EFFECT OF WATER LEVEL ON MIGRATORY BIRDS HABITAT AT LAKE MAGGIORE

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ABSTRACT:

Migratory birds need to stop along their route to rest and feed at so called stopover sites. "Bolle di Magadino" is a protected wetland located near lake Maggiore (CH), an internationally recognized nesting and stop-over site for birds. The waters of Lake Maggiore are important resources for multiple usages, and are artificially regulated through a dam. Even slight variations in the water level are sufficient to cause flooding and draining of large portions of the wetlands, affecting foraging and resting opportunities for birds. We use open data and FOSS4G to study the effect of water level on bird migration. We compared the extent and type of flooded habitat using two approaches: Sentinel-1 remote sensing imagery and simulations based on the measured water level. The effect of type and extent of submerged vegetation obtained with both methods was tested against a time series of bird captures. Both methods had a similar temporal pattern of flooding in autumn, but nearly opposite in spring. The total extent and the type of submerged habitats showed significant differences. The results obtained by simulations based on water level were more correlated to birds captures and species richness than the estimations of flooded habitat derived by with Sentinel-1. The results presented here will contribute to the definition sustainable management tools of water management of lake Maggiore taking into account the effect of lake level on biodiversity.

1. INTRODUCTION

Lake Maggiore, the second-largest Italian sub alpine lake, and the Ticino River are water bodies shared by Italy and Switzerland: they are important water resource for drinking water, irrigation and hydroelectricity production but also for tourism and biodiversity. The cross-border character and the often conflicting needs of the different users make the shared management of this resource very complex, but of great importance. The water level of the lake is artificially regulated through a dam placed at the outflow in the Italian territory (Inderwildi and A., 2016). The north-south orientation of Lake Maggiore, like lake Garda (Tattoni and Ciolli, 2019), breaks the Alpine ridge creating an ideal corridor for the passage of migrant birds. The lake shores also provides important stop-over sites, used by many species of migratory birds to stop and feed during their journey (Saporetti, 2018). Due to their role as a "rest and recovery" habitats, stopover sites have a fundamental importance for migratory species, and are selected and revisited every year because of their geographic location (Tattoni and Ciolli, 2019) and the availability of food resources (Tattoni et al., 2019b). Due to the low retention capacity of Lake Maggiore, slight variations in the water level are sufficient to cause flooding and draining of large portions of surrounding territory (Inderwildi and A., 2016). Even small differences in vegetation or water depth could mean differences in foraging opportunities for birds and different protection from predators (Webb et al., 2010). The "Parchi Verbano Ticino" project supported by Regione Lombardia / EU – INTERREG Italia Svizzera 2014/2020 aims to study the effects of water levels of the lake on several environmental components, with a particular focus on protected natural areas.

In this area, where the lake level is managed, it is important to understand the human influence on stop-over sites and to propose management measures that could limit the alterations of habitat availability and quality for migratory birds. We expect that lake level regulation would cause alterations in migratory flows, especially in the total number of birds as well as the number of different species (species richness) that use this area as a stop-over site. We are going to estimate the extent and type of flooded habitat using two different approaches and data source: satellite imagery and hydrological simulations.

In the last decade, the amount of satellite imagery data freely available for society increased dramatically, thanks to open data policies by governments and space agencies and by technological advances (Gomes et al., 2020). Sentinel-1 is one of the missions that ESA is developing for the Copernicus initiative (ESA, 2021). The two satellites of Sentinel-1 program are designed to record information about water resources through a Synthetic Aperture Radar (SAR) sensor that is not affected by cloud coverage (Ovakoglou et al., 2021). This type of imagery is very promising for this case study, providing a time series of flooded habitat, resulting from the interaction of water level, weather and type of vegetation. Unfortunately, SAR images are not available on a daily basis, since the re-visiting time of the satellites can vary between 2-7 days. Several tools based on cloud computing and distributed systems are available (Gomes et al., 2020) to use and analyse this images with reduced calculation times.

Another way to estimate the inundated habitat is through simulations, using as input the water level and the topography of the area. Free and Opens Source GIS, especially GRASS (GRASS Development Team, 2022), provides the necessary tools for processing of spatial information, from education

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(Ciolli et al., 2017), to image analysis (Zatelli et al., 2019b, Gobbi et al., 2018a, Zatelli et al., 2019a) to hydrological analysis. The advantage of this approach is that the flooded habitat can be calculated on a daily basis (even hourly, id data are available), the limit is that simulations are time consuming and they can over-simplify the behaviour of the water in large and complex water basin such as lake Maggiore.

