SWIM: Safe Water Innovative Monitoring

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1. Introduction

Bathing activity is one of the first tourist attractions of many coastal towns in the period from May to October and the guarantee of swimming in unpolluted waters plays a fundamental role in the tourist activity of the site.
Due to short and intense precipitation events, e.g. summer storms, spills of water rich in suspended solids, accumulated in dry periods, can alter the water quality, specifically the physical, chemical and biological parameters, preventing a safe bathing.
In Italy, following the Water Framework Directive 2000/60/CE (WFD), the quality of the bathing waters is assessed by measuring on set dates, specifically once a month in the bathing season, independently of a precipitation event, only two bacteriological parameters: Escherichia Coli (E.C.) and Intestinal Enterococci (I.E.).
Unfortunately, these measurements carried out by the Regional ARPA fails, in most cases, to catch those accidental spills of the sewage drains result of intense precipitation events or due to the malfunctioning of the system.

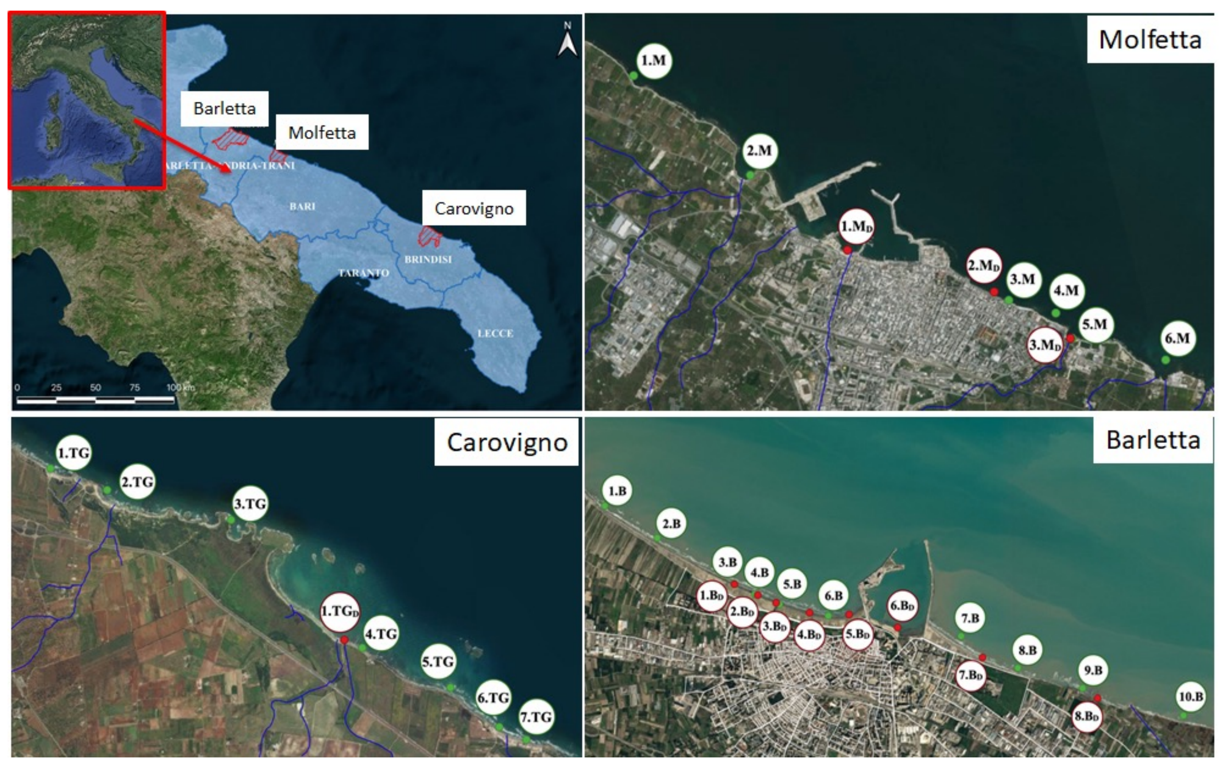
An **innovative methodology** based on the reflectance measurements collected by satellite is developed in order to provide a decision support system for a safe bathing in coastal waters.
This methodology is based on remotely-sensed reflectance changes, both in the VIS and NIR bands, with respect to low base values regardless of the precipitation and of the chemical constituent in the water.
The analyzes are conducted along the Puglia region coasts of three municipalities (Italy) between 2016 and 2019, using multi-satellite information at different spatial and temporal resolutions from Sentinel-2A, Landsat 8 OLI and Landsat 7 ETM.

