



COVID-19 lockdown measures reveal human impact on water transparency in the Venice Lagoon

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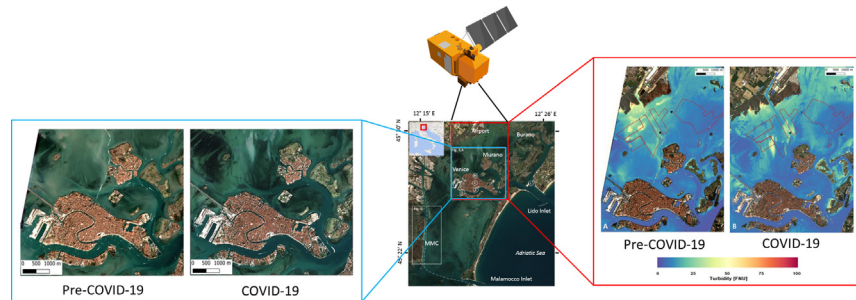
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HIGHLIGHTS

- Lockdown measures in Venice restricted the mobility and stopped water traffic, with a consequent decrease of wake waves.
- An unprecedented water transparency in the city canals was determined by the reduction of boat traffic and tourism.
- Turbidity remained at usual levels in sustained wind conditions.
- Essential activities like fisheries and commercial shipping continued through the lockdown thus revealing their impact.

GRAPHICAL ABSTRACT



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ABSTRACT

The lagoon of Venice has always been affected by the regional geomorphological evolution, anthropogenic stressors and global changes. Different morphological settings and variable biogeophysical conditions characterize this continuously evolving system that rapidly responds to the anthropic impacts. When the lockdown measures were enforced in Italy to control the spread of the SARS-CoV-2 infection on March 10th 2020, the ordinary urban water traffic around Venice, one of the major pressures in the lagoon, came to a halt. This provided a unique opportunity to analyse the environmental effects of restrictions to mobility on water transparency. Pseudo true-colour composites Sentinel-2 satellite imagery proved useful for qualitative visual interpretation, showing the reduction of the vessel traffic and their wakes from the periods before and during the SARS-CoV-2 outbreak. A quantitative analysis of suspended matter patterns, based on satellite-derived turbidity, in the absence of traffic perturbations, allowed to focus on natural processes and the residual stress from human activities that continued throughout the lockdown. We conclude that the high water transparency can be considered as a transient condition determined by a combination of natural seasonal factors and the effects of COVID-19 restrictions.

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1. Introduction

Since February 23rd, 2020, a series of restrictions of increasing severity were enacted in Italy after the identification of two clusters of COVID-19: Codogno in Lombardy and Vò, a village 50 km west of Venice (GURI, 2020a; Grasselli et al., 2020; Onder et al., 2020). Specific strict

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containment measures to control the spread of the epidemic started to introduce quarantine and social distancing in the northern regions, where most cases of SARS-CoV-2 infections occurred. As of March 10th, widespread lockdown measures have been extended to the whole country, restricting social contacts, limiting the individual movement, and closing most businesses, with the exception of those essential to the country supply chains (GURI, 2020b, 2020c; Lazerini and Putoto, 2020).

When the first confirmed cases of COVID-19 were identified in Italy, the city of Venice was celebrating the last days of its famous Carnival. Since March 10th, when the Italian government announced the lockdown, the tourism industry in the city suddenly stopped. Since then, Venice has experienced a major breakdown of its economy, that was mostly based on this single source of revenue. Venice's total apparent population was more than halved, as city users and the overall tourist influx, daily visitors plus overnight stays, largely outnumber the official resident population (Bertocchi et al., 2020). As a consequence of the strict self-isolation measures and the reduction of the number of tourists, the ordinary urban water traffic around Venice, one of the major pressures in the lagoon, came to a halt. Public transportation services, like water taxis and airport shuttles, plus tourist and leisure boats stopped completely, while commercial boats delivering daily supplies in the city and other public boat services, like water buses and the fleet of garbage collection boats, reduced their runs. The drastic reduction of the traffic and an unprecedented water transparency in the city canals were widely covered by international news outlets and social media (e.g. Guy and Di Donato, 2020; Jacobo, 2020).