In this case study, it would be ideal to have information on a daily basis, but since SAR, that we expect being more informative is not available, we are going to understand which approach is more suited for understanding the effect of water level on bird migration as follows: 1) Calculate the inundated bird habitat using a simulation based on measured water level; 2) calculate the inundated habitat from Sentinel-1 remote sensing imagery 3) Compare the flooded area derived from S1 and from simulation; 4) Evaluate the effect of water level and type of submerged vegetation on migrant birds.

2. MATERIALS AND METHODS

The study area is centred around "Bolle di Magadino", a protected wetland located on the north shore of lake Maggiore at the confluence with the Ticino river (Switzerland, 8° 51'56.90"E, 46° 9'42.17"N). The area is a recognized nesting and stop-over site for birds, listed as a Ramsar Wetland of International Importance and as an Important Bird and Biodiversity Area (IBA) (Figure 1).

Daily passage of migrant birds have been recorded at Magadino ringing station during spring migration and since 2019, net captures were coupled with an Avian Vertical-looking Radar. The total number of individuals and the total number of species (species richness) were provided as daily aggregation. In this study, we focus on the following periods, during which bird monitoring systems were both deployed: P1: 2019-05-01–2019-06-20; P2 2019-10-01–2020-02-20 and P3 2021-02-01–2021-07-20.

2.1 Data collection

In order to describe the wetland habitat we used the vegetation map provided by Fondazione Bolle di Magadino, that reported vegetation types derived from a phyto-sociological field survey. We aggregated the original over 100 typologies and their subclasses into 10 categories summarizing the main habitats and land use classes using QGIS 3.20.3-Odense (QGIS Development Team, 2022). The final habitat map covers an extent of 6.7 km², including the 1500 ha of the Bolle di Magadino wetland, see Figure 1. The resolution of all maps was 10 m, except the DTM that has 0.5 m, the CRS used in this work were WGS84 in GEE, and the local CRS GCS_CH1903 for all the other analysis.

2.1.1 Satellite imagery We used the Google Earth Engine Platform (GEE) (Gorelick et al., 2017) to extract Sentinel-1 Synthetic Aperture Radar (SAR) images (ESA, 2021) for the three time frames of interest. GEE is an open source cloud-based platform for planetary-scale geospatial analysis developed by Google (Gorelick et al., 2017) and provides access to a large catalogue of satellite images without the burden of downloading locally entire series of scenes (Stromann et al., 2020, Tattoni et al., 2019a). The calculation was implemented GEE with the approach described by (Gorelick et al., 2017), using the Edge Otsu Algorithm with terrain correction (Markert et al., 2020). The threshold was calculated for our study area and for each of the three time frames, adapting the code provided by (Open Geo Blog, 2021). The inundated areas were then overlapped with the land use map in order to estimate the extent of the submerged vegetation over the three time period defined.

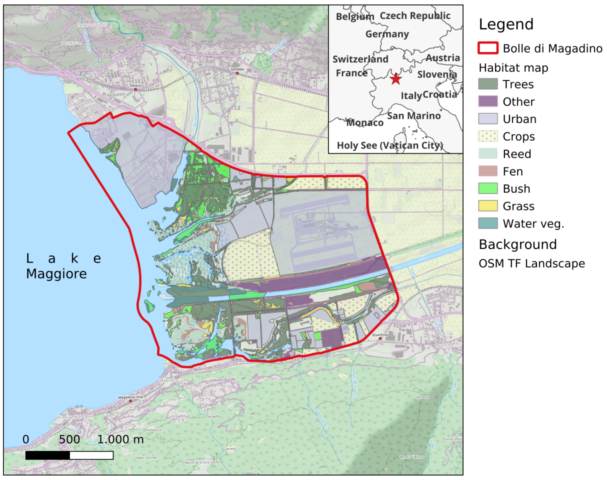

Figure 1. Location of the study area "Bolle di Magadino" (Switzerland) and habitat map. Background map: maps © `www.thunderforest.com`, data © OpenStreetMap contributors `https://www.openstreetmap.org`. World borders in the inlet map: `thematicmapping.org`