2. Case study

The analyzed areas are located in the Puglia region, along the Adriatic coast, specifically, the coastal areas of the municipality of Barletta, Molfetta and Carovigno.

The territory of **Barletta** is part of the Ofanto valley basin, and it's washed by the homonymous river, while the territory of **Molfetta** is located a little further south, in the province of Bari. Both municipalities are characterized by the presence of a port along their coasts. The third area analyzed is **Torre Guaceto**, a protected marine area located in the Salento area, along the coast of the municipality of Carovigno.

All the case studies are characterized by drainage urban systems which flow into the sea water.
Two type of monitoring points along the coasts are considered, specifically the monitoring stations of Puglia Regional Environmental Protection Agency (ARPA) and the outlets of the drains of the sewage systems.



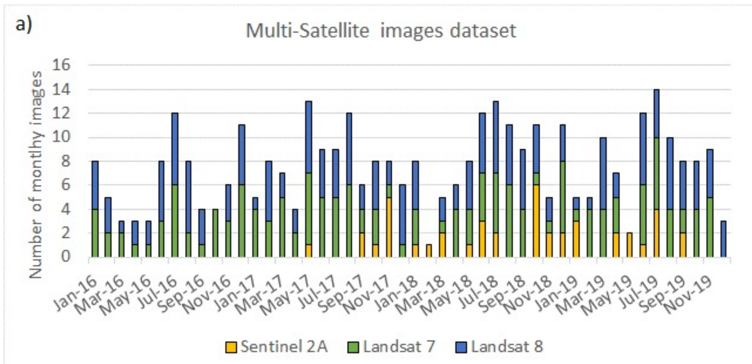
ARPA monitoring stations - Barletta		Drains of the sewage system - Barletta	
1.B	500 mt. Sud Fogna citt.na Barletta	$1.B_D$	Scarico M
2.B	Staccionata	$2.B_D$	Scarico I
3.B	Pilastro funivia	$3.B_D$	Scarico H
4.B	Sfioratore d'emergenza	$4.B_D$	Scarico F
5.B	2° Sfioratore d'emergenza	$5.B_D$	Scarico C
6.B	Strada che scende a mare	$6.B_D$	Scarico canale 3
7.B	Stabilimento balneare militare	$7.B_D$	Scarico collettore E
8.B	Cartiera Burgo	$8.B_D$	Scarico collettore F
9.B	Zona belvedere difronte recinto villino		
10.B	Spiaggia Verde		
ARPA monitoring stations - Molfetta		**Drains of the sewage system - Molfetta**	
1.M	Fogna citt.na Molfetta	$1.M_D$	Scarico Porto
2.M	Scogliera	$2.M_D$	Scarico Lungomare
3.M	Acque pluviali via Isonzo	$3.M_D$	Scarico Lama Martina
4.M	Lido park campo sportivo		
5.M	C.A. Torre lama cupa o 1' cala		
6.M	Il cala ristorante Astoria		
ARPA monitoring stations – Torre Guaceto		**Drains of the sewage system - Torre Guaceto**	
1.TG	Punta bufaloria – Spiaggia aeronautica	$1.TG_D$	Scarico Canale Reale
2.TG	Punta penna grossa		
3.TG	Torre Guaceto Cala antistante		
4.TG	Torre Guaceto Canale Reale		
5.TG	Di fronte allo scoglio di Apani		
6.TG	Lido S. Vincenzo		
7.TG	Lido Azzurro		

3. Input Data

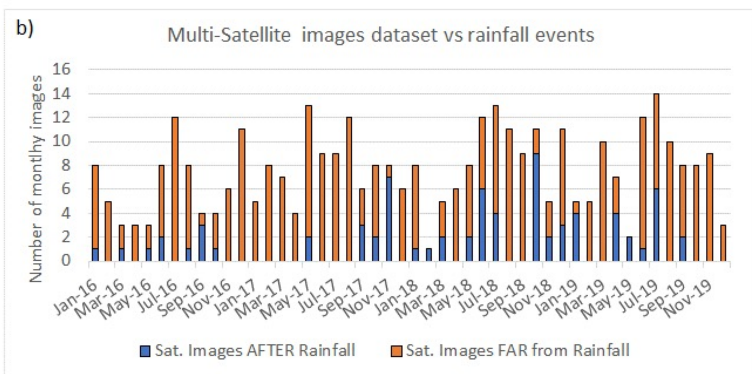
The **pluviometric data** are obtained from the MeteoNetwork stations, part of a network of meteorological stations spread throughout the Italian territory. Daily rainfall data from 2016 to 2019, are extracted from the stations closest to the case study sites. For each site, a series of the precipitation **events characterized** by a **volume greater than 20 mm** is created, to consider only the most intense precipitation events, which should be responsible for sediment movement and load into the sea.
Overall, a total of **16** precipitation events were collected for the site of Barletta, **28** for the site of Molfetta and **34** for the protected marine area of Torre Guaceto.