The lagoon of Venice (Fig. 1) constitutes a complex system of major historical and environmental interests which is under the pressure of anthropogenic factors and global scale processes bringing about progressive environmental transformations (Solidoro et al., 2010; Ferrarin et al., 2013). Several processes influence the amount of dissolved and suspended matter in the water column affecting water transparency in the lagoon: wind - and wave - driven resuspension and erosion (e.g. Sfriso et al., 2005; Defendi et al., 2010; D'Alpaos et al., 2013),

redistribution of suspended sediments by tidal currents (e.g. Ferrarin et al., 2008; Carniello et al., 2012), freshwater runoff and associated sediment delivery from the drainage basin (e.g. Zuliani et al., 2005; Zonta et al., 2005), and the phytoplankton growth cycle (e.g. Bianchi et al., 2003; Bernardi Aubry et al., 2017). Localized sediment mobilization is induced by ship and boat wakes (e.g. Zaggia et al., 2017; Scarpa et al., 2019; Bilkovic et al., 2019), coastal engineering works (e.g. Di Silvio et al., 2017) and clam harvesting (e.g. Pranovi et al., 2003). Moreover, the natural settling of suspended matter may be delayed by turbulence induced by water traffic (e.g. Wolanski et al., 1992; Dabala et al., 2005; Bellafore et al., 2018). Within and around the historical city, wastewater discharge is also a source of dissolved and suspended matter due to the lack of a sewage system (e.g. Dabala et al., 2005; Zaggia et al., 2007).

The major environmental effect of the worldwide lockdown in March–April 2020 has been reported in most cases as an improvement of air quality and environmental noise due to reduction in vehicular traffic (Tobías et al., 2020; Collivignarelli et al., 2020; Zambrano-Monserrate et al., 2020). In this study, we used satellite imagery to describe the environmental effects of the lockdown measures on water transparency in the lagoon of Venice and to ascertain how the changes in human pressure caused temporary positive side effects on the water quality.

2. Materials and methods

Sentinel-2 (S2) A and B satellite images (Level-1C) processed by ESA (European Space Agency) within the European Union's Copernicus programme were downloaded from the Copernicus Open Access Hub (<https://scihub.copernicus.eu/>). In this study, we selected S2 images acquired in the periods before, February 20th to March 9th, and during the lockdown, March 10th to April 25th. The satellite overpass over the Venice Lagoon is every 2–3 days instead of the nominal 5 days of the S2 A and B combined constellation, as the area of interest is almost completely covered by partial images (Drusch et al., 2012). A total of 14 cloud-free S2 images were acquired over the lagoon of Venice during the period from February 20th to April 25th 2020. For the sake of consistency in the direct comparisons, S2 images were selected with corresponding tidal phases and similar tidal levels in order to minimize errors in the interpretation due to variable water depths. Furthermore, a S2 image acquired on April 19th 2019 was also used to assess the situation of one year prior to the SARS-CoV-2 outbreak.

Pseudo true-colour composites and turbidity maps at 10 m resolution were obtained from S2 data, similarly to Brando et al. (2015) and Braga et al. (2017). Briefly, S2 imagery were radiometrically calibrated according to Pahlevan et al. (2019) and atmospherically corrected with ACOLITE, applying the dark spectrum approach (Vanhellemont and Ruddick, 2018; Vanhellemont, 2019). Pseudo true-colour composites of ACOLITE-derived water leaving reflectance at 665, 560, 492 nm with the same stretching were used for qualitative visual interpretation. Further, using ACOLITE, water leaving reflectances were converted into turbidity (expressed in formazin nephelometric unit [FNU]), following Dogliotti et al. (2015). To assess the accuracy of turbidity products derived from S2 imagery, in situ data collected at the Lido inlet were used. In particular, turbidity profiles were recorded during field activities from 2017 onwards with a SeaPoint turbidity meter (SeaPoint®) and continuous data were available, from January 2020, by an OBS501 turbidity meter (Campbell Scientific®), positioned at 2 m depth (L in Fig. 1). The correlation for 140 match-ups between satellite-derived estimates of turbidity versus in situ measurements was statistically significant with a coefficient of correlation r of 0.957, a coefficient of determination R^2 of 0.917, a RMSE of 1.45 (Fig. 2). These results are consistent with the accuracy assessed for ACOLITE-derived turbidity retrieved from Landsat 8 in the North Adriatic coastal waters (Braga et al., 2017).

