Implementing underdrained permeable pavement for runoff reduction in shallow groundwater environments: Is it worthwhile?

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Abstract: Permeable pavement, equipped with an underdrain, is one of the most widely used and efficient types of green infrastructure. It can greatly reduce, delay, and retain surface runoff, given its high surface infiltration rate and storage volume; however, its performance in shallow groundwater environments is poorly understood. Based on the monitoring data of three underdrained permeable pavements in Hong Kong collected from April to November 2017, this study demonstrates and quantifies the impact of shallow groundwater on the hydrologic performance of permeable pavements. All of the permeable pavements achieved 70 % – 100 % and 90 % – 100 % in peak and volume reductions of surface runoff, respectively, for 90 % of the rainfall events, even after one year of service without maintenance. However, 4,000 – 10,000 mm of extraneous water – equivalent to three to six times the rainfall depth during the monitoring period – entered the reservoirs of two pavements and was discharged through their underdrains. The drawdown times of these two pavements, both of which were equipped with underdrains, were >24 and >72 hours for 35 % and 20 % of the rainfall events, respectively. Underdrains did not reduce drawdown times; instead, they discharged the extraneous water from the subsurface into the sewer system. These findings demonstrate the deficiency of underdrains and the need for careful underdrain design for permeable pavements in shallow groundwater environments. In areas of shallow groundwater, detailed site investigations are recommended. Underdrains, when needed, should be elevated and installed with flow restrictors to restrict their maximum outflow, and to strike a balance between drawdown time and underdrain outflow volume. The technical design of underdrain is demonstrated to be a key factor for green infrastructure in shallow groundwater environments; it should be more highlighted and detailed in the design guidance of green infrastructure.

Author keywords: green infrastructure; permeable pavement; stormwater management; underdrain; groundwater

1. Introduction

There is an increasing global focus on improved stormwater management to develop a flood-resilient, hydrologically restored, and environmentally healthy urban environment (Barbosa et al., 2012; Walsh et al., 2012). Green infrastructure (GI) can help to realize these objectives by enhancing infiltration and reducing the peak rate and volume of surface runoff, thus mimicking pre-developmental hydrologic conditions (Dietz, 2007; Roy et al., 2008; Ahiablame et al., 2012). In addition, GI offers various environmental benefits (e.g., pollutant removal and mitigation of the urban heat island effect) and promotes public health (Pugh et al., 2012; Shih, 2017; Zhang and Chui, 2018a; Bellezoni et al., 2021). "Green infrastructure" is analogous to other terminologies such as low-impact development, sustainable urban drainage systems, and water-sensitive urban design (Fletcher et al., 2015), which have been proposed in recent years alongside the global development of urban water management strategies (Brown et al., 2009). Common GI practices include permeable pavement (PP), bioretention cells, green roofs, and infiltration trenches (Fletcher et al., 2015).

PP has been widely adopted in recent years because of its advantages such as easy installation, high durability, low cost, and provision of parking and transportation (Booth and Leavitt, 1999; Imran et al., 2013). Although PP surfaces clog easily (Sansalone et al., 2012; Nichols et al., 2015), the problem can be remediated through improved selection of surface pavers, appropriate and frequent maintenance and rejuvenation, and other such practices (Chopra et al., 2009; Winston et al., 2016; Hu et al., 2020; Liu et al., 2021). Compared with other types of GI (e.g., bioretention cells and infiltration trenches), PP is often more applicable in stormwater management because it can be implemented by retrofitting impervious pavements (e.g., parking lots, low-traffic roads, sidewalks, and driveways) without requiring additional space (Scholz and Grabowiecki, 2007; Xie et al., 2019). Furthermore, although depending on the designs of practices and site conditions, PPs have been reported to be more efficient in runoff retention and reduction in some areas compared with practices such as green roofs and rain barrels (Ball and Rankin, 2010; Qin et al., 2013).

The hydrologic performance of PP, particularly in runoff peak and volume reduction, has been studied extensively (Legret et al., 1996; Horst et al., 2010; Lin et al., 2013; Lewellyn et al., 2015; Martin III and Kaye, 2016; Knappenberger er al., 2017), and the performances of different types of surface pavers (Bean et al., 2007; Collins et al., 2008, 2009) and subsurface materials (Bentarzi et al., 2016) have been compared. The application of PP in different climatic conditions (e.g., cold climates), topographic conditions (e.g., slopes) and soils (i.e., low-permeability soils) has also been widely evaluated (Fassman and Blackbourn, 2010; Drake et al., 2014; Palla et al., 2015; Huang et al., 2016; Winston et al., 2018). Shallow groundwater poses major restrictions, not only on PP but also on other infiltration-based GI practices (USEPA, 2012; Zhang and Chui, 2019). The enhanced infiltration facilitated by PP may become problematic, as it can lead to shallow groundwater contamination (Fischer et al., 2003; Datry et al., 2004). In addition, given the increased water potential beneath PP, surface infiltration and subsurface exfiltration can be inhibited, resulting in less exfiltration and greater surface overflow and underdrain flow (Locatelli et al., 2015; Zhang and Chui, 2017, 2018b; Zhang et al., 2018). However, compared with PPs on low-permeability soils, the hydrologic performance of PPs in shallow groundwater environments has been seldom reported.