2.1.2 Hydrological data We downloaded the daily lake water level and rainfall from the Agrometeo portal `https://www.agrometeo.ch` (Agrometeo Svizzera, 2022). The level of the lake measured at the nearest hydrological station (Locarno, CH) was used to calculate the inundated area using the module *r.lake* in GRASS GIS (GRASS Development Team, 2022) DTM: using a DTM that included also the lake bathymetry (cell size 0.5 m). The DTM was developed merging the EU-DEM 25 m DEM (version 1.1, 2017, available at `https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem`) with local point elevation measures made in the Magadino area. Rainfall was measured at the meteorological station of Cadenazzo (CH), located about 5 km from the wetlands. The average daily rainfall was 5.2 mm (0–71mm), with a seasonal pattern: the heaviest precipitations occurred in autumn/winter.

2.1.3 Time series analysis In order to manage the irregular time series (Sentinel-1 data were not available every day but with an irregular pattern) we used the r-packages *lubridate* (Grolemund and Wickham, 2011), *TSstudio* (Krispin, 2020) and *zoo* (Zeileis and Grothendieck, 2005) that is particularly suited for this data set as it provides several functions for replacing missing observations. The correlation between series was analysed with cross-correlation function in order to explain the variation of the series over time. The available literature about irregularly sampled time series is limited (Kreindler and Lumsden, 2006) and we relied on the results of (Kreindler and Lumsden, 2006). that irregularly sampled data sets with as much as 15 percent missing data can be re-sampled and analyzed with techniques that assume regular sampling without introducing too much errors.

3. RESULTS

We used Edge Otsu Algorithm with terrain correction (Markert et al., 2020) to estimate the inundated areas from a collection of 236 Sentinel-1 images for the three time periods when bird migration was also monitored. During the time considered, Bolle di Magadino were visited by Sentinel-1 satellites on average every 1.6 days, with a maximum of 6 days between to consecutive passages (6 times) and a median of 1 day

The area covered with water, according to S1, varied between 81.45 and 171.17 ha (108.07 ± 19.7 ha), some of the surface is a permanent wetland so it is never completely dry (Figure 1). The GEE script used the re-classified vegetation map to calculate the extent of flooded habitat. Each of the 10 land use classes was affected differently by the flooding: when the water was at its highest, the grassland was completely inundated, crops submerged for 26% of their extent whereas urban areas and infrastructures were not affected (less than 1% underwater), see Figure 2.

During the time considered in this study, the level of the lake ranged between 192.3 and 194.9 m.a.s.l, with a minimum during the months of April and May, when the waters are used to irrigate the rice fields downstream, and a maximum in late autumn. We created a script that called the GRASS module *r.lake* for all water levels inside the range observed, with an increment of 0.01 m at each step. The simulated flooded area calculated from the water level ranged from 74.54 to 251.3 ha (154.41± 39.82). The maps of flooded area for each level were then overlapped to the same habitat map, obtaining the amount of underwater habitat for each level of the water, Figure 2.

Both methods showed a similar temporal pattern (Figure 2), however the extent of the flooded area estimated with GRASS was generally bigger that the one obtained by satellite imagery.

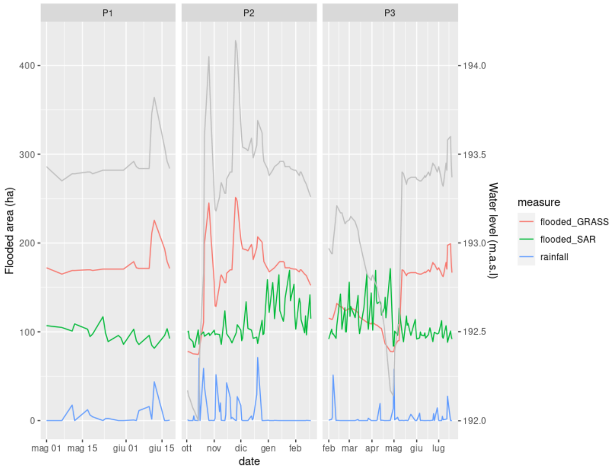

Figure 2. Temporal trend of total flooded area calculated with SAR and GRASS GIS in the protected area of Bolle di Magadino near lake Maggiore (CH) during the three periods of monitoring. The left x axis reports the hectares of inundated area and mm of rainfall, the grey line shows the lake water level reported on the right y axis

