Assessing Water Area Changes in the Eastern Venice Region (2021–2024): A Sentinel-Based Analysis

Amirhossein Donyadidegan - 240353

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Abstract

The Venice area of Italy has been observing considerable water area variations in the last few years due to both natural and anthropogenic reasons. This paper presents trends in water areas in the eastern region of the Venice area between 2021 and 2024 from Sentinel-1 and Sentinel-2 satellite imagery. The average annual water areas were calculated in terms of a percentage of the total AOI, and the research considered deviations below and above the average. The results cast a projection of a gradual growth in the water area, ranging from 55% in 2023 to over 58% in 2024, annually. The results enhance the knowledge of coastal water dynamics and provide the basis for the development of sustainable environmental management policies.

Introduction

Coastal water area changes have great impacts on the local ecosystems and urbanized infrastructure. Measuring the dynamics is vital to mitigate the threats of climate change, sea level rise, and human activities. The Venetian plain in the east, a low-lying flood-prone area, is an ideal region to study the dynamics.

Based on Sentinel-1 and Sentinel-2 satellite imagery, this research assesses water area variation in the area for four years (2021–2024). The methodology includes computation of annual average water areas, identification of below-average and above-average trends, and temporal analysis to detect patterns and drivers. These findings seek to inform sustainable coastal management and urban planning interventions in vulnerable locations such as Venice.

Figure 1: Study Area: Eastern Venice

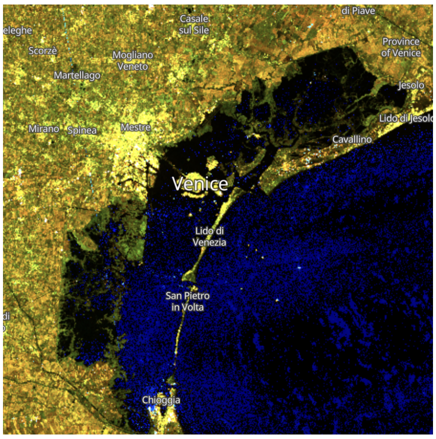

Figure 2: Enhanced Visualization

Materials and Methods

Study Area

The study focuses on the eastern coast of Venice in Italy, its shoreline, and the adjacent water ecosystems, specifically within an Area of Interest (AOI) covering approximately 766 square Kilometers. This is both an ecologically and economically valuable region and, as such, deserves serious attention in efforts to mitigate risks associated with water level changes. By studying the region, this study is intended to inform us on water level change with significant implications on environmental sustainability and sustainable development.

Data Sources

This study utilizes both Sentinel-1 and Sentinel-2 imagery to ensure accurate and robust analysis of water area changes in the eastern Venice region. These datasets were processed and analyzed using Google Earth Engine, leveraging their complementary strengths to detect and monitor surface water dynamics.

- **Sentinel-1 and Sentinel-2 Imagery:** Sentinel-2 data were primarily used for their multi-spectral capabilities, particularly the Green (B3) and Near-Infrared (B8) bands, to compute the Normalized Difference Water Index (NDWI). Sentinel-1 data complemented this analysis by providing radar-based water detection using the VV and VH polarizations, unaffected by clouds or atmospheric conditions. The combination of these datasets ensures accurate water detection during all weather conditions and time periods.
- **Temporal Coverage:** The analysis focuses on the time period from January 2021 to December 2024. This period was chosen to study recent trends in water area dynamics.
- **Spatial Resolution:** Both Sentinel-1 and Sentinel-2 data offer a high spatial resolution of 10 meters, enabling detailed analysis of water area changes.
- **Cloud Coverage Threshold:** For Sentinel-2 imagery, only images with less than 20% cloud coverage were retained to ensure data quality. Sentinel-1, being a radar-based sensor, was unaffected by cloud cover and was used to complement the analysis during cloudy conditions.
- **Filters Applied:**
  - Images were filtered to cover the Area of Interest (AOI) with a minimum of 70% coverage for Sentinel-2 and 80% coverage for Sentinel-1.
  - Sentinel-1 data were further filtered to include only ascending orbit images in Interferometric Wide (IW) mode with both VV and VH polarizations.
- **Number of Images:** After applying the filtering criteria, the dataset included **162 Sentinel-2 images** and **295 Sentinel-1 images** for the study period. These datasets were used in combination to ensure comprehensive water area detection and monitoring.

