hand, the concentrations of organic matter, nitrogen, phosphorus and E.coli were reduced when compared with the conventional system. On the other hand, it should be highlighted that the mass of these substances that can reach the receiving water body in each event is reduced. It should be noted that only 14% of the water volume entering the demonstrator reaches the downstream point, thus the remaining 86 % is managed by the system. Without the SUDS system, this amount of organic matter, nutrients, and other pollutants would reach the final receiving water body. In addition, outputs from the system have a smaller concentration than what it is observed upstream, which represents an additional reduction.

4. Conclusions

Sustainable Urban Drainage Systems (SUDS) constitute an effective alternative to conventional drainage for urban stormwater management. These techniques allow for a better water quantity and quality management, by decreasing the amount of water to be managed by the drainage system and reducing the amount of pollutants. In addition, SUDS provide additional ecosystem services which provide benefits beyond runoff treatment.

Main conclusions and key contributions of this study are here described:

- Main monitoring results from the demonstration case study developed in the framework of the LIFE CERSUDS project have been described and analysed in this paper. A total of 35 rainfall events were recorded during a monitoring period of 13 months, and only 4 of them reported output flows downstream the system. Hence, the system capacity for managing runoff at the demonstration site has been confirmed. It can be concluded from these results that the system performs as expected, allowing water infiltration and reducing the amount of runoff water that finally reaches the downstream drainage network.

- This study contributes to demonstrate hydraulic performance of the proposed permeable pavement solution, representing a novel design which promotes water and ceramic material reuse.
- The conducted work presented a main limitation being the available monitoring period (up to one year). A much longer record would be desirable in future studies to capture more precipitation events.
- Concerning replicability, the LIFE CERSUDS project included the analysis of potential application of the solution in other areas of Spain, as well as in Italy and Portugal. In fact, it is expected that the system will be replicated in Aveiro (Portugal) and Fiorano (Italy), two regions whose respective ceramic clusters stand out and where similar climatic conditions are found.

This new permeable pavement system will help to boost a more sustainable urban development, combining sustainable stormwater management and reuse of materials and water. This demonstration case study represents a reference example of urban retrofitting actions which integrate social, economic and environmental aspects.

Finally, some future research needs have been identified. First, further studies may focus on analyzing permeable pavement system performance in the long term and the impact of different maintenance strategies. Despite the existence of several studies showing monitoring results referring to permeable pavement performance over 10 years, investigations were conducted mainly in areas with climatic conditions that differ from conditions in Southern European regions. Currently, a long-term monitoring is being developed within the system to assess its behaviour regarding the evolution of surface permeability according to maintenance practices which basically may consist of dry sweeping. Second, despite the structure of most common permeable pavement configurations was initially designed years ago and applied, e.g. in the U.K. or Australia, there is still a need for further investigations on the effect of different system configurations on pollutant removal efficiency (e.g. type of subbase material, layer thickness of the subbase, etc.), mainly when new upper layer designs are considered.

Declarations

-Ethical Approval

Not applicable

-Consent to Participate

Not applicable

-Consent to Publish

Not applicable

-Authors Contributions

J.T. Castillo-Rodríguez is the main author, researcher of the LIFE CERSUDS project in the period Jan 2017- Sep 2019, collaborated in the design of the solution, conducting monitoring actions and analysis of results; thus, she was responsible for drafting the manuscript, and define its conception, design and content. I. Andrés-Doménech coordinated the UPV team as part of the LIFE CERSUDS project, and contributed to define the manuscript scope, review of the state-of-the-art and analysis and interpretation of results, and manuscript revision. M. Martín has contributed regarding water quality analysis and interpretation of data; I. Escuder-Bueno and S. Perales-Momparler contributed to review results regarding hydraulic performance of the solution; and J. Mira-Peidro, LIFE CERSUDS coordinator, has contributed in all aspects regarding the use of ceramic material and performance analysis of the final configuration of the proposed permeable pavement.

