Optimization of Flood Protection Interventions in St. Mark's Square in Venice and evaluation of effectiveness through Geotechnical Investigations and Monitoring

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ABSTRACT

Venice is increasingly affected by flooding due to relative sea-level rise and subsidence. Although the MOSE movable barriers, operational since 2020, effectively limit extreme lagoon water levels, they do not prevent flooding in low-lying areas such as St. Mark's Square. This study presents an integrated approach to optimize flood protection measures for the square, combining geotechnical investigations, long-term piezometric monitoring, and evaluation of implemented mitigation works. Since 2018, a dense piezometric network has monitored groundwater response to tidal forcing, MOSE operation, and local interventions. Results show a strong stratigraphic control on pore-pressure propagation: shallow anthropic fills respond rapidly to tides, while an underlying low-permeability silty layer markedly attenuates pressure transmission from deeper sandy units. Consequently, flooding is mainly driven by shallow hydraulic processes, including surface inflow and backflow through the historic drainage system, whereas deep seepage plays a minor role during high tides. These findings led to the adoption of targeted, minimally invasive measures—such as drainage rehabilitation, backflow prevention, pumping systems, local pavement raising, transparent barriers, and wave protection—rather than extensive impermeabilization. Post-intervention monitoring confirms that the combined effect of local measures and MOSE operation significantly reduces extreme piezometric levels and flooding without altering the long-term groundwater equilibrium. The study highlights the key role of long-term monitoring in designing sustainable flood protection strategies for historic coastal sites.

Keywords: St. Marks Square, high tide, piezometric monitoring, seepage, drainage system

INTRODUCTION

The city of Venice, part of the UNESCO world heritage list (https://whc.unesco.org/en/list/394/), is built on islands in a lagoon, and faces a precarious balance with diminishing safety margins due to increasing flooding. This is caused by several different factors including sea-level rise, natural subsidence, and significant man-induced subsidence between the 1940s-70s (Jamiolkowski et al., 2009). In the northern Adriatic Sea, storm surges cause the highest sea levels, but coastal flooding in Venice results from multiple, often compounding drivers; as relative mean sea level rises, tides and long-term meteorological effects increasingly dominate, making recurrent floods common and likely turning today's extreme events into routine high-tide occurrences within the coming decades (Ferrarin et al., 2022).
Given the small elevation gap between Venice's ground level and sea level, flooding begins at tides exceeding +0.80 m above mean sea level (specifically referred to as *Punta della Salute* tide gauge, a specific reference elevation for m.s.l. in the entire Venetian lagoon). At tides above +1.10 m, occurring during storm surges, large portions of the city flood.
To protect Venice, the MOSE system (https://mosevenezia.eu/progetto/), namely tilting movable gates at the three inlets that temporarily separate the lagoon from the sea during tides exceeding +1.10 m, was built up. Additional interventions in the ancient city include raising banks, pavements, and sidewalks to prevent flooding below +1.1 m.

St. Mark's Square is the lowest area of Venice's historic centre, and the one with the most relevant historic buildings. Increasing flooding frequency severely damages masonry, foundations, and architectural elements of historically significant buildings, threatening Venice's cultural heritage. Without any protection measure, flooding begins at +0.60 m near the Basilica, covers 65% of the square at +0.90 m, and fully submerges it at +1.15 m. The MOSE barriers, activated at forecasted tides of +1.10 m or higher, cannot prevent St. Mark's flooding, requiring site-specific solutions that respect historical heritage, accommodate tourism, and remain cost-effective. These site-specific protection measures have been under discussion since the '90s, but only in the last eight years the design has been finally optimized and the solutions have been implemented as shortly discussed in this paper.
Figure 1 shows a cross-section of a typical quay-wall facing the surrounding canals or the St. Mark's basin with an indication of different flow paths potentially concurring to flooding, that is back-flow through the existing drainage system (1), overtopping from the St. Marks' basin (2), heavy rainfalls (3) and seepage through the soil (4).

