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A QGIS PLUGIN FOR OFFSHORE WAVE HINDCASTING BASED ON GEOGRAPHIC TRANSPOSITION OF WAVE GAUGE DATA

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ABSTRACT:

The paper presents a first experimental version of the original QGIS plugin QWaveTransposition that numerically implements the geographic transposition of wave gauge data method proposed by Contini and De Girolamo (1998) for offshore wave hindcasting. The method allows one to transfer wave data measured at a given gauging station to a virtual station located offshore the area of interest, by comparing the effective fetches at both stations. The QWaveTransposition plugin was implemented in Python programming language, including the NumPy package for numerical computations. A graphical user interface was developed to manage the input/output data and model parameters. The fetch geometry at real and virtual stations can be imported by selecting appropriate vector layers from the QGIS map. An application to a sample site in southern Italy is presented for example purposes.

1. INTRODUCTION

The estimation of offshore wave climate is a key issue in maritime and coastal engineering, as it is the first, fundamental step of every project dealing, e.g., with navigation, harbours protection, design of offshore and coastal structures, coastal planning and remediation.

Basically, two main conceptual approaches to estimate wind-generated wave conditions can be distinguished. The first comprises empirical methods and mathematical models in which wave parameters are derived from wind data. When predictive methods are applied to current or predicted meteorological data, the process is referred to as “forecasting”. Otherwise, when the above methods are applied to derive wave information based on historical wind data, the process is referred to as “hindcasting” (Arthur, 1950). The second approach is to gain information from direct measurements of wave parameters at gauging stations close to the study area.

When both wind and wave data are available at a given project site, the choice between the two approaches is a delicate task and a universally accepted rule of thumb cannot be defined. Main factors to be considered are: (a) the data accuracy and acquisition rate; (b) the duration of time series and the gauging station efficiency; (c) the proximity of the station to the project site.

A brief overview of the above introduced families of methods for wave prediction is given in the next sections.

1.1 Estimation of wave parameters from wind data

A number of studies were performed since the 1940s, aimed at deriving empirical methods to predict wave conditions considering the energy transfer from the wind to the sea surface (Sverdrup and Munk, 1947; Arthur, 1950; Bretschneider, 1965). Among them, the SMB method (SPM, 1984), so called from the authors Sverdrup, Munk, and Bretschneider, is the most widely used. In the SMB method spectral significant wave height and

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peak period are predicted by means of empirical formulae as a function of the following parameters:

- the fetch length (*F*), i.e. the linear extent of an ideal region, measured along the wind direction, in which the wind blows with constant speed and direction;
- the wind-stress factor (U_A), i.e. an adjusted measure of wind speed;
- the duration of the wind event (*t*).

The conditions of uniform fetch and constant wind speed and direction are rarely satisfied in practice. However, for inland waters or enclosed basins as bays, lakes or reservoirs, it can be assumed that the wind conditions do not vary significantly over the water body during a meteorological event. In this case the wave generation area is limited by the boundary of the water body and the fetch extent at given point can be estimated measuring the distance to the coast upwind.

The above assumption can be considered realistic also for the Mediterranean Sea, though an upper limit to fetch length is normally imposed (typically, 500 km) to consider valid the hypothesis of uniform wind conditions.

A number of corrective formulations were proposed to achieve a more realistic description of the wave generation process (Saville, 1954; Seymour, 1977). In particular, the concept of "effective fetch" was introduced to account for the effect of fetch shape and directional spreading of wave energy.

In a generalised formulation, for a given wind direction the effective fetch F_{eff} can be defined as follows:

$$F_{eff} = \frac{\sum_{\theta_i = -\theta_w}^{\theta_w} F(\theta_i) \cdot \cos^{n+1}\theta_i}{\sum_{\theta_i = -\theta_w}^{\theta_w} \cos^n \theta_i} \qquad (1)$$

where: θ_i = angle from wind direction, typically varying either over a 90° arc (θ_w=45°) or a 180° arc (θ_w=90°);
$F(\theta_i)$ = straight line fetch length measured along the direction θ_i (commonly referred to as "geographic fetch");
n = exponent that accounts for the wind-generated wave energy directional spreading. Typical values are n=1 or n=2.