Satellite data
From **Sentinel-2A** satellite are acquired only images after the identified precipitation events, considering only clear sky. A maximum of five days of temporal lag is considered between the selected image and the end of the precipitation event.
On the other hand, for **Landsat 7-8** satellites, to enrich the dataset, all available satellite images are taken into consideration from the beginning of 2016 until the end of 2019, without distinguishing between images close or not to a precipitation event (b).
A total of 43 images is available from Sentinel-2A, 154 from Landsat 7 and 166 from Landsat 8 (a). Overall considering all three satellites and all three sites of interest, **were elaborated about 363 images**. Due to the different revisit time of the two satellites and the extremely frequent cloud cover, the number of available scenes of Landsat 7 and 8 coincident with Sentinel-2A images is significantly low: 2 for Barletta, 5 for Molfetta and 4 for Torre Guaceto respectively.

a)

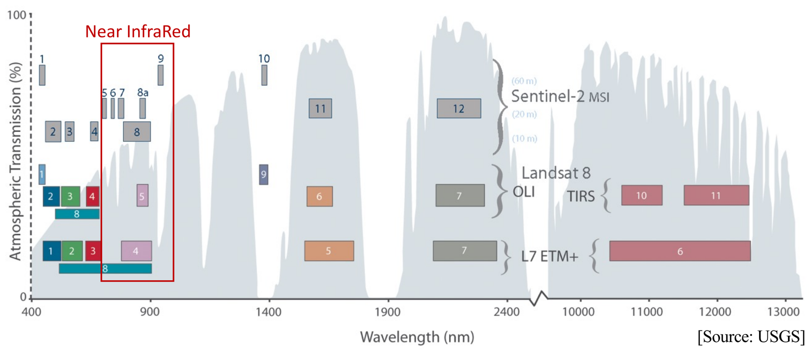


b)



Satellite	Sentinel-2A	Landsat-8	Landsat-7
Sensor	MSI	OLI	ETM+
Wavelength range (μm)	0.443–2.190	0.435–2.294	0.45–2.35 (10.40–12.50)
Number of bands	13	9	8
Spatial resolution (m)	10-20-60	30 (15 panchromatic)	30 (60 thermal – 15 panchromatic)
Repetitivity (days) with constant viewing angles	5	16	16

Characteristics of the selected satellites.



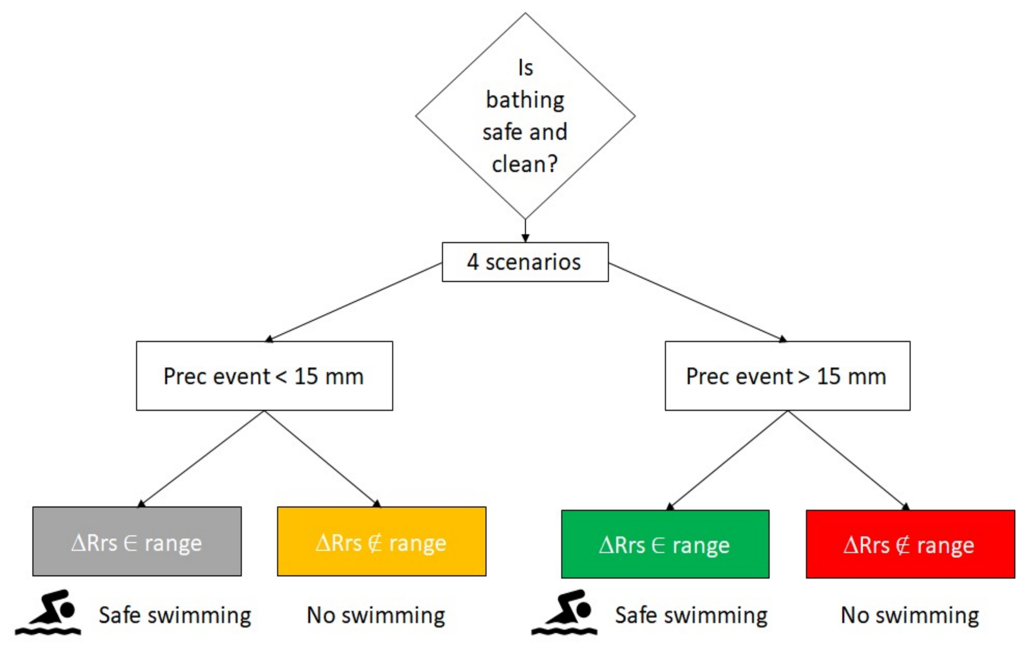
	Sentinel 2A	Landsat 7	Landsat 8
n° images Barletta	8	50	62
n° images Molfetta	12	54	57
n° images Torre Guaceto	23	50	47
Total processed images	43	154	166