Data Processing

Water Detection:

- **Sentinel-2:** The Normalized Difference Water Index (NDWI) was computed using the Green (B3) and Near-Infrared (B8) bands. NDWI highlights surface water by exploiting the high reflectance of water in the Green band and its strong absorption in the Near-Infrared band. Cloud masking was applied, and only images with less than 20% cloud coverage were retained to ensure data quality.
- **Sentinel-1:** Synthetic Aperture Radar (SAR) data from Sentinel-1 were used to complement Sentinel-2 during cloudy periods. The VV (Vertical-Vertical) and VH (Vertical-Horizontal) polarizations were used for water detection. A threshold on the VV/VH ratio was applied to classify water areas, leveraging the distinct scattering characteristics of water surfaces in SAR imagery.

Integration: Sentinel-1 and Sentinel-2 results were merged for comprehensive water area analysis. Sentinel-2 NDWI served as the primary water detection method, while Sentinel-1 SAR data were used to fill gaps caused by cloud cover.

Water Area Calculation: The percentage of the total AOI covered by water was computed for each date by summing the detected water area and dividing it by the total AOI area. This approach ensured standardized comparisons over time.

Statistical Analysis: The processed data were exported from Google Earth Engine and analyzed in Python for enhanced visualization. Yearly mean water areas, as well as below-average and above-average trends, were calculated to identify and highlight incremental changes in water coverage. This analysis revealed a stair-step trend in water area percentages over the years.

Formulas

$$\text{NDWI} = \frac{\text{Green} - \text{NIR}}{\text{Green} + \text{NIR}} \tag{1}$$

$$\text{Water Area (\% of AOI)} = \frac{\text{Detected Water Area}}{\text{Total AOI Area}} \times 100 \tag{2}$$

$$\text{SAR Water Classification: Water} = \frac{\text{VV}}{\text{VH}} < T \tag{3}$$

Explanation of SAR Formula:

- **VV (Vertical-Vertical):** Radar backscatter measured when the signal is transmitted and received in the vertical plane.
- **VH (Vertical-Horizontal):** Cross-polarized radar backscatter, which is weaker for water surfaces.
- **Threshold (T):** A predefined threshold (e.g., $T = 2$) was used to differentiate water from non-water surfaces, as water typically exhibits lower VV and VH values and a distinct VV/VH ratio.

Results and Discussion

Yearly Mean Water Area

The yearly mean water area percentage demonstrates slight fluctuations over the years, with an overall increasing trend. In 2021, the mean water area percentage was 56.75%, which slightly decreased to 56.56% in 2022 and further dropped to 55.46% in 2023. However, in 2024, the percentage rose significantly to 58.39%, marking the highest value within the observed period. This trend suggests variability influenced by environmental or climatic factors.

Below-Average and Above-Average Means

Below-average water area percentages show a steady increase over the years, from 48.19% in 2021 to 49.43% in 2024. This trend may indicate a narrowing difference between below-average and above-average water areas. Meanwhile, above-average percentages fluctuated slightly, starting at 61.53% in 2021 and rising to 63.08% in 2024. This rise aligns with the general upward trend in annual mean water area and indicates shifts toward greater water-covered areas during certain periods.

Interpretation of Trends

The findings exhibit a dynamical interaction between regions of below-average and above-average water percentages, the latter with a more evident increasing trend. This may indicate some climatic or hydrological changes along the eastern coast of Venice, which induce a redistribution of the levels of water. Further analysis is needed to determine a correlation between these results and seasonal trends, human alteration, or extreme weather patterns in order to gain useful information for environmental sustainability and adaptive management applications. While the yearly average percentages of water coverage provide the overall impression of the direction of trend, they do not alone convey the more subtle nuances of fluctuation and change in the data. To get a better picture, we examined the minimum and maximum values of water area reported each year and determined the precise dates when the water area got closest to the aforementioned mean above average levels. These measures are useful in indicating the temporal patterns of water area allocation. For example, the lowest water area percentages over the years were realized in various months, including March in 2021 and 2022, July in 2023, and April in 2024, reflecting seasonal factors. Likewise, the highest water area values also differed by a large margin, occurring in January for 2021 and 2024 but in November for 2022 and 2023. This difference indicates that the yearly mean does not account for the temporal changes in the extreme water cover events. In addition, the dates when the water area was nearest to the above-average mean indicate the quality of how well distributed the water levels were around the mean. For example, in 2021, the closest value of 61.61% was on October 15th, while in 2024, a value such as this was on July 21st at 63.01%. This measure shows the fluctuation in water area compared to the above-average mean, thus providing greater insight into the consistency or lack of consistency in the distribution of water throughout the year. Through the inclusion of these metrics, more subtle trends and seasonal differences not apparent using the annual mean values were apparent. The findings highlight the necessity of complementary statistical analyses to completely encapsulate the dynamics of water area changes for effective environmental monitoring and management.