In areas of low-permeability soil and shallow groundwater, some design guides recommended installing perforated pipes at the base of PPs to drain infiltrated stormwater (Eisenberg et al., 2013). The objectives of installing underdrains are to maintain the storage capacity and shorten the drawdown time of PPs. Studies have demonstrated that underdrained PPs can efficiently restore pre-development hydrologic conditions (Collins et al., 2008), even over relatively impermeable subsoils (Fassman and Blackbourn, 2010). Elevated underdrains can also create an internal water storage zone within PP reservoirs, which can promote anaerobic conditions and improve nitrogen removal efficiency (Braswell et al., 2018). However, underdrains also discharge outflows into drainage systems, which can affect the overall hydrologic benefit of PPs. The advantages and disadvantages of underdrains, especially for PPs in shallow groundwater environments, remains poorly understood.

To fill the research gap regarding the efficiency of PP and the necessity of installing underdrains in shallow groundwater environments, we collected seven-month monitoring data from three PPs in Hong Kong, including surface runoff, underdrain flow, and reservoir water depth. Using this dataset, we performed time series analysis to assess the hydrologic performance of underdrained PPs, including runoff reduction rate, water balance, and drawdown time. This study aimed at evaluating the hydrologic performance of permeable pavements in shallow groundwater environments, performing a comprehensive and critical analysis on the effectiveness of underdrain for permeable pavements, and inferring design recommendations for green infrastructure in shallow groundwater environments. This study addressed the following research and engineering questions:

I. How does shallow groundwater affect the runoff control, water balance, and drawdown of PP?

II. How can underdrains improve or affect the hydrologic performance of PP in shallow groundwater?

III. How can underdrains be installed effectively for PP in shallow groundwater?

2. Materials and method

2.1 Permeable pavement descriptions

Three PPs (each 30 m × 3 m) were laid at Shek Wu Hui Sewage Treatment Works (SWHSTW) and Stonecutter Island Sewage Treatment Works (SCISTW) in Hong Kong for vehicular usage. Two (Panels #1 and #2) were located at SWHSTW, and the third (Panel #3) was located at SCISTW. The laying of the PPs took place between July 2016 and January 2017. The location and layout of the PPs at the two sites are shown in Figure 1.

Each PP had two types of surface pavers and subbase designs (i.e., with/without underdrains or impermeable liners). More specifically, each PP was separated into two sections; for the smaller section (3 m in length), impermeable liners were used at the bottom and sides to minimize exfiltration (hereinafter referred to as partially exfiltrating PP), and the longer section (27 m in length) was unlined (hereinafter fully exfiltrating PP). The section that included impermeable liners was only partially exfiltrating because its base was not fully impermeable, even with the impermeable liners. A perforated underdrain pipe was installed in each of the partially exfiltrating sections (i.e., those with impermeable liners) to quickly drain water and empty the PP reservoir within a specific timeframe. The surface pavers used at SWHSTW were open cell pavers (OCPs; Panel #1) and porous blocks (PBs; Panel #2), and permeable interlocking concrete pavers (PICPs; Panel #3) were used at SCISTW. The pavers differed in terms of material, block size, and block shape; the OCPs, PBs, and PICPs were 400 mm × 400 mm × 80 mm, 200 mm × 100 mm × 80 mm, and 225 mm × 112.5 mm × 80 mm, respectively. The OCPs and PICPs themselves were impervious, but there were large gaps between the blocks that were filled with fine aggregates. The PBs were pervious, and openings were filled with coarse sand. Photographs of these three types of porous paver are shown at the top of Figure 2. The surfaces of the PPs sloped at 1 % toward the trench drain, and they were elevated by ~ 20 mm to prevent the influx of additional surface runoff from the surrounding impervious covers.

The subbase designs (i.e., depth and composition) of the PPs were the same at both sites. The total depths were 480 mm, comprising an 80 – mm surface paver, a 50 – mm fine aggregate layer (2 – 6 mm in diameter), a 200 – mm hydraulically bound coarse aggregate (HBCA) layer, and a 150 – mm coarse aggregate layer (4 – 20 mm in diameter) at the bottom. The HBCA layer was a mixture of aggregate, cement, water, and chemical admixtures (i.e., retarders and hydration stabilizers), which was designed to provide adequate support for vehicular traffic loading while allowing water percolation. Geotextile was installed between the fine aggregate and HBCA layers, surrounding the underdrain, and at the bottom of the coarse aggregate layer; this aimed to prevent fine aggregate mixing with the HBCA layer and avoid clogging in the perforated underdrains. The detailed designs of the PPs at both sites are shown schematically in Figure 2 and illustrated in Table 1.

The permeability of the subsoil at SWHSTW was measured before the PPs were laid, whereas that in the surrounding soil at SCISTW was measured after PP laying. Permeability was measured on site using Guelph and single-ring permeameters, and soil sample particle sizes were determined using mechanical sieves and laser particle size analyzer in the laboratory. As shown in Figure 2 and Table 1, the subsoil at SWHSTW was clayey with a smaller grain size (D10 of 0.07 mm; D60 of 2 mm) and lower permeability (0.7 – 9.5 mm/h) than that at SCISTW, which was sandy with a larger grain size (D10 of 0.4 mm; D60 of 6 mm) and higher permeability (60.5 – 789.6 mm/h).