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-Competing Interests

Not applicable

-Availability of data and materials

All reports and documentation of the LIFE CERSUDS project is available on the website www.lifecersuds.eu

Acknowledgments

This research was developed within the LIFE CERSUDS project and was financed by the LIFE Programme 2014-2020 of the European Union for the Environment and Climate Action [Reference LIFE15 CCA/ES/000091] with the collaboration of the Generalitat Valenciana through IVACE.

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Figures

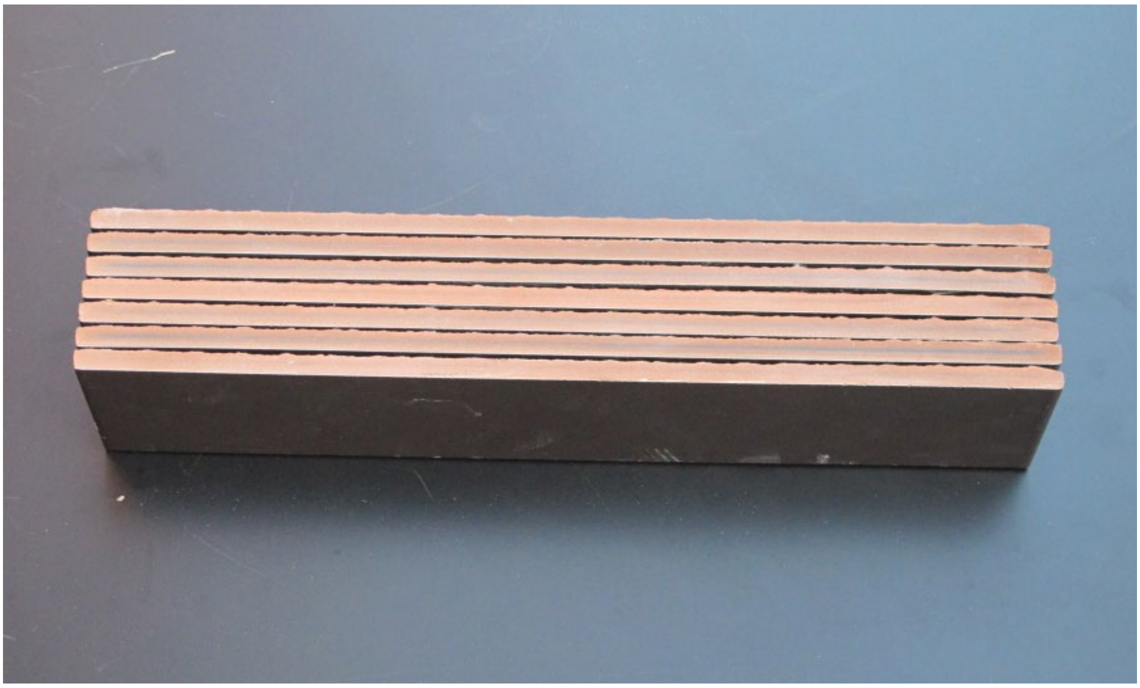

Figure 1. Ceramic permeable module (LIFECERSUDS project). Copyright: ITC-AICE.