Rainfall data for the city and tributary basin were made available by the Agenzia Regionale per la Prevenzione e Protezione Ambientale

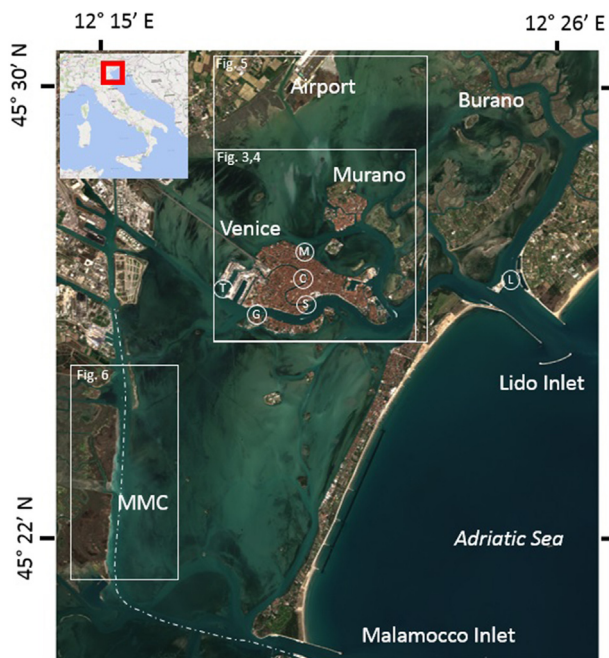


Fig. 1. Copernicus Sentinel-2 (ESA) true-colour composite of the central area of the Venice Lagoon (19th March 2020). The dashed-dotted white line indicates the Malamocco-Marghera Channel (MMC). The map shows the location of: Misericordia (M) and Punta Salute (S) gauge stations, Lido turbidity station (L), Grand Canal (C), Giudecca channel (G) and passenger terminal (T). White boxes show the locations of the following figures.

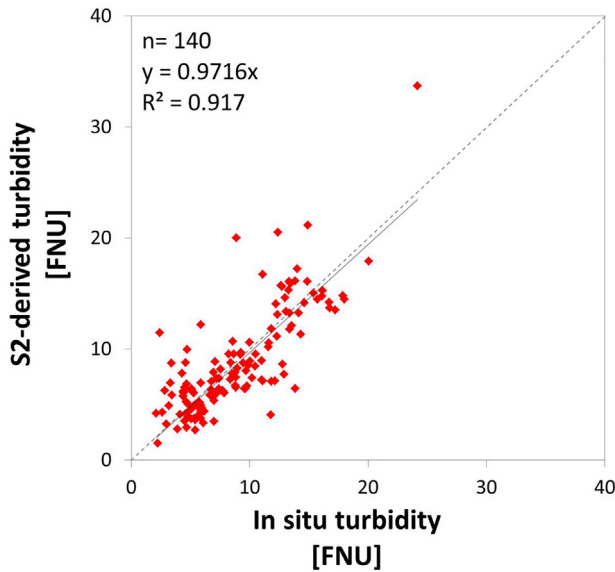


Fig. 2. Scatter plot of the S2-derived turbidity vs in situ turbidity measurements for 140 match-ups stations, sampled in 2017–2020. Turbidity values were retrieved according to Dogliotti et al. (2015). Solid line is the best-fit regression. Grey dotted line is the 1:1 line.

del Veneto (ARPAV). Tidal levels and wave data from gauge stations in the city centre (*Punta Salute* and *Misericordia*, respectively; S and M in Fig. 1), wave and wind data from the *Acqua Alta Oceanographic Tower* (AAOT, at 16 km off the coast of Venice) were provided by the *Centro Previsione e Segnalazione Maree* of the city of Venice.

In the absence of available monitoring data, we estimated the intensity of local water traffic from the comparative analysis of significant wave height (H_s) data records for *Misericordia* and AAOT, even if H_s does not generally apply to the analysis of boat wakes. The *Misericordia* station is located in an area of heavy traffic, that induces a continuum of perturbations from a multitude of direct waves and reflections from channel sides. During periods of no wind-waves, H_s can then be used as a proxy of the overall effects of traffic on the water surface. Therefore, the mean of H_s values ($\overline{H_s}$) at *Misericordia* station was calculated for each period when H_s at AAOT station (not affected by traffic) was

lower than 0.2 m and longer than 24 h, thus excluding wind-wave intervals.