2.2 Data collection

All the data involved, including precipitation, runoff, underdrain flow, and PP reservoir water depth, was collected in this study. The PPs received only direct surface rainfall, with no additional surface runoff from the surrounding areas. The surface runoff from the PPs was drained to the nearby equipment bay through a trench drain (red dashed lines in Figure 1). The underdrain flow generated from the partially exfiltrating sections was also collected. The flows were measured using water level dataloggers (model HOBO U20L) inside weir boxes in the equipment bays. More specifically, the water level dataloggers first measured the water depth, then the flow rates were calculated based on rating curves determined in the laboratory. A filter box was installed atop each weir box to remove leaves, debris, and aggregates in the surface runoff, and fine sand and clay in the underdrain flow, to prevent blockages in the weir boxes (Figure 2).

Several monitoring wells were installed within the PPs, in which the water depths of PP reservoirs were measured using water level dataloggers. In total, four, four, and five sensors were installed in Panels #1–#3, respectively; one was within the partially exfiltrating section and the others were within fully exfiltrating sections. The locations of the observation wells are marked as blue circles in Figure 1. Owing to site-access constraints, the nearby groundwater table was not monitored. However, the underdrain flow and drawdown time of the water storage inside the PPs can be used to infer the existence and potential impact of shallow groundwater. Rainfall was monitored at both sites using tipping bucket rain gauges (locations marked as orange circles in Figure 1). All data had a temporal resolution of 1.5 min from March 30 to October 31, 2017, which covers the wet season in Hong Kong.

The inter-event time was assumed to be six hours, which is consistent with previous studies (Dunkerley, 2010; Joo et al., 2014). This means that two consecutive rainfall events were deemed as separate events when the dry period between them was equal to or greater than six hours. A total of 81 and 95 rainfall events were captured at SWHSTW and SCISTW, respectively, during the observation period. The rainfall characteristics differed slightly between the sites, resulting in different numbers of events being captured at each site. However, as shown in Figure 3, the general rainfall patterns were similar. Data were not captured during some events (i.e., on April 14, June 13, and July 12), owing to equipment failure, which also contributed to the difference in captured events.

2.3 Data analysis

First, the time series characteristics of precipitation, surface runoff, underdrain flow, and reservoir water depth were evaluated. Continuous wavelet transform (CWT) was performed, and the wavelet power in the time–frequency domain was calculated to investigate the time–frequency characteristics of the time series. Compared with Fourier transform, CWT better represents non-stationary time series that experience high oscillation at fine temporal scales; CWT calculates the convolution of the time series using the shifted and scaled mother wavelet Ψ (Eq. 1). This is identical to applying the wavelet to the time series as a bandpass filter. In doing so, CWT converts the data from one-dimensional to multi-dimensional through scaling and shifting. A "Morlet" mother wavelet was selected, given its validity in representing hydrological timeseries (Labat et al., 2000; Zhang and Chui, 2018b).

$$W_n^X(s) = \sqrt{\frac{\delta t}{s}} \sum_{n'=1}^{N} x_{n'} \psi_0\left[(n' - n)\frac{\delta t}{s}\right] \quad (1)$$

where ψ_0 is the complex conjugate of the scaled mother wavelet; s is the wavelet scale at which the transform is performed; x_n is the time series with a length of N and interval of δt.

The rainfall events during the seven-month monitoring period were extracted as described above, using a six-hour inter-event dry period. The dry periods between events were deemed part of their preceding rainfall events. As such, the hydrologic performance of the PPs can be more robustly assessed and compared, as the likelihood of including underdrain flow or other variables from the former event in the latter event is reduced.

The peak rainfall intensity, total rainfall depth, and 10-day pre-event cumulative rainfall depth (PRD) before each rainfall event were calculated. The PRD represents the wetness of the surrounding soil and pavement surfaces, and a length of 10 days was considered suitable given the "memory" of soil moisture in urban landscapes (Zhang et al., 2015; Escorihuela and Quintana-Seguí, 2016). In addition, the hydrologic performance indicators (i.e., volume and peak intensity of surface runoff and volume of underdrain flow) for each rainfall event were calculated. Then, the peak reduction (PR) and volume reduction (VR) of surface runoff were further calculated using Eqs. 2 and 3, respectively. The outflow-to-rainfall volumetric ratio (RO), representing the ratio of the total volume of surface runoff and underdrain flow to rainfall volume, was calculated for each rainfall event using Eq. 4. The drawdown times of the PP reservoirs were also calculated, i.e., the times at which the PP reservoir was emptied (reservoir water depth < 5 mm). The drawdown was deemed to have ended if the PP reservoir was not emptied by the end of a rainfall event. Together, these indicators reflect different aspects of the hydrologic performance of PPs.

$$PR = \frac{\max_t R_t - \max_t SR_t}{\max_t R_t} \quad (2)$$

$$VR = \sum_{t=0}^{T} \frac{R_t - SR_t}{R_t} \quad (3)$$

$$RO = \sum_{t=0}^{T} \frac{SR_t + UF_t}{R_t} \quad (4)$$

where PR and VR are the peak reduction and volume reduction of surface runoff (%), respectively; RO is the outflow-to-rainfall volumetric ratio; T is the duration of the rainfall event (h); and SR_t, UF_t, and R_t represent surface runoff rate (L/h), underdrain flow rate (L/h), and rainfall intensity (L/h), respectively.