Numerosity of the satellite images dataset for each site.

Looking at the spectral resolution, the principal difference between the three selected satellites can be found in the **NIR spectral region** (NearInfraRed bands). Specifically, the two Landsat satellites are characterized by a single spectral band in the NIR region (851 – 879 nm for Landsat 8 and 772 – 898 nm for Landsat 7), while Sentinel 2A has a richer spectral configuration, where 6 bands can be found.

4. Methodology

The developed methodology provides a **DECISION SUPPORT SYSTEM** for a safe and clean bathing, or, on the contrary, discouraging the bathing activities, based on the evaluation of the variations of the remote sensing reflectance over time in respect of a pre-defined average reflectance value of clean water and confidence thresholds.
This methodology aims at people's sensitivity, based on the simple color of the water (clear blue or brownish), not on the health hazard defined by the values of E.C. and I.E. in the Water Framework directive.
In the end, from the developed methodology, it is suggested a safe and clean bathing when the analyzed reflectances are categorized as "grey points" or "green points", while the bathing activities are discouraged when the reflectance are categorized as "yellow points" or "red points".



5. Results

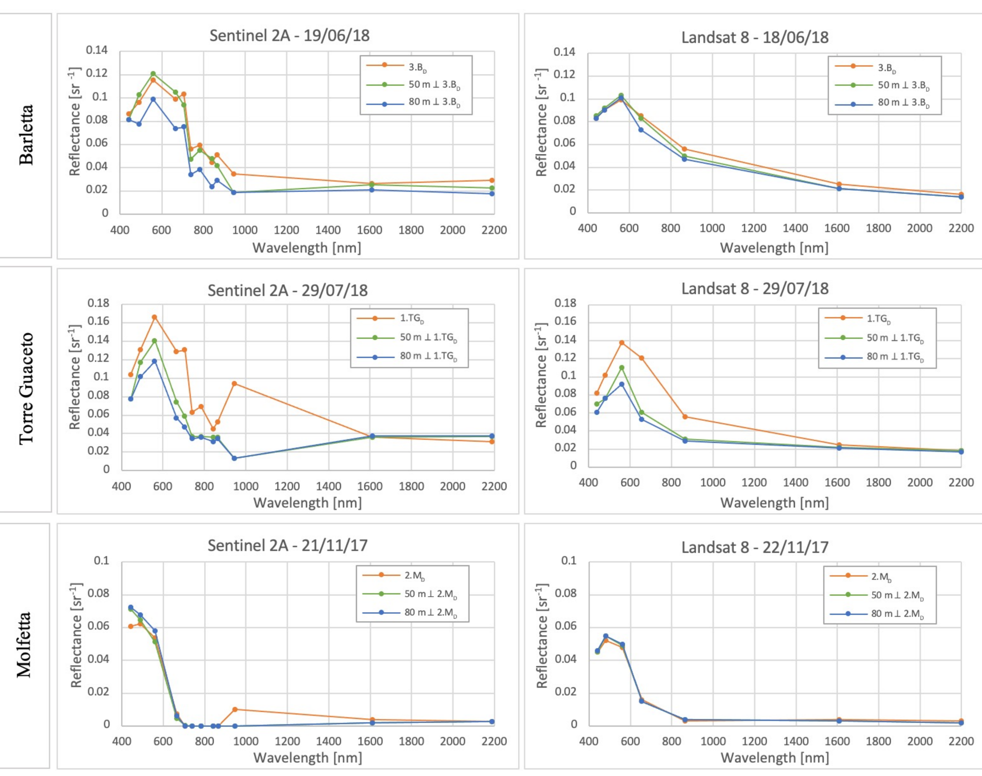
Sentinel 2A and Landsat 7/8 reflectance spectra comparison

The resulting spectrums obtained from the Sentinel-2A images are firstly compared with the spectrums obtained from the two Landsat satellites (7/8) that refers to the same precipitation event. For one drain point of each site, the variation of the reflectance spectrums moving away from the coast into the open sea is analyzed.