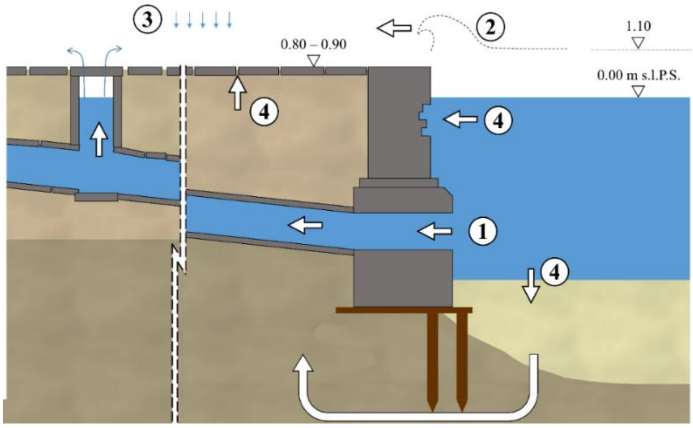


***Figure 1** Main flooding mechanisms of St. Mark's Square: 1. Back-flow through the drainage system, 2. Overtopping, 3. Heavy rainfalls, 4. Seepage through the soil*

A 1998 preliminary project proposed very invasive flood protection measures for the square, including: (1) continuous sheet pile walls around St. Mark's island perimeter to prevent water infiltration through and below quay walls, and (2) an impermeable membrane beneath the stone pavement to block seepage through permeable joints (mechanism 4 in Figure 1).
In the late 2010s, doubts arose about the necessity and effectiveness of these extensive interventions, prompting further studies. Hydraulic and maritime research (P. Salandin, 2020; Ruol et al., 2020) investigated mechanisms 1-3, suggesting restoration of the drainage system with installation of valves to avoid sea water backflow and adequate pumping system, installation of seawalls and raise of the quay walls (details are outside the scope of in this paper). Mechanism 4 (seepage) is examined and discussed in this study as well as the mitigation systems carried out so far and planned in the next future.
This paper first describes the site investigations and monitoring system, then analyzes groundwater response and flooding mechanisms, and finally evaluates the effectiveness of the implemented and planned flood protection measures.

SITE INVESTIGATIONS AND MONITORING SYSTEM

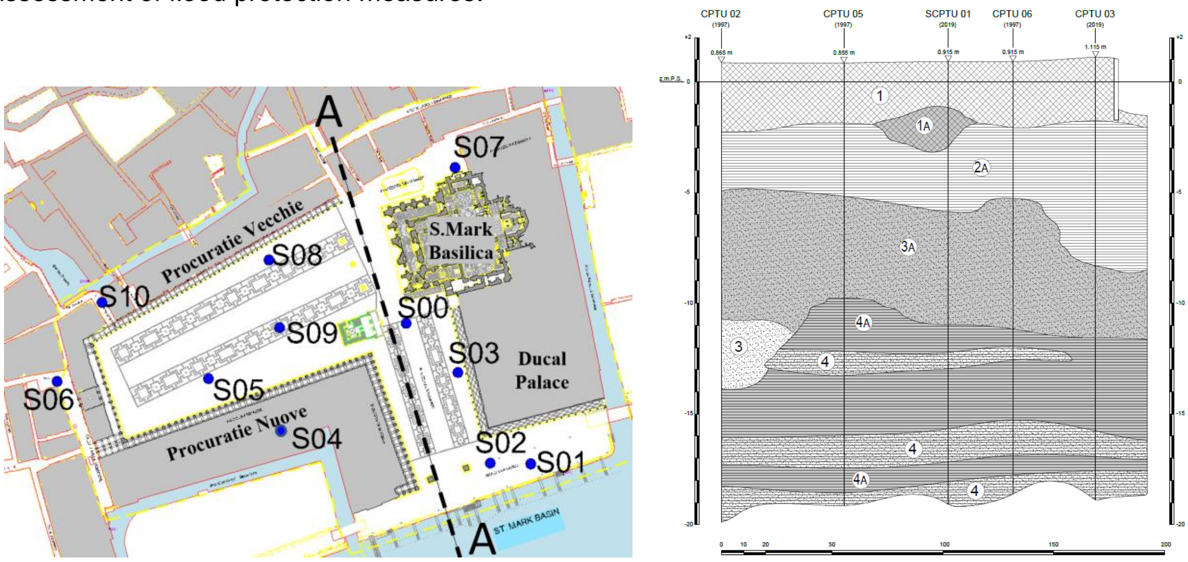
The geotechnical study of St. Mark's Square integrated data from three investigation campaigns (1993, 1997-98, and 2019) to address the heterogeneous Venice lagoon subsoil (Ceccato et al., 2021; F. Ceccato et al., 2021).
The 1993 campaign involved six 16 m-deep boreholes with undisturbed sampling, SPT, Lefranc permeability, and CPTU tests. In 1997-98, additional boreholes (20-32 m deep) included SPT, CPTU, and Boutwell permeability tests. The 2019 campaign comprised ten 20 m-deep boreholes with undisturbed sampling, CPTU, SCPTU, DMT, SDMT, and field permeability measurements. Laboratory tests included soil classification, triaxial permeability (constant and variable head), and oedometer tests.
Data integration identified a characteristic stratigraphic profile for St. Mark's Square (Figure 2b). The top layer (Units 1/1A, 3.0-4.5 m thick) is heterogeneous anthropic fill containing the historic drainage network, with highly variable hydraulic conductivity. Below lies a low-permeability sandy-to-clayey silt layer (Units 2/2A, 2.0-7.0 m) acting as a partial hydraulic barrier, underlain by a permeable sandy formation (Units 3/3A, 0.5-8.0 m). Below approximately −9.8 m the stratigraphy is characterized by