During this study, the surface runoffs from both fully and partially exfiltrating PPs were drained to the same trench drain and were thus measured altogether. As such, the PR and VR values of fully and partially exfiltrating PPs cannot be distinguished and compared. However, the underdrain flow was only measured for partially exfiltrating PPs, and the reservoir water depths in both types of PP were measured independently, allowing comparison of their RO and drawdown times.

3. Results

3.1 Time series analysis

Figure 3 shows the time series data for all three PPs over the study period. Compared with Panels #1 and #2, Panel #3 performed better in reducing the peak of surface runoff. For example, for the rainfall events on June 13, July 4, and July 18, the peak intensities of surface runoff were 85, 64, and 38 mm/h in Panel #1 and 41, 47, and 44 mm/h in Panel #2, respectively, but only 22, 4, and 5 mm/h in Panel #3 (Figures 3a and 3b).

The peak intensity of underdrain flow was somewhat comparable among the three PPs. For the rainfall events on June 13, the peak intensity of underdrain flow was higher in Panel #1 (239 mm/h) and lower in Panels #2 (60 mm/h) and #3 (121 mm/h). In contrast, for the events on July 4 and July 18, the peak intensities were 45 and 53 mm/h in Panel #1, 39 and 73 mm/h in Panel #2, and 21 and 64 mm/h in Panel #3, respectively (Figure 3b). However, the patterns of underdrain flow for Panels #1 and #2 differed markedly from that of Panel #3. For Panel #3, the underdrain flow hydrograph was similar to that for surface runoff, and the underdrain flow decreased quickly after the rainfall peaks. However, the underdrain flow hydrographs for Panels #1 and #2 clearly showed slow recessions at the tails of the hydrographs, indicating that underdrain flow was generated continuously during the dry periods after rainfalls (Figure 3c). Therefore, although the peak intensity of underdrain flow in Panels #1 and #2 was comparable to that of Panel #3, the depth of underdrain flow in these two panels may be greater. Using the event on July 4 as an example, although the peak intensity of underdrain flow was comparable among the three PPs, the underdrain flow depths were 265 and 231 mm in Panels #1 and #2, respectively, but only 10 mm in Panel #3.

The hydrographs for reservoir water depth in Panels #1 and #2 also differed from that in Panel #3. The reservoir water depth in Panel #3, especially in the fully exfiltrating section, was low with substantial noisy data due to the relatively large sensor errors when measuring low water pressure. In comparison, the reservoir water depths in Panels #1 and #2 were much higher. In addition, the reservoir water depths in Panels #1 and #2 experienced slower drawdown than that in Panel #3, which is consistent with the hydrographs for underdrain flow. Using the event on July 18 as an example, the peak reservoir water depths for fully exfiltrating PPs in Panels #1 and #2 were 264 and 379 mm, but that for Panel #3 was only 9 mm. Drawdown in Panels #1 and #2 took 82 and 81 hours, respectively, whereas that in Panel #3 took only one hour (Figure 3d).

The difference in patterns of underdrain flow and reservoir water depth between Panels #1 and #2 and Panel #3 can be more clearly seen from the June 12 – July 30 time series shown in Figure 4. This period was specifically chosen for analysis because of its more extreme rainfall events and greater responses of runoff and underdrain flow. For example, although only minor rainfall occurred between June 13 and 17 and between July 16 and 25, the PP reservoir was never emptied (Figure 4d-1 and 4d-2) and there was consistent underdrain flow, particularly in Panel #1 (Figure 4c-1 and 4c-2). Using June 13 – 17 as an example, with only 37.2 mm of rainfall on Jun 14 and June 15 – 16, the rate of underdrain flow was consistently ~ 5 mm/h after rainfall for ~ 10 days, and its depth was 1234.2 mm over this period. This was markedly different from Panel #3, in which the underdrain flow showed a rapid response to rainfall and decreased quickly, with almost no underdrain flow during the dry periods between events (Figure 4c-1).

The hydrographs for reservoir water depths in partially exfiltrating Panels #1 and #2 showed different responses to rainfall, but they recessed to similar levels and fluctuated together after drawdown. As shown in Figure 4d-1 and 4d-2, during the rainfall events on June 13 and July 4, the partial-exfiltrating PPs in Panels #1 and #2 initially increased to different levels. However, after the rainfall, they recessed at different rates and reached similar levels after approximately 1 day and then fluctuated together; this similarity in water depth hydrographs was not observed for Panel #3.

3.2 Wavelet analysis

To further compare the hydrologic performance of different PPs, the wavelet power spectra of the datasets were obtained, as shown in Figure 5. Consistent with the time series shown in Figure 3, surface runoff in Panels #1 and #2 was generated mostly around June – July, as shown by the high and significant wavelet power during that period. Compared with rainfall, the surface runoff in Panels #1 and #2 fluctuated at coarser temporal scales over the same period (Figure 5a-1, 5a-2, 5b-1, and 5b-2). For Panel #3, the spectrum of surface runoff was very similar to that of rainfall; surface runoff was generated relatively uniformly throughout the period (Figure 5a-3 and 5b-3). Overall, the time-averaged wavelet power spectra of rainfall and surface runoff were very similar among the PPs (Figure 5a-4 and 5b-4).