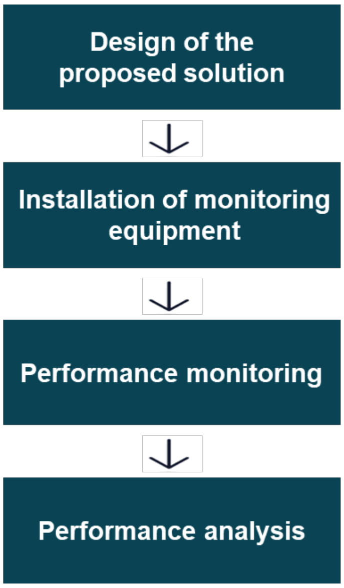

Figure 2. Stages of the research methodology

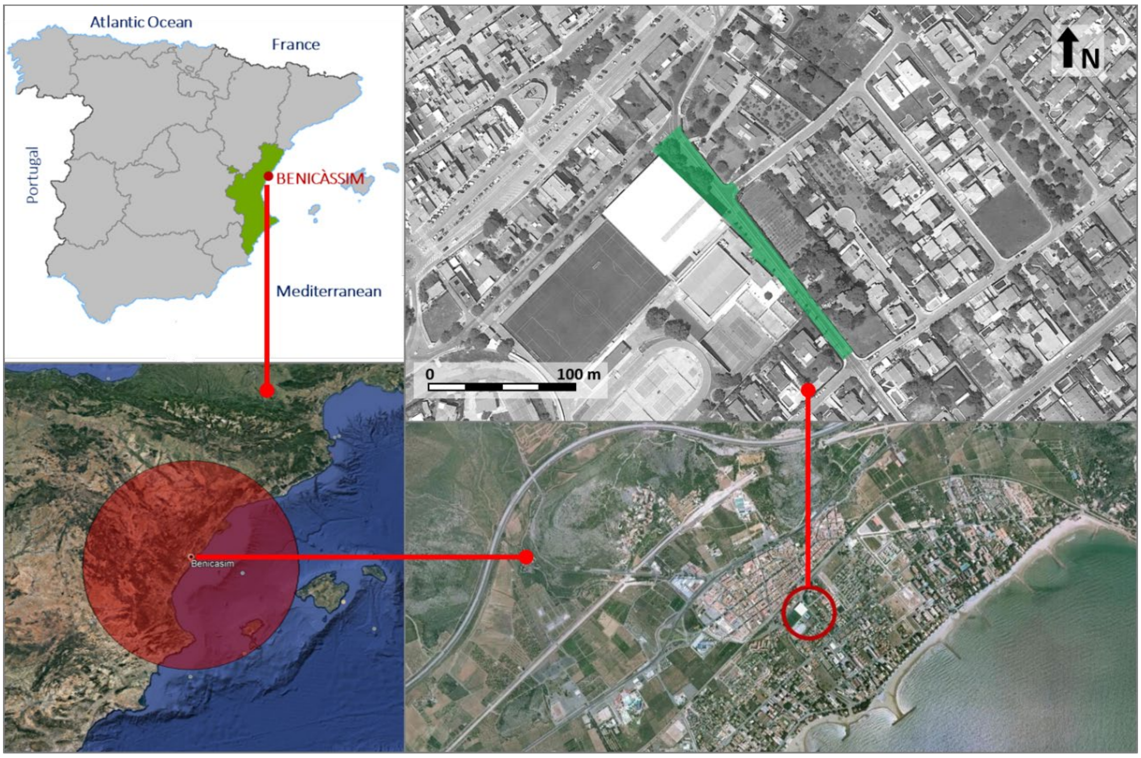

Figure 2. Location map of the study site: (upper-left) Benicàssim (Comunitat Valenciana, Spain); (down-left) influence area, and (right) demonstration site in Torre Sant Vicent street.

Figure 3. View of the urban retrofitting action executed in Benicàssim as demonstrator case. Copyright: Milena Villalba.