Seymour (1977) also argued that due to wave energy directional spreading, wave direction generally does not coincide with wind direction. Based on field data analysis, Donelan (1980) proposed to estimate the wave direction from the input wind direction by maximizing the resulting wave period that depends on the fetch lengths and wind-wave angles (figure 1). Following Donelan's approach, Smith (1991) proposed to predict the wind-generated wave direction by maximizing the function given below:

$$\Phi(\theta) = (\cos\theta)^{0.44} \cdot F(\theta)^{0.28} \qquad (2)$$

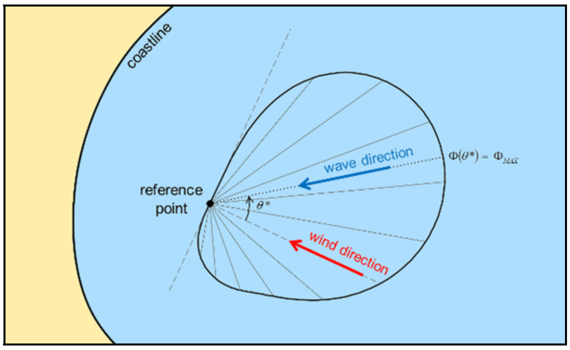

Figure 1. Relation between incident wind and wave direction

In the above formula the angle θ between wind and wave direction can theoretically vary in the range 0-180° and $F(\theta)$ is the corresponding fetch length. In practical applications, the wind-wave angles in Equation (2) are discretized, e.g., at 1° increments (Leenknecht et al., 1992).

Besides the above introduced empirical methods, a number of mathematical models were proposed for the estimation of wind-generated wave parameters, based on different formulations of the wave growth and decay equations, as reported, e.g., in Komen et al. (1994), Holthuijsen et al. (1989), Booij et al. (1999), and Liu et al. (2002). Wind-wave modelling experienced a very rapid development and diffusion over the last decades, similarly to other computer-based numerical techniques (Cavaleri et al., 2007; Rogers et al., 2014). The literature on this topic is very extensive and its discussion is beyond the aim of the present work. It is just noteworthy to observe that numerical models generally require a computational effort that can be justified when significant variations in meteorological conditions takes place, and frequent and accurate input data are available (Catini et al., 2010; Liberti et al., 2013; Carillo et al., 2015; ENEA, 2016; ISPRA, 2016).

1.2 In situ measurement of wave parameters

Visual observations of waves from coastal stations or ships are the first historically reported methods for the direct estimation of wave parameters. However, they normally produce data with a high degree of subjectivity and not compatible with those obtained from instrumental measures.

Since the 1960s, a number of different techniques and instrumentations for in situ measurement of wave parameters were proposed by scientists, practitioners, and manufacturers, based on different theoretical formulations and operation principles. Available methods (WMO, 1998) comprise measurements: (a) from below the sea surface; (b) at the sea surface; (c) from above the sea surface. A review can be found in Barstow et al. (2005) and DBCP (2016).

Direct measurements of wave parameters experienced a significant growth during the last decades and monitoring programs by means of wave gauging networks were established in most of developed countries.

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As an example, the first wave data collection stations along the U.S. Pacific coast were deployed in the mid-1970s (Seymour and Sessions, 1976), giving rise to the monitoring network known as Coastal Data Information Program. The network steadily grew during the last decades and currently covers the entire U.S. coastline (CDIP, 2016).

In Italy, the Italian Data Buoy Network (RON, acronym of the Italian words “Rete Ondametrica Nazionale”) was established in 1989. Initially composed of 8 directional buoys, the RON was successively upgraded and extended over the years, and currently consists of 15 wave gauging stations (figure 2) deployed at about 100 m depth along the Italian coastline (Corsini et al., 2006; Bencivenga et al., 2012).

Figure 2. The Italian Data Buoy Network. Data from Bencivenga et al. (2012). Basemap: © OpenStreetMap contributors, license CC-BY-SA

2. GEOGRAPHIC TRANSPOSITION OF WAVE GAUGE DATA

The “geographic transposition of wave gauge data” method, originally formulated by Contini and De Girolamo (1998), is a widely used hindcasting procedure for the estimation of offshore wave parameters at a given project site (that can be referred to as a “virtual station”) based on wave data measured at a “real” gauging station. The method is based on the following hypotheses:

a) the wind speed and direction are the same at both real and virtual stations;

b) the extent of the wave generation region can be described by the effective fetches;

c) the wind blows over the fetch long enough to assume that wave conditions are independent of the wind duration (fetch-limited conditions).