In comparison, the differences in wavelet powers of underdrain flow and reservoir water depths among the PP panels were more significant. Compared with Panel #3, the wavelet powers of underdrain flow and reservoir water depths for Panels #1 and #2 were significantly greater (Figure 5c-1 – 5c-3, 5d-1 – 5d-3, and 5e-1 – 5e-3). Large regions of high wavelet power of underdrain flow were observed during the wet season (i.e., June – September). Given the very low water depth in Panel #3 (as shown in Figures 3d, 4d-1, and 4d-2), the reservoir water depth in the panel fluctuated at finer temporal scales, and noisy data were common at fine temporal scales due to errors in the water level dataloggers (Figure 5d-3 and 5e-3).

The differences among panels can be more clearly seen from the time-averaged wavelet powers shown in Figure 5c-4, 5d-4, and 5e-4. The wavelet powers of underdrain flow and reservoir water depths for Panels #1 and #2 were very similar, and their wavelet powers at temporal scales coarser than 50 hours were significantly greater than that of Panel #3. This is consistent with Figure 4, which shows that the underdrain flows and reservoir water depths of Panels #1 and #2 had longer-term fluctuations than those in Panel #3.

3.3 Hydrologic performance analysis

3.3.1 Runoff reduction

Figures 6 illustrates the performance of the PPs with respect to runoff control, represented by the runoff peak reduction (PR) and runoff volume reduction (VR). The PR and VR of the three PPs were high and comparable ($0.25 < p < 0.60$ for PR; $0.35 < p < 0.69$ for VR). For > 90 % of the rainfall events, the PR was between 70 % and 100 % (Figure 6a and 6b), and the VR was between 90 % and 100 % (Figure 6c and 6d). In contrast, the PR and VR were slightly higher and their ranges of variation smaller in Panel #3 due to its better runoff reduction during extreme rainfall events. As shown in the exceedance probability graphs (Figure 6a and 6c), the PR and VR in Panel #3 are slightly lower than those of Panels #1 and #2 for exceedance probability ranges of 0 % – 40 % and 0 % – 60 %, respectively, whereas they are greater when the exceedance probability exceeds 40 % and 60 % for PR and VR, respectively. The smaller range of variation in the PR and VR in Panel #3 is represented by the thinner boxes shown in Figure 6b and 6d.

Figure 7 further illustrates the temporal variation of PR and VR and their relationship with RD and PRD. Overall, both PR and VR were lower during wetter periods, especially between June and August when there were frequent continuous rainfall events. This was reflected in the greater RD and PRD values during that period (Figure 7a). Compared with VR, which was relatively stable, PR showed greater variation during the monitoring period, especially for Panels #1 and #2. During October, in which very little rainfall was recorded and pavement surfaces were dry, the VR in Panels #1 and #2 was close to 100 %, but the PR of corresponding events ranged from 50 % to 100 % (Figure 7b and 7c). The PR was lower overall for more extreme rainfall events, forming a negative relationship between PR and rainfall depth ($R^2 = 0.42$ and 0.27, RMSE = 13.54 and 14.19 for Panels #1 and #2 respectively). The PR for Panels #1 and #2 dropped from 90 % – 100 % to 40 % – 50 % when rainfall depth increased from 1 – 10 mm to around 100 – 200 mm (Figure 7d). The VR was also lower for rainfall events with greater depth, but the correlation was not statistically significant ($R^2 = 0.09$ and 0.03, RMSE = 4.20 and 3.77 for Panels #1 and #2 respectively). The VR for Panels #1 and #2 also dropped from 90 % – 100 % to ~ 50 % when rainfall depth increased from 1 – 10 mm to 100 – 200 mm (Figure 7e). In contrast, the PR and VR in Panel #3 were not as sensitive to rainfall depth, which remained at around 70 % – 100 % for almost all the rainfall events (Figure 7d and 7e).

3.3.2 Water balance

Figure 8 illustrates the outflow-to-rainfall volumetric ratio (RO; Figure 8a and 8b) in the three PPs. The result is consistent with the observations made in the time series shown in Figures 3 and 4. For Panel #3, the RO remained around or lower than 1 for most of the rainfall events because the underdrain flow responded quickly to rainfall and subsequently decreased (Figure 8a and 8b). In contrast, the RO was significantly larger for Panels #1 ($p < 0.01$) and #2 ($p < 0.01$) because of the large amount of underdrain flow during dry periods. The 75th percentiles of RO for Panels #1 and #2, represented as the sides of the boxes, were around 7.5 and 2 respectively, and the RO reached 35 – 45 and 10 – 25 in Panels #1 and #2, respectively, during some rainfall events (Figure 8b).

The total depths of rainfall and outflow during the monitoring period are summarized and illustrated in Figure 8c. Rainfall is shown as positive values, whereas outflow is denoted by negative values. In Panel #3, the outflow depth was lower than that of the rainfall; this difference may be due to factors such as exfiltration and evapotranspiration. However, in Panels #1 and #2, the outflow depths were significantly larger than those of rainfall. The outflow depths during the monitoring period, which consisted of 92 % – 94 % underdrain flow and 6 % – 8 % surface runoff, were around six and three times the rainfall depths for those two panels, respectively. For some rainfall events, the outflow depth even measured dozens of times the rainfall depth (Figure 8a and 8b).