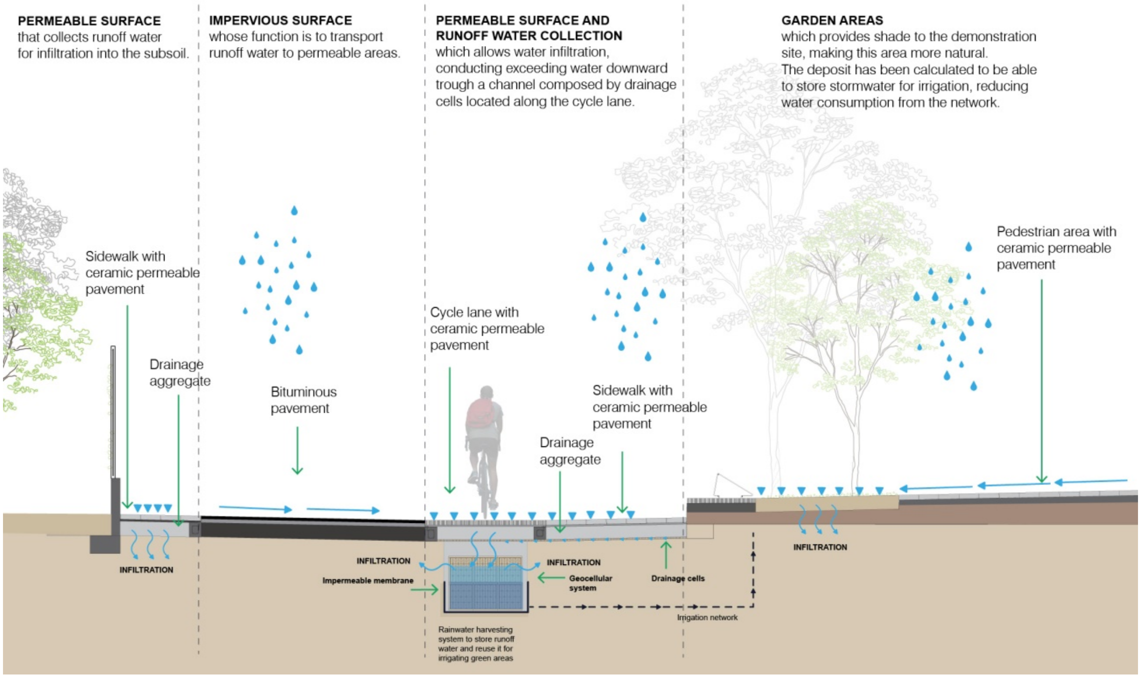

Figure 4. Scheme of the sustainable drainage system performed in Benicàssim (CERSUDS 2019).

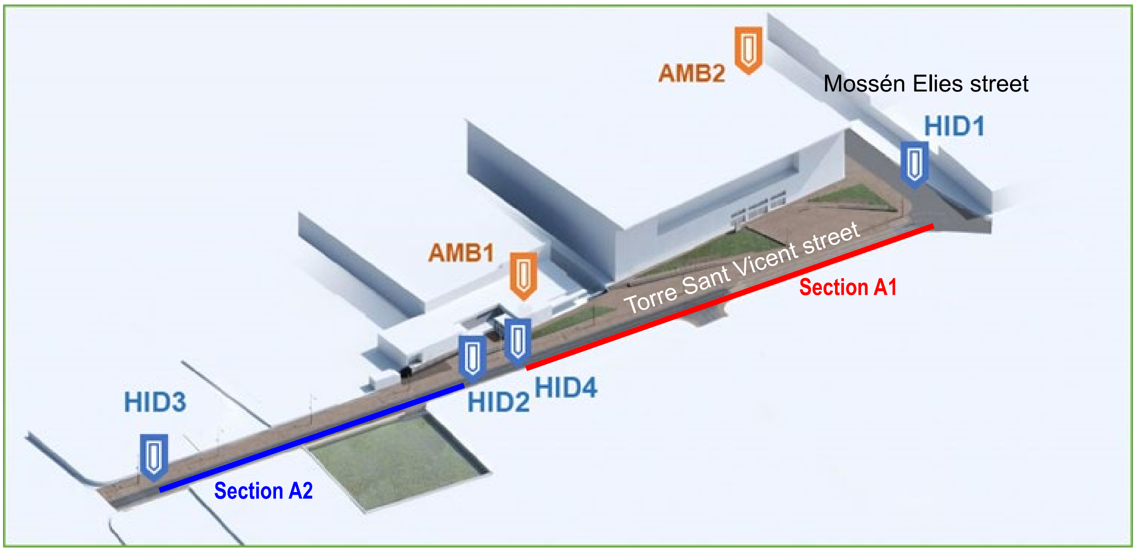

Figure 5. View of street sections and monitoring points.