Under the above conditions, the spectral significant wave height H_m and peak period T_m in deep water can be predicted, using the SMB method, as a function of fetch F and wind-stress factor U_A by the following empirical formulae (SPM, 1984):

$$\frac{g\,H_m}{U_A^{\,2}} = 1.6\cdot10^{-3}\left(\frac{g\,F}{U_A^{\,2}}\right)^{\frac{1}{2}} \tag{3}$$

$$\frac{g\,T_m}{U_A} = 2.857\cdot10^{-1}\left(\frac{g\,F}{U_A^{\,2}}\right)^{\frac{1}{3}} \tag{4}$$

Under the assumption that wind conditions are the same at real and virtual station, writing the Equations (3) and (4) at both sites, the following equations can be derived:

$$\frac{(H_m)_V}{(H_m)_R} = \left(\frac{F_V}{F_R}\right)^{\frac{1}{2}} \tag{5}$$

$$\frac{(T_m)_V}{(T_m)_R} = \left(\frac{F_V}{F_R}\right)^{\frac{1}{3}} \tag{6}$$

The ratios at the right-hand side of Equations (5) and (6) are referred to as “transposition coefficients” and allow one to derive the wave height and period at the virtual station from the data measured at real station, considering the different wave exposures due to the different geographic positions of the sites.

The deviation between wind and wave direction is also to be considered. Namely, for each recorded wave event with direction $(\theta_{wave})_R$ the corresponding wind direction θ_{wind} (that is the same for both real and virtual station) must be computed, maximizing the function in Equation (2) for the real station fetches. Then, considering the transposition coefficient for the direction θ_{wind}, the wave height and period at virtual station are computed using Equations (5) and (6). Finally, the wave direction $(\theta_{wave})_V$ at virtual station is estimated by maximizing the function in Equation (2) for the virtual station fetches.

3. THE QWAVETRANSPOSITION PLUGIN

The geographic transposition method is much appreciated by coastal scientists and engineers and is conceptually simple to use. However, in practical applications where a huge amount of wave data is to be processed, computer-based automated procedures are needed. To this aim, the original software QWaveTransposition was developed as a plugin to QGIS Geographic Information System (QGIS Development Team, 2016). The code was implemented in Python, including the NumPy (2016) package for numerical calculation. The QWaveTransposition plugin can be run by clicking on the special icon added to the QGIS toolbar (figure 3).

The input/output data and model parameters can be managed through a graphical user interface (GUI). The user form is composed of three sections (Fetch data, Wave data, and Calculation), as described below.

3.1 Fetch data

In this section the geographic fetches (input data) are specified for the real and virtual wave station. Two options are available,

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that can be chosen checking one of the two boxes on the right side of the form (figure 3):

- Load from map layers. If this option is checked, the user selects from the map a line vector layer containing the straight line fetches at real/virtual station over the entire 360° compass, discretized at 1° steps. The azimuth relative to north and the corresponding fetch length are read from the attribute table of the layer.
- Load from text files. If this option is checked, the paths of external ASCII files containing the azimuth and fetch length data are specified by the user. In this case, it is not necessary that fetch layers are present in the QGIS map.

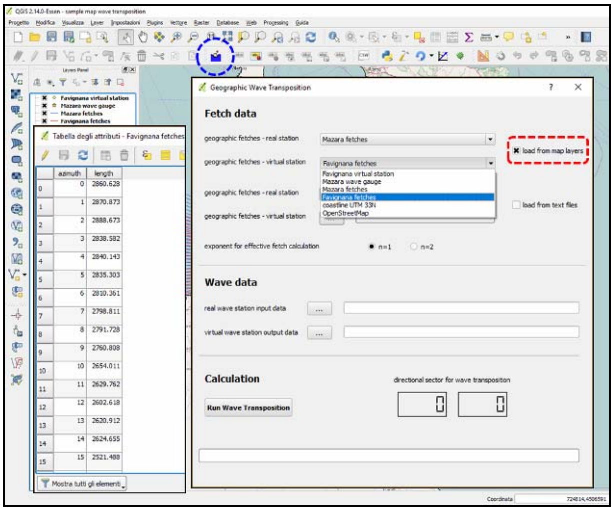

Figure 3. The QWaveTransposition user interface and icon (blue circle). If the option "load from map layers" is checked (red rectangle), appropriate layers containing the fetch data are selected from map layers' list

Since the geographic transposition method is based on non-dimensional equations, the input fetch lengths can be indifferently expressed in any unit of measurements (e.g., meters, kilometres, or nautical miles), provided that the units are the same for real and virtual station.

The value of n exponent in the Equation (1) for the effective fetch calculation is also specified by the user. The available options (n=1 or n=2) can be selected checking one of the radio buttons in the form.

3.2 Wave data

In this section the user selects the paths for input and output wave data files (figure 4).