alternating clayey layers with interbedded silty sand lenses. This stratigraphic profile plays a key role in controlling vertical hydraulic gradients and the propagation of tidal pressure within the subsoil.

A monitoring system was progressively implemented to study groundwater response to tidal forcing. In 2018, nine Casagrande piezometers were installed near St. Mark's Basilica at the narthex protection system, located at various depths within the anthropic fill, clayey silt layer, and deeper sandy formation to assess vertical pore pressure distribution (S00 in Figure 2a).

In early 2019, the network expanded with 25 additional piezometers across ten monitoring stations in St. Mark's Square (Figure 2a). Each vertical had two or three piezometers measuring absolute pore water pressure in the main permeable units. Standpipe piezometers were used in the anthropic fill and sandy layers, while Casagrande piezometers were installed in the low-permeability intermediate layer. Boreholes were sealed to prevent inter-unit hydraulic communication, and piezometer heads were capped to avoid surface flooding influence during high tides. In the following, piezometers installed in Unit 1 (anthropic fill) are named “A”, those installed in Unit 2 (low-permeability sandy-to-clayey silt) are named “B” and those installed in Unit 3 (sand) are named “C”.

The monitoring system included atmospheric pressure and sea level instruments, with tidal data from the *Punta della Salute* tide gauge. All measurements were time-synchronized and referenced to the same vertical datum, with quality control applied to ensure data consistency. The spatially distributed, long-term pore pressure measurements provided a unique dataset for analyzing tidal transmission into the subsoil and evaluating the role of stratigraphic units and boundary conditions. These observations formed the basis for understanding flooding mechanisms and guiding the design, implementation, and assessment of flood protection measures.



(a) (b)

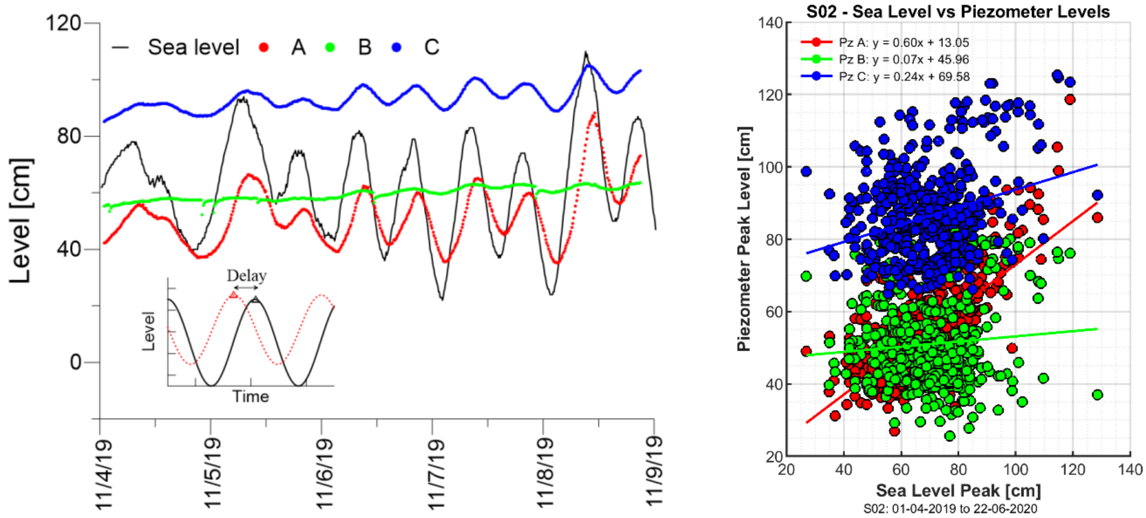
Figure 2 *(a) Plan of S. Mark square with location od monitoring stations. (b) typical stratigraphy*