Figure 6. Example of automatic sampler used for monitoring.

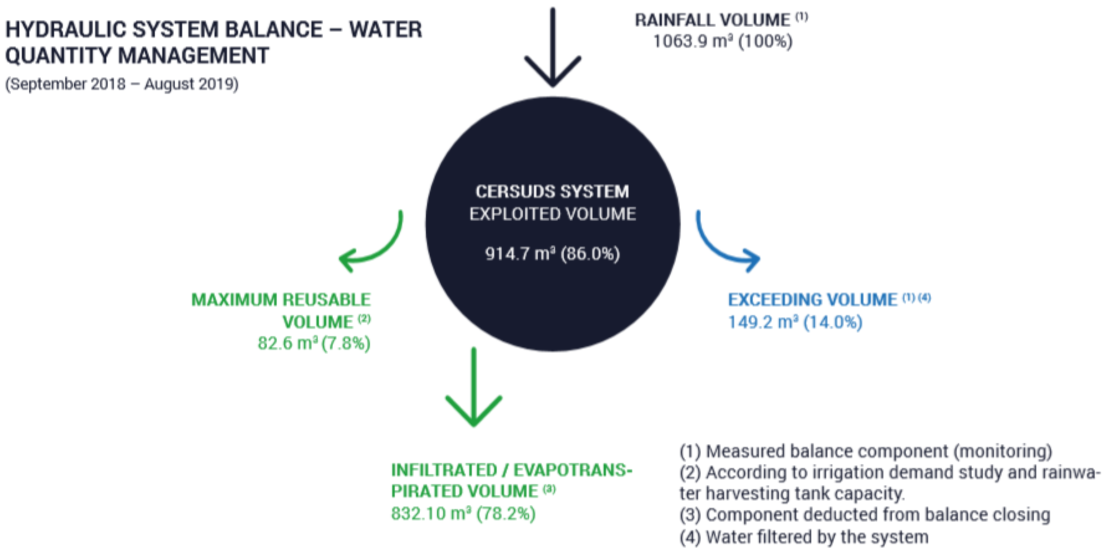

Figure 7. Volumetric balance of the system for the period September 2018 - August 2019 (CERSUDS 2019)