In general, there are two reflectance peaks for each spectrum: one is located between 550 nm and 750 nm, and the other between 750 nm and 800 nm. This is clearly visible in the Sentinel-2A spectra, while Landsat satellites, due to their spectral configuration that doesn't have a NIR spectral band around that specific wavelength, miss it. The first reflectance peak in the VIS region is usually the highest one and allow to immediately identify if there is a variation in water quality, whereas the second one located in the NIR region is characteristic of highly turbid waters.

Moving away from the coastline the second peak, visible near the shoreline, reduces significantly or completely disappears due to the strong absorption of water which become clearer.

In open water the spectra of all satellites assume a similar shape that is the typical one of a clear coastal water. At the wavelengths lower than 490 nm and higher than 950 nm, the reflectance are similar at all analyzed points.



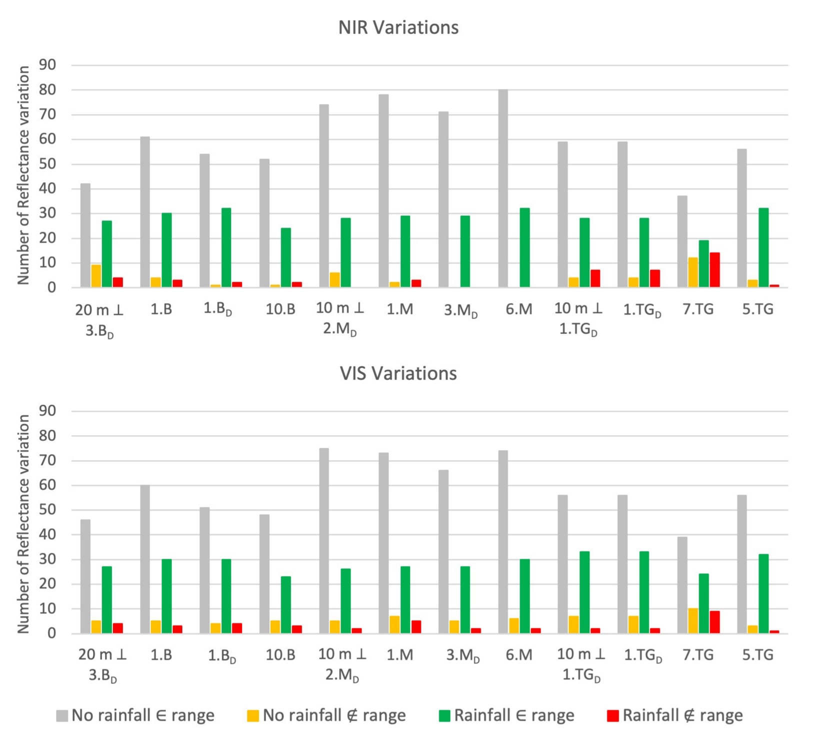
Comparison between precipitation and reflectance variation (VIS and NIR)