ANALYSIS OF PRE-INTERVENTION CONDITIONS AND EARLY MONITORING RESULTS

The data collected from October 2018 to June 2020 demonstrate that groundwater levels are predominantly governed by tidal oscillations, with responses varying significantly across the different geological layers. Figure 3a shows the piezometric level and sea level for the piezometers of station S02 at the beginning of November 2019. Sensor installed in Unit 1 (A) shows very rapid response to tides with minimal attenuation. Sensor placed within Unit 2 (B) shows a markedly different response and the tidal signal is significantly attenuated. The sensor located in Unit 3 (C) confirms that the tidal influence persists at depth. The average piezometric level in Unit 3 is slightly higher than the average level in Unit 1, meaning that Unit 3 behaves as a confined artesian aquifer and that these two layers can be considered hydraulically disconnected and Unit 2 can effectively prevent the flooding mechanism 4. This is confirmed by the scatter plot of daily maximum sea level and daily maximum piezometric level shown in Figure 3b for each piezometer with the equation of the regression line. The slope of the regression line quantifies the sensitivity of the subsoil to sea-level fluctuations and confirm that Unit 1 is very sensitive to tidal fluctuation, while Unit 2 is almost insensitive.

Figure 4 shows that the maximum daily piezometric levels are relatively homogeneous across stations: piezometers A and C exhibit comparable medians and limited dispersion, indicating a broadly uniform response in terms of peak levels, although Unit C consistently reaches higher median values than Unit A. Some inter-station differences are present but remain moderate when considering maximum levels. In contrast, Figure 5 reveals a markedly different behavior in terms of timing. In Unit 1, the delay between sea-level and piezometric peaks varies widely among stations, with medians ranging from about 12 to 100 minutes, highlighting strong spatial heterogeneity in the dynamic response. Conversely, Unit 3 shows much more consistent delays, clustered between 36 and 60 minutes, indicating a more uniform and stable propagation of tidal signals at depth.

These observations confirm that the piezometric levels in the superficial layer are controlled by local conditions, including distance from ancient drainage pipes (*gatoli)* or quay walls, heterogeneities in the permeability, while unit 2 and 3 are not significantly affected by this. Moreover, during high tide the flow from the bottom is small. The gradients are small, thus the discharges due to soil seepage are limited.



(a) (b)

Figure 3 *(a) Sea level and piezometric level with time; (b) daily maximum sea level versus daily maximum piezometric level in different soil units.*

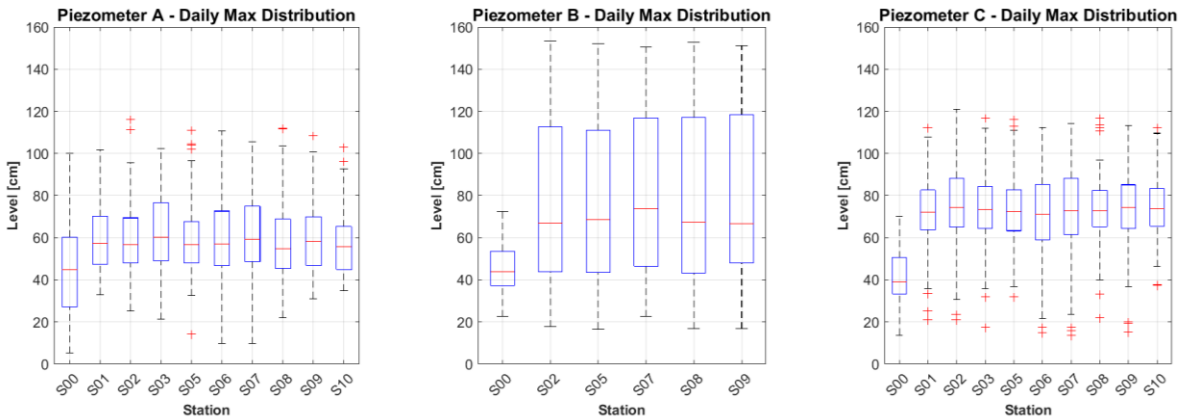


Figure 4 *Boxplot of daily maximum piezometric level recorded from October 2018 to June 2020. Central line is the median, box edges are the first and third quartiles. Points beyond the whiskers represent outliers, i.e., unusually distant values.*