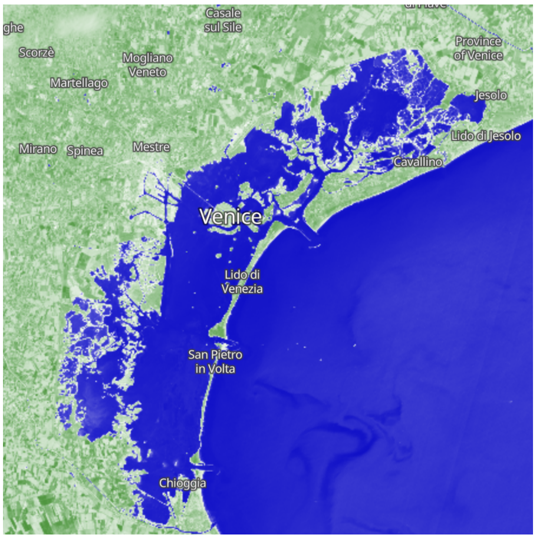

Figure 3: NDWI on April 13 : Maximum Water Coverage in 2021

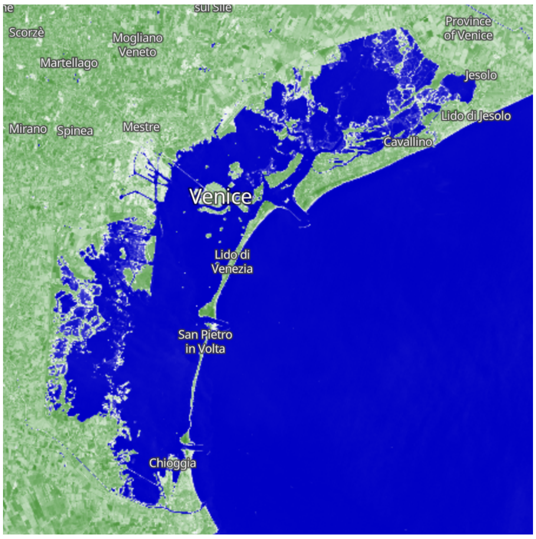

Figure 4: NDWI on March 06: Lowest Water Coverage in 2021

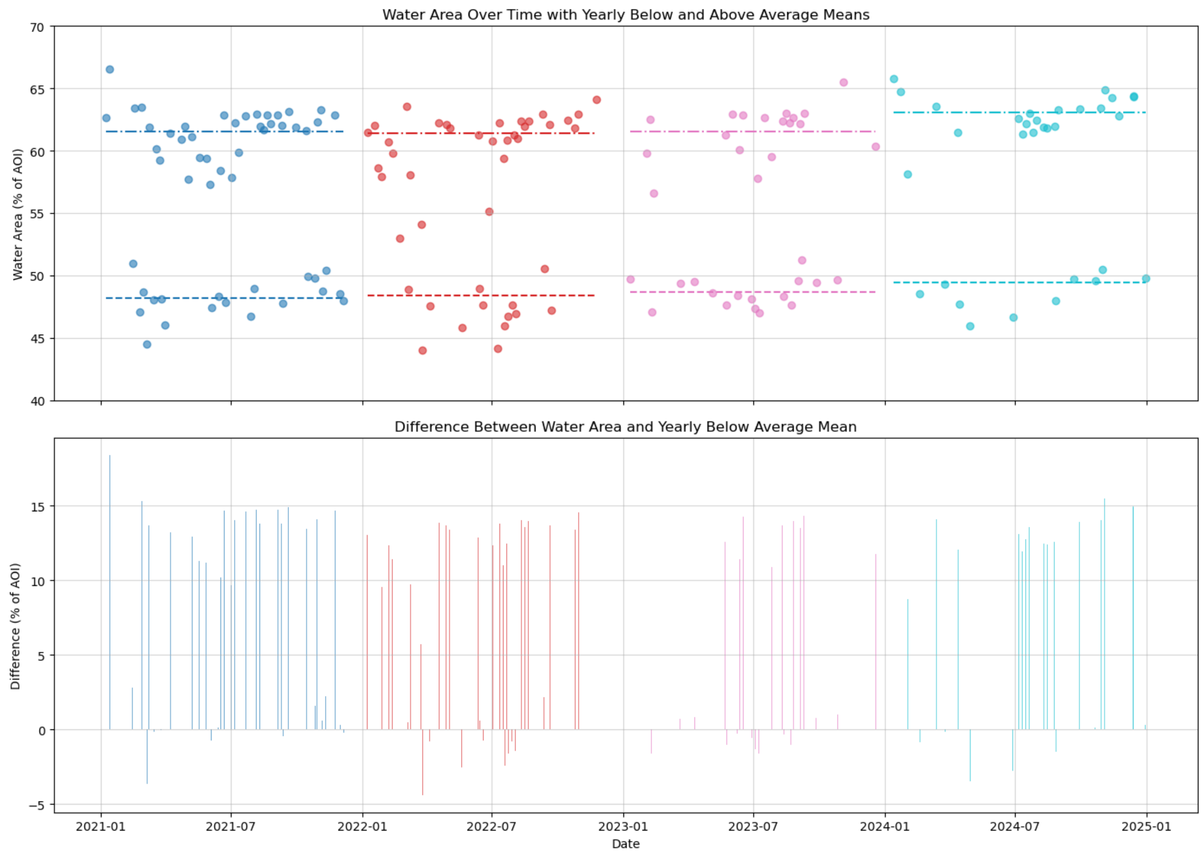

Figure 5: Below-Average and Above-Average Water Area Percentages (2021–2024)

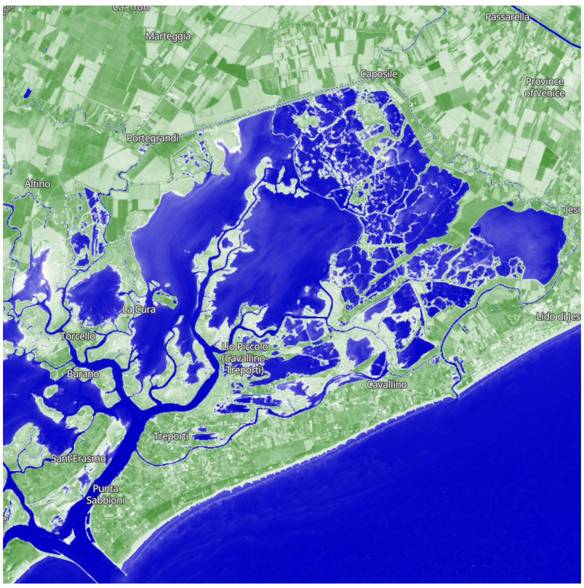

Figure 6: NDWI on March 06: Lowest Water Coverage in 2021

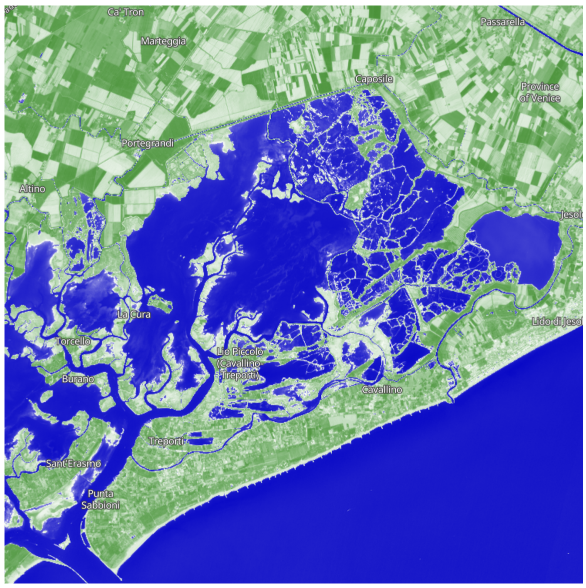

Figure 7: NDWI on April 29: Lowest Water Coverage in 2024

Despite these dates representing the minimum water-covered area within their respective years, the comparison highlights a notable increase in water coverage from 2021 to 2024. This trend suggests a general rise in water levels over time, even during periods of minimal water extent.

Conclusion

This study looked at how the water-covered area in the eastern Venice region has changed over the past four years. The results show a clear trend: the water area has been steadily increasing, not just in the yearly averages but also during periods of low water coverage. Even on the days with the least water, the area covered by water in 2024 was noticeably larger than in 2021.

This increase highlights the changing dynamics of the region's coastal ecosystems. It's a reminder of how environmental and climatic factors are influencing water levels in ways that could have long-term impacts. For a place as ecologically and economically important as Venice, understanding these changes is crucial.

By keeping a close eye on these trends, we can better prepare for the challenges they bring, whether it's managing rising water levels or protecting the delicate balance of the ecosystem. This study is a step toward making informed decisions to ensure the region remains sustainable and resilient in the face of change.

References

- Copernicus Open Access Hub, Sentinel-1 and Sentinel-2 Imagery.
- Förstner, W., & Wrobel, B. (2016). Photogrammetric Computer Vision. Springer Nature.
- GRASS Development Team (2015). Geographic Resources Analysis Support System.

Code and Resources

The Google Earth Engine (GEE) script used for data analysis is available at the following link: GEE.

The complete processing workflow, including additional scripts and resources, can be accessed on GitHub: Repository.