3. Results

Sentinel-2 true-colour images of Figs. 3 and 4 are framed on the historic centre of Venice and show part of the central and northern lagoon on selected dates. The reduction of the vessel traffic and their wakes from the periods before and during the SARS-CoV-2 outbreak was observable. On February 20th (Fig. 3A), the density of white wakes, that trace the moving boats, was relatively high alongside the large tidal channel of Giudecca and the Grand Canal, in the heart of the city (G and C, respectively, in Fig. 1). Particularly evident were also the wakes of speedboats and waterbuses connecting the city to the airport, north of the image area, and the other islands to the west. The situation recorded by the image was close to normal, as this was the busiest week of the Venice Carnival that attracts thousands of visitors to the city. On March 19th (Fig. 3B), the lockdown was already enforced with strict social distancing measures, the closing of commercial activities and boat traffic almost stopped. Few boat wakes were still visible around the city of Venice. The lagoon water was clearer with less suspended matter in the channels surrounding the city, particularly from Venice to Murano, towards the airport and the channel at east of Murano. The dark patches, which were visible north of the city on both dates, are the submerged vegetation over the tidal flats.

Variations in the intensity of the local water traffic following the lockdown are confirmed by the analysis of wave data at the *Misericordia* station (M in Fig. 1). In detail, the values of $\overline{H_s}$, the proxy for the traffic perturbations based on the wave measurements, decreased from 0.12–0.13 m in February to 0.05–0.06 m in mid March and April, even if H_s retained the day-night and weekdays-weekend modulations (see S1 in Appendix A Supplementary data). $\overline{H_s}$ values lower than 0.06 quantify the residual traffic, as observed in Fig. 3B, mostly composed of essential public services such as links to and from minor lagoon islands, garbage collection boats, and ambulances from the nearby city hospital.

Fig. 4 presents the comparison of the traffic intensity in the historic centre of Venice and around the Island of Murano during the Easter weekend of 2019 and 2020, a typical period of peak tourism influx similar to the conditions during the summer months. In the April 19th 2019 image (Fig. 4A), the boat traffic was more sustained than on February 20th, 2020 (Fig. 3A). This was almost completely absent during the

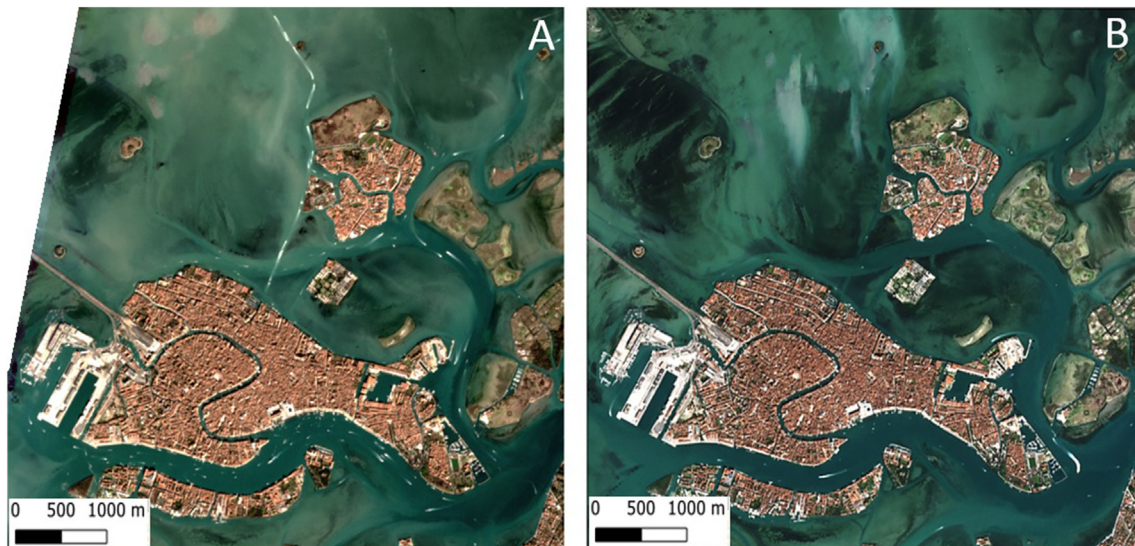


Fig. 3. S2 true-colour images in the lagoon of Venice on: A) February 20th (the last cloud-free day before any restrictive measure); B) March 19th (during lockdown). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