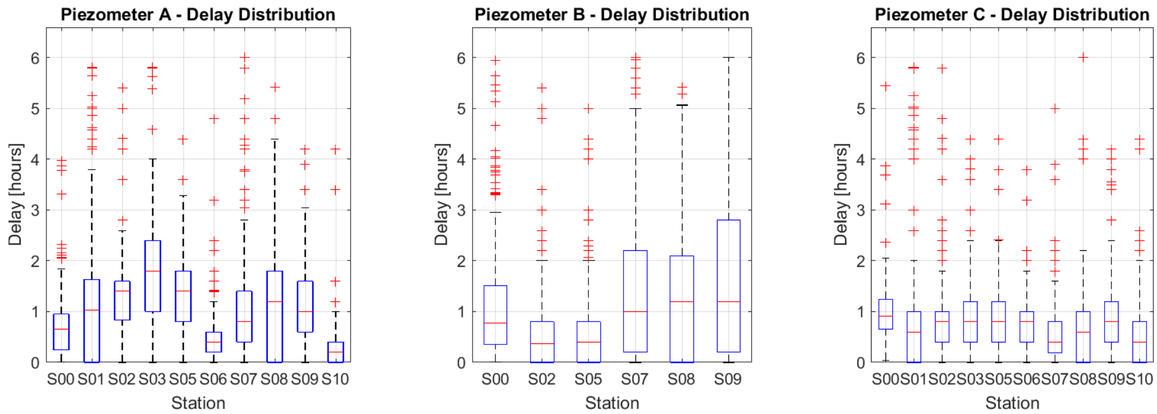


Figure 5 *Boxplot of delay between peak seal level and peak piezometric level recorded from October 2018 to June 2020*

PROTECTION MEASURES OF S. MARK SQUARE

St. Mark's Square's flood protection strategy evolved adaptively, based on comprehensive geotechnical studies and long-term groundwater monitoring. The chosen interventions target specific flooding mechanisms, balancing effectiveness with preservation of subsoil hydraulics and historical integrity, avoiding extensive impermeabilization.

Geotechnical studies presented in the previous sections, together with maritime (Ruol et al., 2020) and hydraulic (P. Salandin, 2020) studies revealed that St. Mark's Square flooding is primarily driven by shallow hydraulic processes tied to tides, drainage backflow, and surface inflow, with minimal deep seepage impact. These insights challenged previous design concepts of perimeter cut-offs and impermeable membranes, leading to a more focused and sustainable flood mitigation approach.

In 2019, a new drainage system was implemented for St. Mark's Basilica's narthex, the most vulnerable area of the square. It combines rehabilitated conduits, backflow prevention, and a custom pumping station for intermediate tides. Monitoring confirmed its effectiveness in reducing surface flooding and shallow pore pressures without causing pavement uplift (Simonini & Ceccato, 2022).

The MOSE system, operational since October 2020, reduces extreme flooding in Venice by limiting high tidal levels to 1.10 m. However, moderate tides, uncontrolled by MOSE, still cause flooding in the square through local mechanisms. This confirms that large-scale tidal control alone is insufficient, necessitating site-specific interventions for low-lying historic areas.

From September 2021 to October 2022, additional protective measures were implemented for St. Mark's Basilica. These included enhancements to the narthex drainage system and the installation of a visually unobtrusive transparent glass barrier around the Basilica to prevent direct inflow during higher tides

From 2023 to current time, flood mitigation efforts expanded to larger areas of St. Mark's Square. This involved rehabilitating underground drainage pipes, including cleaning and restoring the entire drainage system, installing anti-backflow valves, and selectively raising pavement levels in vulnerable perimeter areas. Moreover, a wave barrier will be installed to minimize wave overtopping.

POST-INTERVENTION MONITORING

In order to evaluate the effects of the mitigation measures realized across the years in the square, we consider the data of the station S00, which has the longest time series, while the piezometers distributed on the square (from S01 to S10) did not transmit any data since June 2020 and reactivation of the system is planned soon.