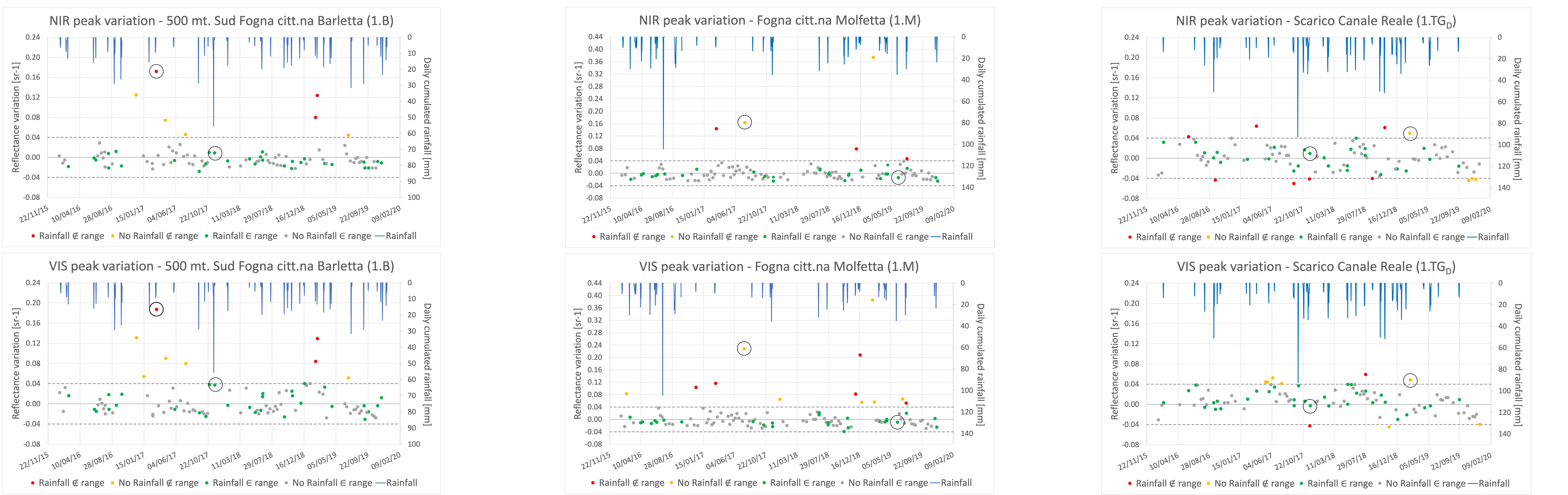
Following the methodology, the average reflectance values and their confidence interval related to clean water (± 0.04 sr^{-1}) are evaluated in the NIR and VIS bands, characteristic of those days where no rainfall was registered.

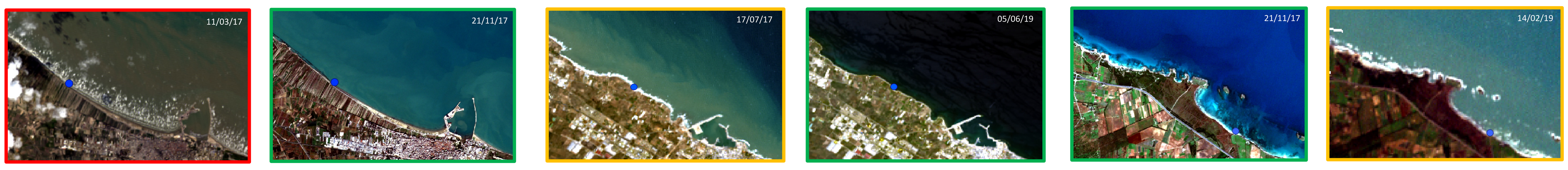
Mean reflectance value of clear water	Barletta	Molfetta	Carovigno
NIR	0.03	0.03	0.05
VIS	0.04	0.04	0.04

In general, similar results are obtained for both the analysis (VIS and NIR). Anyhow, as already stated, some differences are observable due to the different level of water colour variations: the reflectance changes in the VIS allow to immediately identify if there is a variation in water quality, while the NIR peak allows to discriminate which are the most polluted areas being present only for more turbid waters.
Overall, in any analyzed point, most of the collected data refers to days when no rainfall is recorded (66.5 % of total data in both spectral bands) and, among these, most of the reflectance variations are not exceeding the considered limits (93.4 % for NIR and 90.7 % for VIS of no rainy days) ("grey points"). Between 20 and 30 days fall the numerosity of the data related to precipitation events characterized by a volume bigger than 15 mm that anyhow shows a small variation of reflectance, keeping consequently inside the set limits (89.1 % for NIR and 89.8 % for VIS of the total rainfall days) ("green points").Much smaller are the two classes related to the high variations of reflectance that exceed the imposed range limits. In particular, the "yellow points" constitute the 6.6 % for NIR and 9.3 % for VIS of the non rainy days. The "red points" represent the 4 % and 3.5 % of the total analyzed images for NIR and for VIS, respectively, while about the 10 % of the rainy days.