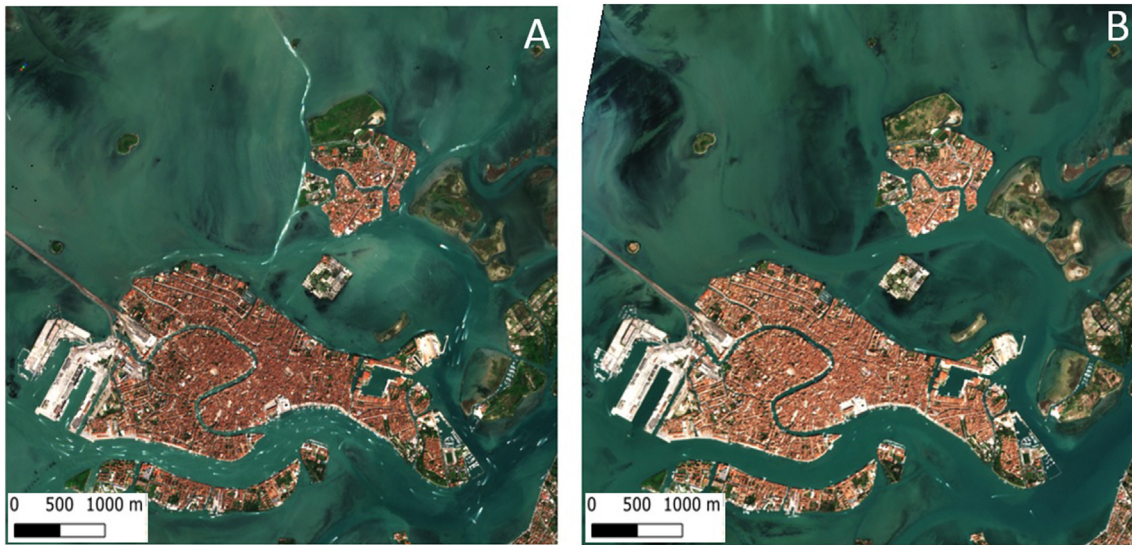


Fig. 4. S2 true-colour images in the lagoon of Venice on Good Fridays of 2019 and 2020: A) April 19th 2019; B) April 10th 2020 (during lockdown). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

COVID-19 lockdown period, the only vessels still visible being those of essential services (April 10th 2020, Fig. 4B). Cruise ships, visible in the passenger terminal on April 19th, 2019, are absent in the 2020 imagery. In February 2020, the cruise season had not started yet, while in the following weeks, the cruise industry underwent a deep worldwide crisis (Mallapaty, 2020; Moore, 2020). This caused a decrease of 65% in 2020 compared to 2019 in the port of Venice throughput statistics for the first trimester (North Adriatic Sea Port Authority, 2020).

Fig. 5 presents the S2-derived turbidity maps in ebb tidal phase for a portion of the northern lagoon extending from the airport to the city. Overall and around the city, the turbidity ranged 1–10 FNU for February 20th and March 19th images (Fig. 5A and B). On February 20th 2020 (Fig. 5A), the resuspension due to the wakes of speedboats, water taxis and airport shuttles, was quite intense in the channel connecting the airport water terminal to the city and in the nearest areas of the

adjacent sub-tidal flats, where the turbidity reached about 50 FNU. In the map of March 19th (Fig. 5B), when the lockdown was in place and boat traffic almost stopped, the turbidity in the channel and the airport harbour was comparable to that observed around the city (~5 FNU).

In the hours before the April 15th satellite overpass, northeasterly winds (*Bora*, N-NE) reached 20 m/s and determined a $\overline{H_s}$ of 0.3 m at the *Misericordia* gauge station. Wind- and wave-driven resuspension increased turbidity to a range of 25–50 FNU in the northern lagoon as seen in Fig. 5C.