Data of the piezometers installed in the same layer are grouped together and 4 main periods are analysed:

1. October 2018 - March 2019: this is the baseline, when both the drainage system of the basilica and the MOSE barrier where not functioning yet;
2. April 2019- September 2020: the drainage system of the basilica is fully operative for medium-high tides, but the MOSE barrier are not operational yet, i.e. very high levels are still possible;
3. October 2020-September 2021: the drainage system of the basilica and the MOSE system are both functioning;

4. October 2021-October 2022: additional works are being implemented for the basilica, and the measurements are disturbed and not very reliable in this period;
5. October 2022 – December 2024: mitigation measures are being implemented in the square, but not close to station S00.

Figure 6 shows the average piezometric level in units 1, 2, and 3 during the activation of the system. Only the piezometric level in Unit 1 appears to be influenced. When the sea level reaches 62 cm, the system switches on and the pressure immediately decreases. Afterward, it increases again following the tide, but the maximum piezometric level is lower compared to the case without an operating system. After the peak, when the tide decreases below 62 cm the system is deactivated and the pressure increases slightly, but it reduces rapidly following the descending sea water level. If the tidal level exceed 88cm the system is switched off and the nartex is flooded.

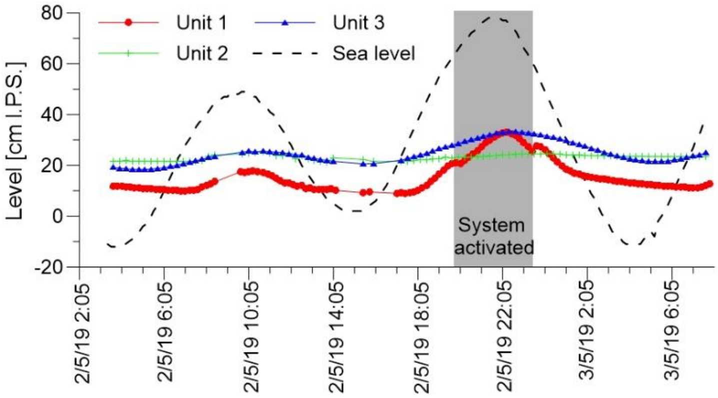


Figure 6 *Piezometric level and sea level during activation of the system.*

Figure 7 presents boxplots of the maximum daily piezometric values recorded in the three units for each period. In Unit 1, Period 1 exhibits the largest variability and the highest piezometric levels. Period 2 occasionally shows very high values, appearing as outliers associated with extreme tides when the system is inactive, while the interquartile range is reduced. In Periods 3, 4, and 5, the extreme values linked to very high tides disappear because the MOSE barriers are operational. Units 2 and 3 do not display significant differences among the analyzed periods. Overall, both the median and mean piezometric levels remain stable over time in all units, confirming that the system mitigates extreme tides responsible for flooding the square without altering the long-term mean piezometric level.

Figure 8 shows the scatter plot of daily maximum sea level versus daily maximum piezometeric level for each layer in different periods with the equation of the regression line. It can be observed that the regression line is stable in all soil units and all periods. Only the last period of unit 2 shows a different behaviour, but this is attributed to the fact that two of the piezometers installed in this layer were malfunctioning and are excluded from the elaboration.

Overall these results prove that the implemented measures can effectively mitigate high piezometric levels in the soil and flooding of the square, without perturbating the average equilibrium of the groundwater system.