Figure 9a further illustrates the temporal variation of RO during the monitoring period. The RO was highest during May–August for all three PPs. The highest RO in the three PPs occurred in May, August, and June for Panels #1, #2, and #3 respectively. No significant relationship was observed between total rainfall depth and RO (R^2 = 0.02, 0.004, and 0.004, and RMSE = 53.78, 25.50, and 0.29 for Panels #1, #2, and #3 respectively). In Panels #1 and #2, for rainfall events of a few millimeters in depth, the RO was 100 – 150 and 20 – 30 in Panels #1 and #2, respectively (Figure 9b). However, although not statistically significant (R^2 = 0.006 and 0.04, and RMSE = 54.08 and 25.01 for Panels #1 and #2 respectively), RO was greater when the 10-day pre-event cumulative rainfall was greater, especially in Panels #1 and #2 (Figure 9c). For rainfall events that had less than a few millimeters cumulative rainfall before the events, the RO was mostly around 1 – 2 for Panels #1 and #2 and <1 for Panel #3. During rainfall events that had 10 – 100 mm prior cumulative rainfall, the RO was in the range of 1 – 100 for Panels #1 and #2 (Figure 9c).

3.3.3 Drawdown time

The drawdown time of the PP reservoirs is shown in Figure 10. For the fully exfiltrating Panel #3, the drawdown times of 80 % and 97 % of the rainfall events were less than 24 hours and 72 hours (Figure 10a), which are normally the design thresholds for a PP. However, the drawdown times were significantly longer in Panels #1 ($p < 0.01$) and #2 ($p < 0.01$). The drawdown times of around 35 % and 20 % of the rainfall events in Panels #1 and #2 were greater than 24 hours and 72 hours, respectively (Figure 10a and 10b). The drawdown time even reached > 200 hours for some events. The lower permeability of the clay soils beneath Panels #1 and #2 compared with those below Panel #3 (i.e., permeability of 0.7 – 9.5 mm/h versus 60.5 –

789.6 mm/h) may be one of the causes of the longer drawdown times. Although underdrains were installed in the partially exfiltrating PPs, their drawdown times were very similar to those of fully exfiltrating PPs without underdrains (p = 0.69, 0.86, and 0.54 for Panels #1, #2, and #3 respectively; Figure 10a and 10b).

Figure 11 illustrates the temporal variation in drawdown times during the monitoring period. Rainfall events with long drawdown times occurred throughout the period with no significant temporal variation. The drawdown time for all PPs was slightly lower during the wet periods between June and August. This was because the frequency of rainfall events was higher during that period; for most rainfall events during this period, the PP reservoirs were not completely empty by the end of the event (Figure 11a and 11b). The drawdown time of the partially exfiltrating section of Panel #3 correlated with rainfall depth to an extent (R^2 = 0.26, RMSE = 40.54; Figure 11c), whereas weaker correlation with rainfall depth was observed for Panels #1 and #2 (R^2 = 0.006 and 0.008, and RMSE = 77.34 and 76.67 for the partially exfiltrating sections of Panels #1 and #2, respectively; R^2 = 0.007 and 0.01, and RMSE = 76.97 and 74.84 for the fully exfiltrating sections of Panels #1 and #2, respectively). No significant relationship was observed between 10-day pre-event cumulative rainfall depth and drawdown time in any of the three PPs because their reservoirs were not completely emptied following several events, as mentioned above (R^2 = 0.03, 0.02, and 0.01, and RMSE = 76.52, 76.11, and 46.53 for partially exfiltrating PPs; R^2 = 0.02, 0.03, and <0.01, and RMSE = 76.29, 74.22, and 25.04 for fully exfiltrating PPs; Figure 11e and 11f).

4. Discussion

4.1 Effect of shallow groundwater on the hydrologic performance of permeable pavements

All PPs achieved 70 % – 100 % and 90 % – 100 % in peak and volume reductions on surface runoff for 90 % of the rainfall events, even after one year of service without maintenance. Similar runoff reduction performance was reported elsewhere (LeFevre et al., 2010; Liu and Chui, 2017), but the performance was higher than some other underdrained PPs (Drake et al., 2014; Alam et al., 2019). This high runoff reduction rate may be partially attributable to the high permeability of the surface pavers (Li et al., 2013). Despite no maintenance being conducted during the monitoring period, the surface pavers were not significantly clogged and remained functional owing to the relatively low traffic load at these sites. PPs with similar long-term durability and consistency in runoff reduction were reported (Brattebo and Booth, 2003). However, lower permeability and poorer performance is expected after few years of operation without proper maintenance (Bean et al., 2007; Sansalone et al., 2012; Chen et al., 2020). In addition, the runoff reduction rate is also expected to decrease with the increase of rainfall intensity (Qin et al., 2013; Liu and Chui, 2017), increase in surface slope (Palla et al., 2015; Hou et al., 2019), and the increase in spatial scale of concern (Hu et al., 2018; Bell et al., 2020).

There are several indications that Panels #1 and #2 were affected by subsurface water environments, such as soil moisture and nearby shallow groundwater. Continuous underdrain flow generated in the days following rainfall events in Panels #1 and #2 resulted in large amounts of underdrain flow (92 % – 94 % in water balance; six and three times the rainfall depths for Panels #1 and #2, respectively), which indicates that external subsurface water flowed into the pavement systems and was discharged through underdrains. The depths of the observed underdrain flows were comparable to the numerical simulation results obtained by Zhang et al. (2018). They considered groundwater conditions in the simulation of GI and quantified the water budget of PPs in respect to different rainfall events, surrounding soils, and groundwater table depths, and found that underdrain flow accounted for 79 % – 93 % of the outflow. Although the specific sources of this extraneous flow cannot be tracked accurately owing to the lack of soil moisture or groundwater level data, this substantial extraneous flow might have been derived from either infiltrated stormwater from pervious covers in proximity to the PPs or from groundwater when there is a positive pressure gradient toward the pavement reservoir (Herrera, 2013; Brown and Borst, 2014; Zhang and Chui, 2019). Some of the extraneous flows could have been derived from a perched groundwater table formed by low-permeability clayey soils in proximity to the PPs (e.g., Panels #1 and #2) (Schlea et al., 2014). However, considering the substantial amount of extraneous water, it more likely came from shallow groundwater.