Considering the seasons of the year instead of the three periods, we observed a seasonality in the correlation between the flooded habitat calculated with the two methods. The temporal cross-correlation between the inundated areas obtained using GRASS and S1 was significant for winter time, periods P2 and P3, but not for P1 and P3 spring times(Figure 3). The blue dashed lines of Figure 3 show significance interval and the bars that run through these lines have statistical meaning: a greater correlation occurred with more recent lags, 0-3 days, and decreased over time, meaning that the two series are temporally correlated.

In winter when the level of lake is not so heavily managed in order to store water for spring, there is a significant agreement between the two methods. During spring instead, when the water is used for irrigation, the inundated areas calculated from WL and from satellite imagery have opposite temporal trends. This is especially evident in P3 spring, the total flooded area obtained by SAR imagery was greater than the one issued by GRASS simulations. This effect was probably due to the sensitivity of SAR to the amount of rainwater retained by some habitats (see Figure 1) even if the water of the lake was heavily taken for irrigation.

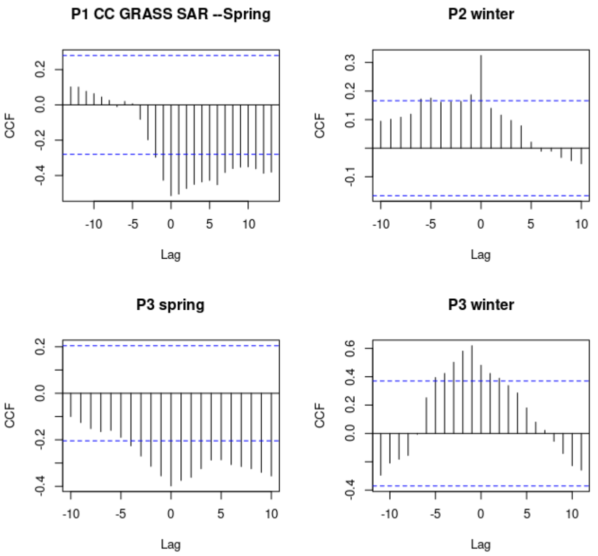

Figure 3. Seasonal variation of the cross correlation function (CCF) between the inundated areas calculated with GRASS from the lake water level and from Sentinel-1 (SAR), lags are expressed as days. The blue dashed lines are referent to a significance interval, the bars that run through these lines have statistical meaning

The differences in the type and extent of flooded habitat were taken into into account and summarised in the box-plot of Figure 4. Two land use classes ’not classified’ and ’permanent water’ were omitted from the graph of Figure 4, because the first was not informative and the latter had no variation. Multiple T-test were performed in R grouping the data by habitat: the flooded area was significantly different ($p<0.05$) between the two methods for all habitat types. The effect of the rain, showed by Sentinel-1, was probably more evident in the habitats located at a certain distance from the lake shore, such as croplands and grasslands, that were less influenced by the water level, Figures 1 and 4. The vegetation in the proximity of the lake instead, like reeds and fens, was more subject to the variation in the water level regardless of the rain.

Since the spring estimations of flooded habitat were different for the reasons exposed, probably capturing different effects of

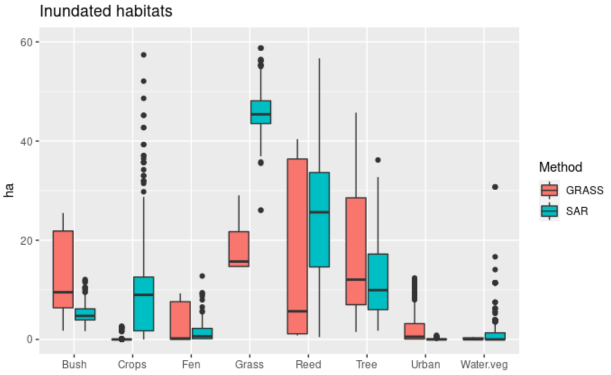

Figure 4. Differences in the extent of the flooded habitats at Bolle di Magadino (CH) calculated with two methods: filling the area around the lake according to water level (GRASS) and from remote sensing observation Sentinel-1 (SAR). All differences in mean were statistically significant ($p<0.05$)

the water in the basin, we tested which of the methods provided information that could explain the intensity of bird migration in the wetland of Bolle di Magadino.