In the sub-tidal flats north of the Island of Murano, small plumes of brown and grey suspended sediments are visible in the true-colour composites (Fig. 3) and in the turbidity maps (35–50 FNU) in Fig. 5. These originate within the clam harvesting concession areas where bottom sediments are mobilized by the shellfishing gears as point sources. The activity, normally performed on weekdays, is a recurrent source of

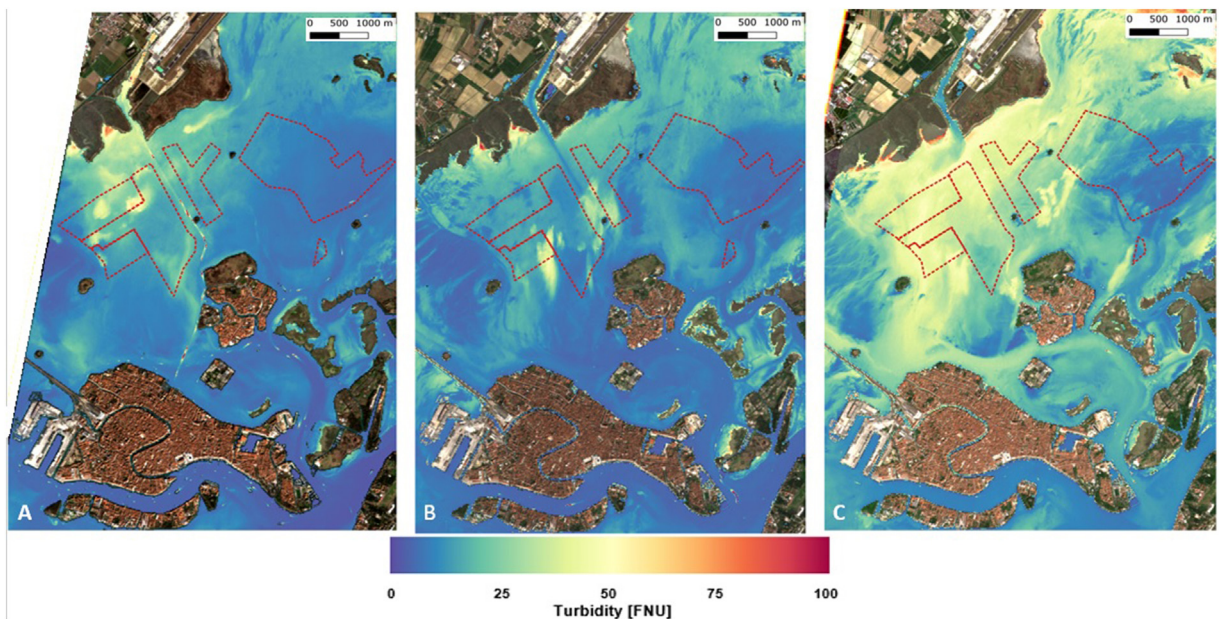


Fig. 5. S2-derived turbidity maps for the North Lagoon: A) February 20th, B) March 19th and C) April 15th 2020. Red dotted lines outline the clam harvesting concessions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

suspended particles which are then diffused across the sub-tidal flats. On weekends and holidays, this perturbation is normally absent as shown by the maps in S2 Appendix A Supplementary data (cf. April 5th, 13th, 25th). Clam harvesting plumes could not be clearly delineated on the April 15th map (Fig. 5C), because of the higher background turbidity due to wind-driven resuspension. In the same area, also distinguishable is a plume of low-turbidity water ebbing from the airport water terminal, sheltered from the wind, into the sub-tidal flat. This situation was never observed before in the presence of traffic. In the terminal, turbid water (35–60 FNU) is normally maintained by turbulence, due to boat manoeuvres (Fig. 5A). This water mixes with the relatively less turbid water of adjacent shallows in ebb tide.

Commercial shipping is one of the essential activities that continued throughout the lockdown and was not subjected to restrictions (GURI, 2020b, 2020c), as confirmed by official port of Venice throughput statistics for the first trimester of 2020 (North Adriatic Sea Port Authority, 2020). It is not frequent that a satellite image captures the passage of a commercial vessel in the navigation channel and only a few such images are available in the Copernicus catalogue. Fig. 6 shows an example of the transit of a cargo ship in the Malamocco-Marghera Channel (MMC; Fig. 1) which is locally 60 m wide and 11 m deep. Consistent with the northern lagoon on other dates (Fig. 5), the turbidity ranged 3–10 FNU in the central lagoon basin, on April 3rd. The ship wakes increased suspended particulate in the channel as well as on sub-tidal flats, and the impacts are visible both in the true-colour composite (Fig. 6A), as brown resuspended clouds, and in the turbidity map (Fig. 6B), as patches of high values exceeding 50 FNU. By comparison, the smaller vessel heading south in Fig. 6 had limited displacement and produced only a surficial wake in the channel. The localized resuspension at the channel edges provides a synoptic demonstration of the effects of ship traffic

on the morpho-dynamics of the area documented with in situ observations, aerial and satellite imagery by Zaggia et al. (2017) and Scarpa et al. (2019).