The groundwater table rose in response to low dissipation rates during rainfall events (Locatelli et al., 2015; Jackisch and Weiler, 2017; Zhang and Chui, 2017).

Although the slow drawdown for fully exfiltrating PPs may be due to the low-permeability clayey soils near Panels #1 and #2, the slow drawdown for partially exfiltrating PPs with underdrains indicates that there was high soil matric potential near the PPs. Furthermore, the consistent fluctuation of reservoir water depth hydrographs after rainfall events in the partially exfiltrating sections of Panels #1 and #2 demonstrate that the pavements may be hydraulically connected to shallow or perched groundwater formed by low-permeability soils.

4.2 Impact of underdrains on the hydrologic performance of permeable pavements

The high runoff reduction rates of the PPs observed in this study may be partially attributable to the installation of underdrains in partially exfiltrating PPs in addition to the use of high-permeability surface pavers. By discharging the stored water more quickly, underdrains can, to an extent, help maintain the storage capacity of PPs in preparation for consecutive rainfall events (Qin et al., 2013; Zhang and Chui, 2020). The effectiveness of underdrains in increasing storage capacity and reducing peak flow has been demonstrated by several studies (Collins et al., 2008; Drake, 2013; Zhang and Chui, 2020). However, the results of the present study demonstrate that the drawdown time was still >24 and >72 hours for 35% and 20% of the rainfall events, respectively, in partially exfiltrating PPs with underdrains. In other words, although underdrains reduced the peak reservoir water depth, they did not efficiently empty the PP reservoirs and maintain drawdown times within design standards (Eisenberg, 2013) when the groundwater table was shallow.

The underdrains used in this study contributed 92 % – 94 % of the outflow, constituting both stormwater and groundwater, the depth of which was three to six times that of the rainfall during the monitoring period. Although most of the flow was of a low rate, its volume was surprisingly large. In addition, although the flow is drained into sewer systems instead of onto the ground, this takes up a certain amount of the drainage and storage capacity of the sewer systems and increases the risk and frequency of system over-capacity (Zhang et al., 2018; Zhang and Chui, 2019). This problem may not be as severe for separate stormwater systems because most of the underdrain flow occurs during dry periods and act as base flows, as shown in Figures 3 and 4. However, this may be more problematic for combined sewer systems because the water is combined with sewerage and drained together to wastewater treatment plants. It can induce pulses in the volume and nutrient concentration of the inflows, and thus affect their treatment effectiveness (Weiss et al., 2002; Ellis and Bertrand-Krajewski, 2010; Zhang et al., 2017; Razaee and Tabesh, 2022).

4.3 Implications for the design of permeable pavements

As demonstrated in this study, PPs are efficient stormwater management practices, given their high surface permeability and runoff reduction rates. They present a useful GI option, especially for locations that require pavers (e.g., parking lots), have surface runoff with limited pollution and containing few solids, or that are accessible for appropriate maintenance. However, the discharge of infiltrated stormwater and groundwater through underdrains into sewer systems and the deficiency of underdrains in shortening the drawdown times of PPs observed in this study raise questions regarding (1) whether implementing underdrained PPs in shallow groundwater environments is worthwhile, and (2) the appropriate designs for PPs in shallow groundwater environments should they need to be implemented.

Although the limitations of underdrained PPs are demonstrated in this study, their effectiveness cannot be ignored. The adoption and design of underdrains in PPs in shallow groundwater environments should consider not only climatic factors (e.g., rainfall characteristics) but also hydrogeologic conditions (e.g., soil types, groundwater table conditions), given the distinct hydrologic performances of the PPs in the two studied locations. The permeability of surrounding soils is normally the main limiting factor in the infiltration process (Warnaars et al., 1999; Zhang and Chui, 2020), and soil type and groundwater table conditions can determine the risk of extraneous flows and the drawdown rate/time of the system (Maimone et al., 2011; Nemirovsky et al., 2015). Detailed investigations (e.g., groundwater table depth measurements, soil taxonomic tests, and permeability tests) are recommended to determine the hydrogeologic conditions of a site, which control the GI performance in a complex and dynamic manner (Jackisch and Weiler, 2015). For areas without shallow groundwater or low-permeability soils, underdrains are not especially necessary if the drawdown time is within an acceptable range, based on estimations from physical and/or numerical experiments. For areas with shallow groundwater, low-permeability soils, or shallow impermeable bedrock layers, an underdrain is normally necessary, but it should be elevated to allow some exfiltration and to reduce the amount of groundwater discharge through the underdrain (Zhang et al., 2018; Zhang and Chui, 2020). Elevated underdrains may also create an internal water storage zone, which has proved beneficial for both water quantity (e.g., allowing exfiltration) and quality control (e.g., nitrogen removal) (Collins et al., 2008; Fassman and Blackbourn, 2010; Braswell et al., 2018). The specific elevation of underdrains needs to be determined on a case-by-case basis upon consideration of groundwater table elevation, soil permeability, and rainfall characteristics. Overall, higher underdrains should be installed if the groundwater table is high, the soil is more permeable, and the rainfall is less frequent. Flow restrictors can also be implemented in underdrains to restrict the maximum flow rate in these cases to strike a balance between runoff reduction and underdrain flow control. They have been recommended (GVRD, 2005) and demonstrated as being efficient by Drake et al. (2014) for areas with low-permeability subsoils.