The most complete series of data from the ringing station was available for P3. During the 41 days of activity in spring of 2021, an average of 55 birds (2–149) and 10 different species were captured and ringed every day (2–19).

Since Sentinel-1 derived data were irregularly sampled, missing data were replaced with interpolated values using the *zoo* tools where values are processed according to their time index. We explored the temporal cross-correlation of the total number of birds per day and species richness against rainfall, water level, total flooded area and extent of flooding for each habitat type obtained with both methods. The total number of birds had significant and positive temporal cross-correlation with: GRASS total flooded area, GRASS bush flooded area and GRASS GRASS tree flooded area and a negative correlation with rainfall and SAR water vegetation. Species richness showed a similar pattern, as expected, with a significant positive temporal cross-correlation with the same variables as number of individuals, thus cross correlation plots are shown only for species richness in Figure 5.

4. CONCLUSIONS

The great flexibility and interoperability provided by FOSS for spatial analysis, such as GRASS, R, QGIS and GEE proved very useful for the management and analysis of the maps and data of heterogeneous types and origin as often happens with ecological data (Rocchini and Neteler, 2012, Gobbi et al., 2018b). The possibility of scripting all the operations was crucial for these type of procedures that can be replicated as soon as new data are collected.

We use open data and FOSS4G to study the effect of water level on bird migration using as case study a wetland of international importance. We compared the extent and type of flooded habitat using two approaches: Sentinel-1 remote sensing imagery using GEE and simulations based on the measured water level and DTM using GRASS.

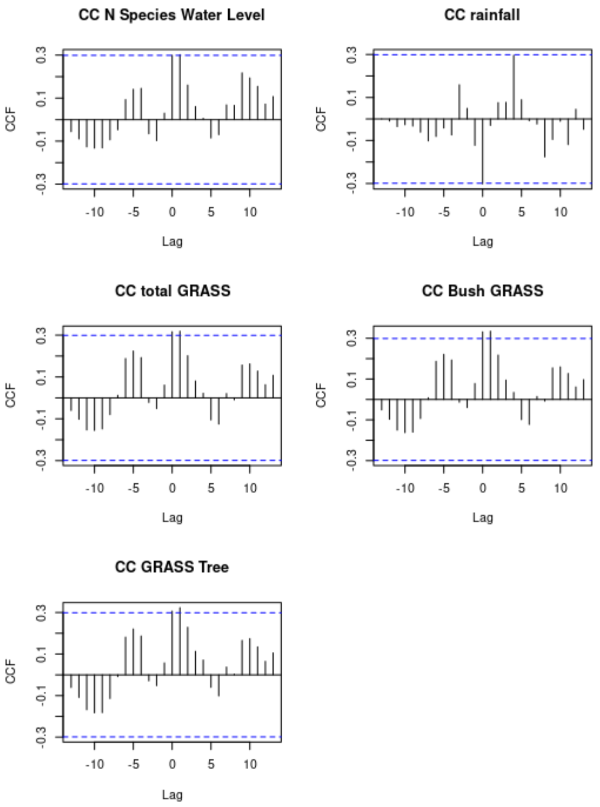

Figure 5. Cross correlation functions (CCF) between the species richness and only the significant covariates: rainfall, water level and the results of inundated areas calculated with simulations. Lags are expressed as days, the blue dashed lines are referent to a significance interval

Both methods have a similar temporal pattern of flooding in autumn, but the total extent and the type of habitats filled with water presented significant differences during spring, when water level management is intense because of agricultural needs. Probably Sentinel-1 data are able to capture the retained rainfall on the terrain, whereas GRASS simulations takes into account only the changes due to water level, regardless of the rain and of more complex interactions between water and vegetation. The effect of type and extent of submerged vegetation obtained with both methods was tested against a time series of bird captures, in order to find out which of the two methods was able to better explain migration. The result obtained with GRASS and simulations, contrary to our expectations, showed some correlations with number of passing birds and species richness. We found that when water was taken for irrigation in spring, the number of birds also plummeted, and we hypothesize that lake water level plays a more important role for birds then the amount and type of flooded habitat in this area.