Some exceptions are clearly identified as the most critical points where the highest number of exceedances are recorded. In this category fall points 7.TG (Lido Azzurro), 1.B (500 mt sud Fogna citt.na Barletta) and 1.M (Fogna citt.na Molfetta). Points $3.M_D$ and 6.M are perfect examples of the differences caught by VIS and NIR peak. Both have some exceedance values in the VIS spectrum while no one is registered in the NIR bands, showing that there is a variation in water quality but not so high to be detected as very turbid waters.



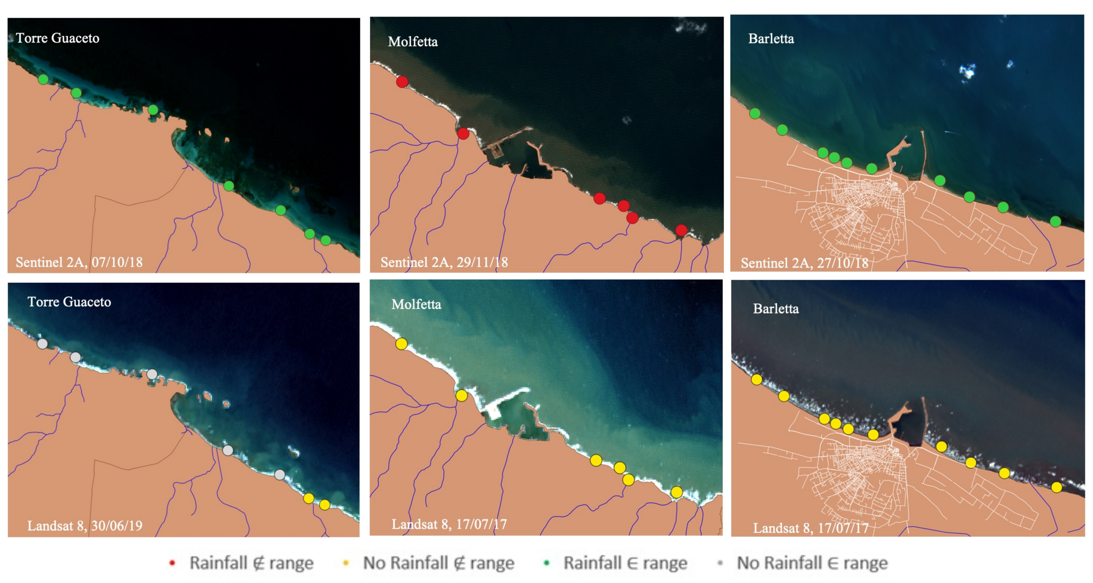




6. Safe and clean swimming suggestion

The developed methodology allows to produce pixel-based images, and hence points information, of bathing advice based on VIS or NIR peaks variations. In general, for being conservative in the identification of water turbidity water changes, the swimming suggestion is based only on the VIS reflectance variations. Analyzing case by case, according to the classification of the reflectance variation, it is possible to provide an indication relating to bathing in all monitored points along the coasts.

Here are shown two examples of safe and clean swimming maps suggestion for each site analyzed. Specifically, the Sentinel-2A images are post precipitation images, while the Landsat 8 images are of days far from precipitation.



7. Discussion and Conclusions

The implemented methodology allows to define the quality of the coastal water intended for bathing through the direct analyses of the variations of satellite reflectance values in the VIS and in the NIR bands based on the overpasses of clean water thresholds and their link to precipitation events. In particular, the NIR peak allows to discriminate the degree of turbidity of the water. These results highlight the potentiality of Sentinel-2A data thanks to its NIR band, able to detect this second reflectance peak.

The main characteristic of the proposed methodology is that it is not based on absolute reflectance values, but on variations not influenced by satellites differences. In addition, the methodology is also not based on any algorithm for the retrieval of turbidity or TSS developed for a specific sensor.

On the other hand, an uncertainty embedded in the developed methodology is related to the fact that the detection of reflectance variations may be not always due to the individuation of a land source of pollution into the sea, but on some occasion may be related to larger water currents which transport sediments. Anyhow, this doesn't interfere with the validity of the proposed methodology, indeed it confirms its robustness, which aims on providing a suggestion for a safe and clean bathing.

Another uncertainty that needs to be taken into consideration is the temporal lag elapsing between the satellite acquisition and the end of a precipitation event, i.e. the time after which the effects of a precipitation event are detectable by satellite.

Overall, the obtained results are an important step ahead in respect to the available literature on bathing advice services which are mainly based on ground data or on satellite derived data of suspended solids or turbidity estimates that are mainly related to open waters.