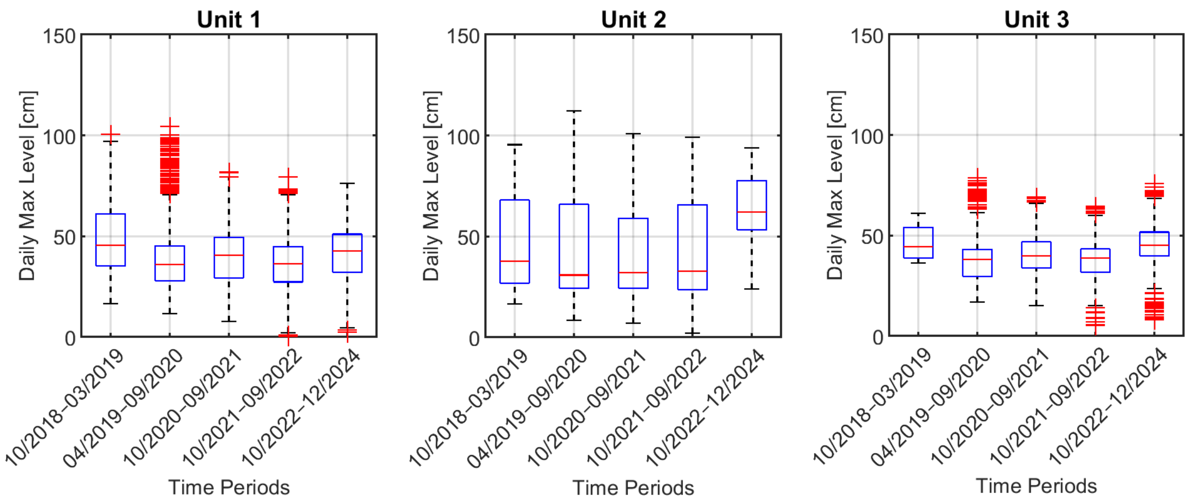


***Figure 7** Boxplots of the maximum daily piezometric values recorded in Unit 1 (a), Unit 2 (b) and Unit 3 (c) for each period.*

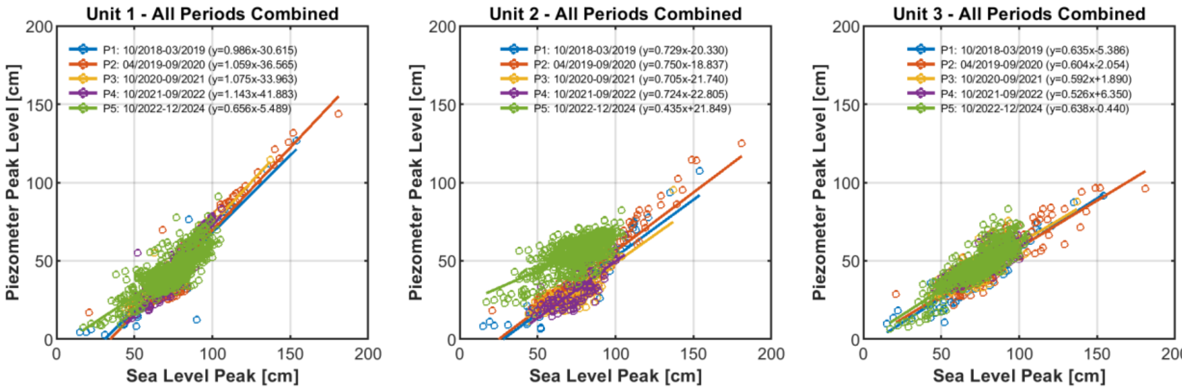


***Figure 8** Scatter plots of the maximum daily piezometric values versus maximum daily sea level recorded in Unit 1 (a), Unit 2 (b) and Unit 3 (c) for each period.*

CONCLUSIONS

This study demonstrates the effectiveness of a data-driven and adaptive flood protection strategy for St. Mark's Square, based on integrated geotechnical investigations and long-term piezometric monitoring. The analysis confirms that flooding mechanisms are primarily controlled by shallow hydraulic processes linked to tidal oscillations, surface inflow, and backflow through the historic drainage network, while deep seepage from underlying permeable layers plays a minor role during high tides. Monitoring data highlight the key influence of local stratigraphy in attenuating tidal pressure transmission and support the adoption of targeted, minimally invasive mitigation measures that comprises restoration of the drainage network and installation of valves to avoid water backflow and pumping system, raising of the quay walls, installation of transparent wall around the Basilica and wave barrier. Very invasive measures such as the impermeabilization of the pavement and quay walls are not necessary.

The progressive implementation of local drainage improvements, combined with the operation of the MOSE barriers, significantly reduces extreme piezometric levels in the shallow anthropic layer without affecting the long-term mean groundwater conditions. This confirms that the adopted interventions effectively mitigate flooding while preserving the hydraulic equilibrium of the subsoil and the integrity of the historic structures.

The results underline the crucial role of long-term, spatially distributed monitoring in understanding complex hydro-geotechnical interactions, optimizing design choices, and verifying performance under real operating conditions. The proposed approach provides a robust framework for the sustainable protection of St. Mark's Square and offers valuable guidance for other low-lying historic coastal areas facing increasing flood risk under future sea-level rise scenarios.

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