In addition to field monitoring, as conducted in this study, computational tools such as numerical models can be useful prior to design and installation to determine the optimal designs for PPs. In addition to facilitating the selection of appropriate surface pavers, media materials, and thickness of the pavement subbase, pre-design computation can help to determine whether to install an underdrain, the elevation at which it should be installed, and whether a flow restrictor is necessary (Li et al., 2017). Real-time control (RTC) systems can also be used with flow restrictors to optimize the PP performance in areas with shallow groundwater environments, on the basis not only of the water level but also of the moisture content of media or surrounding soils (Kertesz et al., 2014; Oberascher et al., 2018; Xu et al., 2021). Studies have found that water level and soil moisture-based controls have an impact on the water quality treatment performance of GI (Persaud et al., 2019; Shen et al., 2020). More specifically, if the groundwater level is lower than the base of the pavement, the underdrain can be opened to allow a pre-event discharge when the reservoir water level and soil moisture both reach certain thresholds. This is because a lower exfiltration rate is expected, and more storage space is needed for the upcoming rainfall events. If the groundwater table reaches the pavement base, RTC algorithms should be able to identify whether the water in the reservoir stems from stormwater runoff, groundwater, or a combination of the two based on the time–frequency characteristics of the reservoir water depth and the moisture condition of the surrounding soils. If the water stems from groundwater, the underdrain can be closed until rainfall runoff inflow is identified to avoid continuous drainage of groundwater into drainage systems during dry periods, as observed in this study.

There are some limitations to this study. First, the surface environments near the studied PPs (e.g., the moisture content of surrounding soils and groundwater levels) were not monitored. Such monitoring may allow better determination of the potential infiltration of soil water and groundwater, and better estimation of the water balance of the PP systems. Second, the surface runoff of both fully and partially exfiltrating PPs was monitored together; therefore, their individual surface runoff controls cannot be distinguished and compared.

5. Conclusion

The hydrologic performances of three permeable pavements (PPs) at two sites in Hong Kong were monitored for seven months during the wet season in 2017. The characteristics of the time series were evaluated, and the hydrologic performance of the PPs – represented by the peak reduction in surface runoff, volume reduction of surface runoff, outflow-to-rainfall volumetric ratio, and drawdown time of the PP reservoir – were assessed for different rainfall events. The primary contributions of this study included demonstrating the impact of shallow groundwater on the runoff control performance of underdrained PPs and exploring the appropriate designs of underdrains in PPs in shallow groundwater environments. Our results demonstrate several key points:

First, all three PPs achieved 70 % – 100 % and 90 % – 100 % in peak and volume reductions on surface runoff for 90 % of the rainfall events, even after one year of service without maintenance, given their high-permeability surface pavers and underdrains, which reduced the peak reservoir water depth and avoided frequent generation of surface runoff.

Second, despite the comparable runoff reduction performance among the PPs, each showed distinct performance in water balance and drawdown owing to different subsurface hydrogeologic conditions (soil type and groundwater table conditions). Owing to shallow groundwater tables nearby and extraneous flows into the pavement systems, Panels #1 and #2 generated continuous and large volumes of underdrain flow during dry days after rainfall events (92 % – 94 % water balance; six and three times the rainfall depths for Panels #1 and #2 respectively) and showed unexpectedly long drawdown times not only during wet seasons, but also in relatively dry periods (> 72 hours for 20 % of the rainfall events).

Underdrains were found to be ineffective in shallow groundwater areas, as they did not reduce drawdown time and discharge groundwater into sewer systems. Thus, the adoption and design of underdrains in PPs should be more carefully considered; in shallow groundwater environments, climatic factors (e.g., rainfall characteristics) should be considered alongside hydrogeologic conditions (e.g., soil type and groundwater table conditions). Detailed site investigations (e.g., groundwater table depth measurements, soil taxonomic tests, and permeability tests) are recommended to better understand the hydrogeologic conditions. For areas without shallow groundwater or low-permeability soils, underdrains are not necessary if the drawdown time is within an acceptable range, based on estimations from physical and/or numerical experiments. For areas with shallow groundwater, low-permeability soils, or shallow impermeable bedrock layers, an underdrain is normally necessary, but should be elevated to allow some exfiltration and reduce the amount of groundwater discharged through the underdrain. Flow restrictors can be implemented in these underdrains to restrict the maximum flow rate to strike a balance between runoff reduction and the control of underdrain flow. Flow restrictors can be used alongside real-time control systems to reduce the discharge of groundwater through underdrains and better utilize the storage capacity of PPs.

Data Availability Statement

All data generated or used during the study are proprietary or confidential in nature and may not be provided. All codes generated or used during the study are available from the corresponding author upon reasonable request. (Codes used to identify rainfall events and calculate hydrologic indicators.)

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