Here hydrological simulations were calculated on a daily basis, but could also be calculated for day and night time, including an important factor migrant birds, that usually move at night (Richardson, 1990). The main limit of SAR derived time series, was in fact their irregularity forced us to simulate missing data probably introducing an over simplification. Weather conditions are known to have an affect on bird flying, (Erni et al., 2002) due to limited visibility and against winds. This relationship has been studied for many decades(Richardson, 1990) and also in this little area rainfall had a negative impact on the number of passing birds.

Longer series of data should be analysed in order to confirm these preliminary tests, but the importance of a tight time series of data seems to appear also in this case study.

The results presented here will contribute to the definition of policies for the management of lake Maggiore waters level, taking into account the effect of lake level on biodiversity in general and on bird habitat in particular. Sustainable regulation of the waters should balance the multiple needs of people, economic development, health, recreation with nature conservation (Cantiani et al., 2016).

To conclude, water in spring is important for the rice fields downstream but also for migratory birds and water management should take this result in account.

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REFERENCES

Agrometeo Svizzera, 2022. https://www.agrometeo.ch. Confederazione Svizzera.

Cantiani, M. G., Geitner, C., Haida, C., Maino, F., Tattoni, C., Vettorato, D., Ciolli, M., 2016. Balancing Economic Development and Environmental Conservation for a New Governance of Alpine Areas. *Sustainability*, 8(8), 802. doi.org/10.3390/su8080802.

Ciolli, M., Federici, B., Ferrando, I., Marzocchi, R., Sguerso, D., Tattoni, C., Vitti, A., Zatelli, P., 2017. FOSS Tools and Applications for Education in Geospatial Sciences. *ISPRS International Journal of Geo-Information*, 6(7). doi.org/10.3390/ijgi6070225.

Erni, B., Liechti, F., Underhill, L. G., Bruderer, B., 2002. Wind and rain govern the intensity of nocturnal bird migration in central Europe-a log-linear regression analysis. *Ardea*, 90(1), 155–166.

ESA, 2021. Copernicus Sentinel-1 data. Retrieved Feb-2022.

Gobbi, S., Cantiani, M., Zatelli, P., Tattoni, C., Ciolli, M., Porta, N. L., Rocchini, D., 2018a. Fine spatial scale modelling of trentino past forest landscape (trentinoland). *European Landscapes for Quality of Life? Paysages européens et qualité de la vie?*, PECSRL, Clermont-Ferrand–Mende, France - FRA, 179–179. Abstract in Atti di convegno.

Gobbi, S., Maimeri, G., Tattoni, C., Cantiani, M. G., Rocchini, D., La Porta, N., Ciolli, M., Zatelli, P., 2018b. Orthorectification of a large dataset of historical aerial images: Procedure and precision assessment in an open source environment. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 42, International Society for Photogrammetry and Remote Sensing, Dar es Salaam; Tanzania - DEU, 53–59. Oral contribution.

Gomes, V. C., Queiroz, G. R., Ferreira, K. R., 2020. An overview of platforms for big earth observation data management and analysis. *Remote Sensing*, 12(8), 1253. doi.org/10.3390/RS12081253.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*. doi.org/10.1016/j.rse.2017.06.031.

GRASS Development Team, 2022. Geographic Resources Analysis Support System (GRASS GIS) Software. http://grass.osgeo.org.

Grolemund, G., Wickham, H., 2011. Dates and Times Made Easy with lubridate. *Journal of Statistical Software*, 40(3), 1–25.

Inderwildi, A., A., S., 2016. Regolazione del lago maggiore. schede sulla regolazione dei livelli lacustri. Technical report, Ufficio federale dell’ambiente UFAM (CH). [In italian].

Kreindler, D. M., Lumsden, C. J., 2006. The effects of the irregular sample and missing data in time series analysis. *Nonlinear Dynamics, Psychology, and Life Sciences*, 10(2), 187–214. doi.org/10.1201/9781439820025-9.

Krispin, R., 2020. TSstudio: Functions for Time Series Analysis and Forecasting. R package version 0.1.6.