4. Discussion

The COVID-19 lockdown has provided a unique opportunity to observe the lagoon without water traffic, one of the main anthropic disturbances. Pseudo true-colour composites Sentinel-2 imagery proved useful for qualitative visual interpretation and the validated turbidity images allowed a quantitative analysis of suspended matter patterns. The capabilities of S2 imagery were adequate to address the investigated processes as: i) the 10 m spatial resolution is suitable to describe the several natural and human-induced processes controlling the water transparency in the Venice Lagoon; and ii) the 2–3 days effective revisit time of the S2 A and B combined constellation generally enables the selection of cloud-free images acquired in similar tidal conditions.

In the period of March–April 2020, the local water traffic was dramatically reduced among public transportation, tourist and leisure boats, and commercial boats delivering daily supplies in the city, as shown in Figs. 3 and 4. This reduction also reflects the decrease in city users and tourism-related demand for the transport supply chain. When the boat traffic almost stopped, the proxy $\overline{H_s}$ decreased from 0.12–0.13 m to 0.05–0.06 m and the turbidity in the airport-city route and the airport water terminal became comparable to that normally found in lagoon areas around the city.

The unprecedented water transparency reported in the city canals is certainly a positive environmental consequence of the lockdown following SARS-CoV-2 epidemic. However, we observe that this is an ephemeral condition due to a combination of factors:

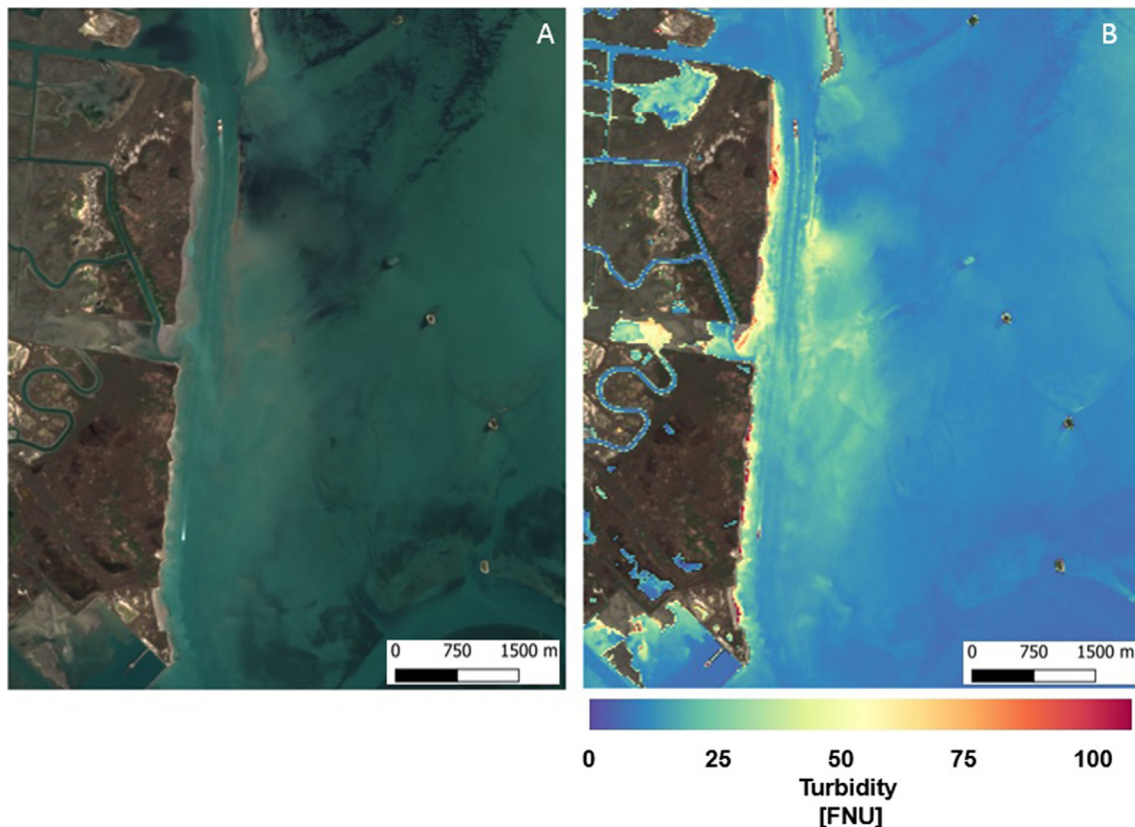


Fig. 6. S2 image of April 3rd 2020 along the Malamocco-Marghera Channel: A) true-colour; B) turbidity map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- The minimized impact of boat and cruise ship wakes, which generate erosion and particle resuspension on the tidal flats and marshlands, around the city and in the northern lagoon (Fig. 5A and B).
- The release of the traffic pressure, which suggests a reduction of turbulence in the water column, potentially favouring particle settling and deposition.
- A decreased wastewater discharge in the canals, as it can be inferred from the halving of the apparent population to only the official residents.
- A lower runoff from lagoon tributaries: the first four months of 2020 were characterized by the lowest precipitation in the last two decades. The cumulative rainfall for 2020 and average 2001–2019 are respectively 94 mm vs 248 mm in the city centre and 127 mm vs 283 mm in the tributary basin.
- The phytoplankton phenology, that is at the start of the growth cycle in late winter/early spring, leading to high water transparency in the lagoon and the Adriatic Sea.

As we already observed, wind-driven resuspension is an important natural process affecting the suspended sediment across the lagoon and the canals, as confirmed by the turbidity pattern on March 6th and April 5th, 2020 (not shown, see S2 in Appendix A Supplementary data) and April 15th, 2020 (Fig. 5C) in the absence of boat traffic. The high water transparency reported by the media and evident in some of the S2 imagery corresponded to periods of low wind speed.

The lower turbidity levels in the water column increase light penetration, and may have positive impacts on marine benthic ecosystems in the area. Furthermore, this is likely to reduce in the city canals the contaminants commonly associated with suspended particulate matter (Dabala et al., 2005). Alas, satellite observations cannot provide information on the chemical composition of the particulate assemblage and thus dedicated field studies are being carried out to describe the changes in contaminant loads in the lagoon.

In the mid-term, the intensity of boat traffic will remain anomalous for the remainder of 2020, even as lockdown measures will be progressively eliminated (GURI, 2020d). Normally, in spring and summer, the local water traffic is mainly in and around the city, and along the extremely congested airport-city route and from the mainland, passing through the delicate ecosystems of tidal flats and marshlands. Particularly affected are the St. Mark's basin and the Giudecca Channel, where the regular traffic shares the channels with large cruise ships that during the warm season, commonly amount to 5 vessels per day for a total of 10 passages. A new start of the cruise industry and associated traffic in Venice is unlikely to occur before the end of 2020. At the same time, it is possible that the traffic of minor vessels related to tourism will remain markedly below the pre-outbreak levels.

The positive environmental consequences of COVID-19 pandemic for the Venice canals and the lagoon will then presumably continue for most of 2020, even if the water transparency will decrease as an effect of the summer phytoplankton growth peak. This unexpected large-scale experiment will allow the research community to continue to investigate the seasonal evolution of this ecosystem under reduced anthropic pressures. Future research work should take into account the in situ observations acquired at monitoring stations across the Venice Lagoon that unfortunately were not readily available during these particular times, carry out specifically designed field activities and also consider the use of modelling tools to quantitatively describe the processes affecting water transparency.

CRedit authorship contribution statement

Federica Braga: Conceptualization, Writing - review & editing, Formal analysis, Investigation. **Gian Marco Scarpa:** Writing - review & editing, Formal analysis, Investigation. **Vittorio Ernesto Brando:**

Conceptualization, Writing - review & editing, Formal analysis, Investigation. **Giorgia Manfè:** Formal analysis, Investigation. **Luca Zaggia:** Conceptualization, Writing - review & editing, Formal analysis, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2020.139612>.

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