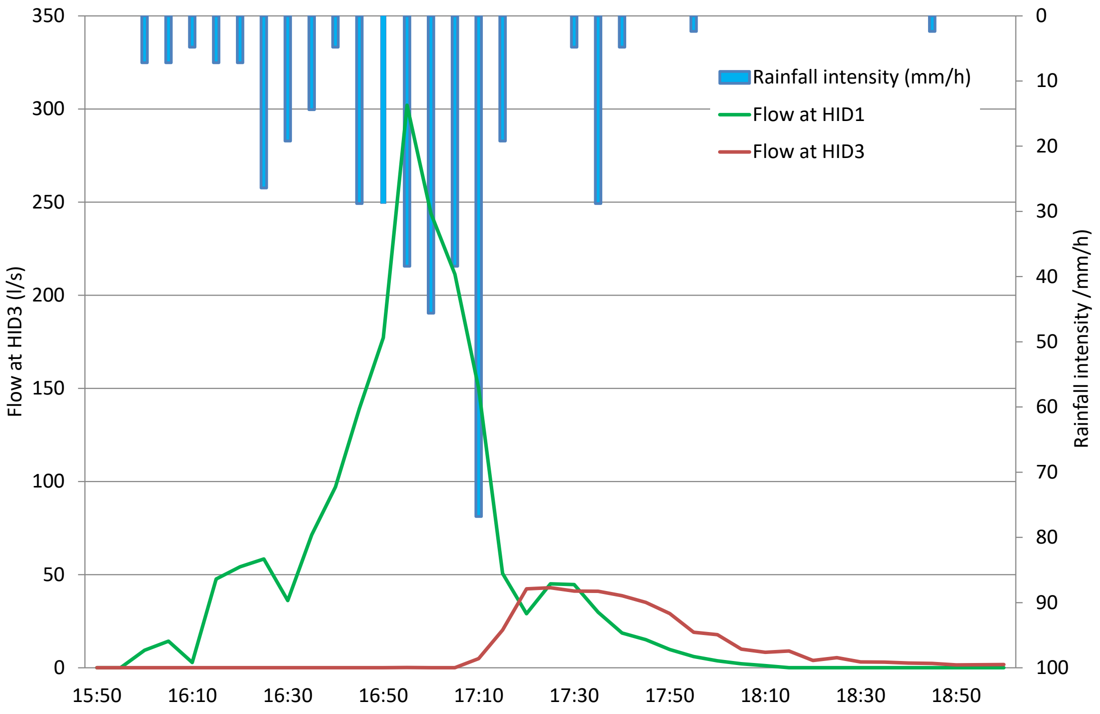

Figure 8. Hyetograph and hydrographs for the rainfall event registered on 18 Oct 2018.

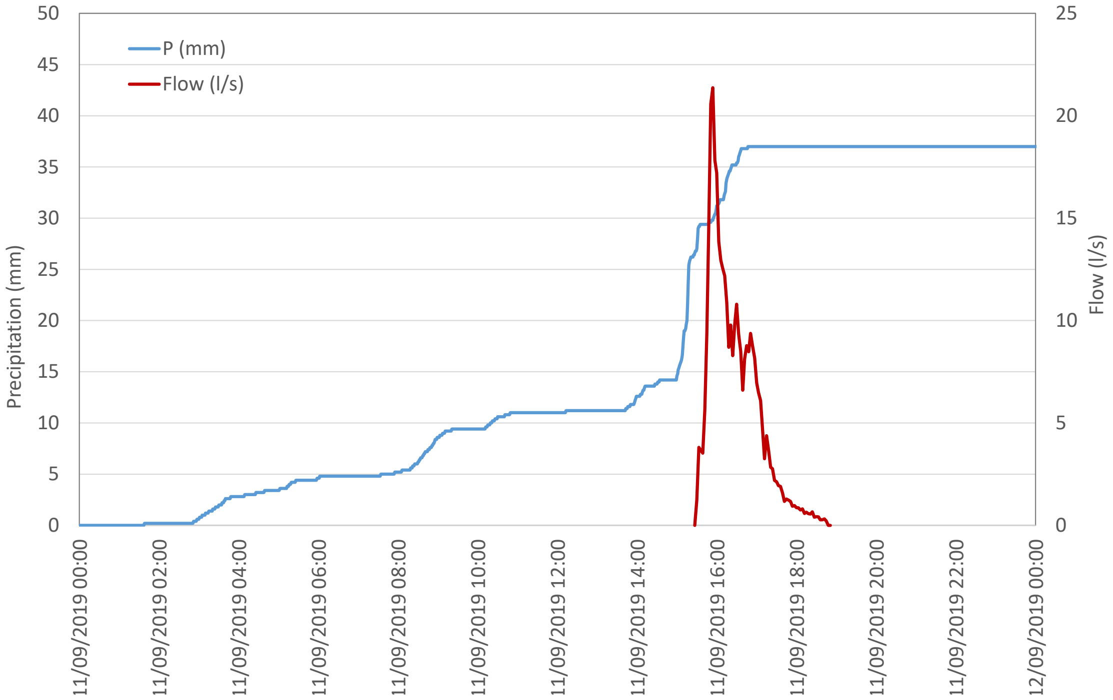

Figure 9. Hyetograph and hydrograph for the rainfall event registered on 11 Sep 2019.