Markert, K. N., Markert, A. M., Mayer, T., Nauman, C., Haag, A., Poortinga, A., Bhandari, B., Thwal, N. S., Kunlamai, T., Chishtie, F., Kwant, M., Phongsapan, K., Clinton, N., Towashiraporn, P., Saah, D., 2020. Comparing Sentinel-1 surface water mapping algorithms and radiometric terrain correction processing in southeast Asia utilizing Google Earth Engine. *Remote Sensing*, 12(15). doi.org/10.3390/RS12152469.

Open Geo Blog, 2021. Edge-otsu for surface water mapping detection. https://mygeoblog.com/2021/01/25/edge-otsu-for-surface-water-mapping-detection/. Last visited Feb.2022.

Ovakoglou, G., Cherif, I., Alexandridis, T. K., Pantazi, X.-E., Tamouridou, A.-A., Moshou, D., Tseni, X., Raptis, I., Kalaitzopoulou, S., Mourelatos, S., 2021. Automatic detection of surface-water bodies from Sentinel-1 images for effective mosquito larvae control. *Journal of Applied Remote Sensing*, 15(01), 014507. doi.org/10.1117/1.jrs.15.014507.

QGIS Development Team, 2022. QGIS Geographic Information System https://www.qgis.org.

Richardson, W. J., 1990. Timing of bird migration in relation to weather: Updated review. E. Gwinner (ed.), *Bird Migration*, Springer Berlin Heidelberg, Berlin, Heidelberg, 78–101.

Rocchini, D., Neteler, M. G., 2012. Let the four freedoms paradigm apply to ecology. *Trends in Ecology and Evolution*, 27(6), 310–311. doi.org/10.1016/j.tree.2012.03.009.

Saporetti, F., 2018. L’ avifauna acquatica della ZPS IT 2010502 ”Canneti del Lago Maggiore” - Risultati del monitoraggio 2015–2017. Technical report, Gruppo Insubrico di Ornitologia Onlus – Clivio (VA). [In italian].

Stromann, O., Nascetti, A., Yousif, O., Ban, Y., 2020. Dimensionality Reduction and Feature Selection for Object-Based Land Cover Classification based on Sentinel-1 and Sentinel-2 Time Series Using Google Earth Engine. *Remote Sensing*, 12(1). doi.org/10.3390/rs12010076.

Tattoni, C., Chianucci, F., Grotti, M., Zorer, R., Cutini, A., Rocchini, D., 2019a. Long-term comparison of in situ and remotely-sensed leaf area index in temperate and Mediterranean broadleaved forests. *Trends in Earth Observation*, 1(1), 81–84. doi.org/10.978.88944687/17.

Tattoni, C., Ciolli, M., 2019. Analysis of Bird Flyways in 3D. *ISPRS International Journal of Geo-Information*, 8(12), 535. doi.org/10.3390/ijgi8120535.

Tattoni, C., Soardi, E., Prosser, F., Odasso, M., Zatelli, P., Ciolli, M., 2019b. Fruit availability for migratory birds: a GIS approach. *Peerj*, 7(e6394). doi.org/10.7717/peerj.6394.

Webb, E., Smith, L., Vrtiska, M. P., Lagrange, T. G., 2010. Effects of local and landscape variables on wetland bird habitat use during migration through the Rainwater Basin. *J. Wildl. Manag.*, 74(1), 109–119.

Zatelli, P., Gobbi, S., Tattoni, C., Cantiani, M. G., La Porta, N., Rocchini, D., Zorzi, N., Ciolli, M., 2019a. Relevance of the Cell Neighborhood Size in Landscape Metrics Evaluation and Free or Open Source Software Implementations. *ISPRS International Journal of Geo-Information*, 8(12). https://www.mdpi.com/2220-9964/8/12/586.

Zatelli, P., Gobbi, S., Tattoni, C., La Porta, N., Ciolli, M., 2019b. Object-based image analysis for historic maps classification. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-4/W14, 247–254. doi.org/10.5194/isprs-archives-XLII-4-W14-247-2019.

Zeileis, A., Grothendieck, G., 2005. zoo: S3 Infrastructure for Regular and Irregular Time Series. *Journal of Statistical Software*, 14(6), 1–27. doi.org/10.18637/jss.v014.i06.

APPENDIX

4.1 Data availability

The GEE code is available at the following link:
`https://code.earthengine.google.com/e9ac2208f79bc8049afb7d057a09d254`.
The GRASS and R scripts are available at `10.5281/zenodo.6627333`