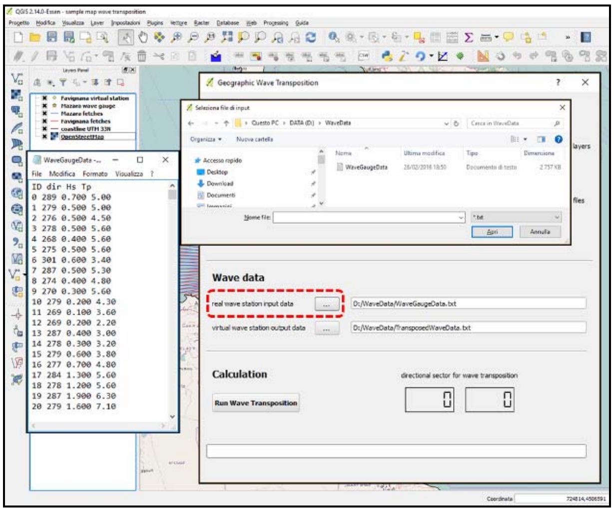

Figure 4. Input wave data are imported from a text file specified through the command button shown in the red rectangle

The input data are the wave conditions measured at the real gauging station and are imported as an ASCII file Each line of the text file represents a wave record, described by the following data:

- ID number;
- wave direction;
- significant wave height;
- peak wave period.

The above information can be derived from available wave gauging station data and normally not much effort is required for data preparation.

The model output is an ASCII file formatted in the same way as the input file, reporting transposed wave parameters for each event in the input wave series.

3.3 Calculation

Once all the input/output files have been defined and model parameters have been set, the "Run Wave Transposition" command button can be clicked to run the model.

In the first steps of software execution the fetch data are processed. Namely, the following actions are performed for both real and virtual station:

- Reading of geographic fetches azimuth and length;
- Computation of effective fetches for each direction. The summation in Equation (1) is extended over a 180° arc centred on the current azimuth value.
- Computation of the wind-wave angles for each direction, maximizing the function Φ in the Equation (2) for different values of effective fetches computed at previous step.
- Computation of the wave height and period transposition coefficients for each direction, applying Equations (5) and (6).

Once the previous calculations have been executed, the input waves are processed to derive the transposed wave parameters at virtual station. Namely, for each wave record described by a single row in the input file the following steps are performed:

- Reading of input wave direction, height and period at real station;
- Computation of wind direction from wave direction, considering the estimated wind-wave angles at the real station;
- Computation of transposed wave height and period at virtual station. The input wave parameters are multiplied by the transposition coefficients corresponding to the wind direction computed at the previous step;
- Computation of transposed wave direction at virtual station, considering the estimated wind-wave angles at the virtual station;
- Writing of transposed wave parameters to the specified output file.

It is to be observed that the estimation of wind directions at real station based on measured wave directions and wind-wave angles reduces, in practice, the directional range of the incident waves that can be processed. Namely, when fetch-based wind-wave angles are computed for each potential wind direction in the range 0-360°, the resulting range of potential wave directions is generally narrower than 360°, depending on the values of the effective fetches that maximize the function Φ in Equation (2).

Thus, a wave record with direction outside the above computed theoretical range cannot be processed, as it cannot be associated to any wind direction. In this case the model returns a zero values for wave height and period, and the record is flagged assigning the 360° value to wave direction. Despite it can appear unrealistic, the effects on the final results are generally limited, since directions excluded from calculation are normally characterized by short fetches and low values of wave height and period are expected.

The above considerations will be better clarified in the next section in which an example application is presented.

4. EXAMPLE APPLICATION

For example purposes, the QWaveTransposition software were applied to estimate the incident wave climate offshore Favignana Island, near the western coast of Sicily, in southern Italy.

Input wave data were derived from the Mazara gauging station of the Italian Data Buoy Network, located at latitude 37°31’05’’N, longitude 12°32’00’’E (Bencivenga et al., 2012). A virtual wave station was placed off the southern coast of Favignana island, at about 45 km from the Mazara station (figure 5).

Figure 5. Geographic setting of the real and virtual station. Basemap: © OpenStreetMap contributors, license CC-BY-SA

Polar plots of geographic and effective fetches at real and virtual stations are reported, respectively, in figures 6 and 7. Geographic fetches were limited to maximum 500 km. The value n=1 was chosen for the exponent in Equation (1) for the effective fetches calculation.

The computed wind-wave angles and wave directions for each wind direction at both stations are plotted in figures 8 and 9. It can be observed that, as previously specified, the directional range of the waves that can be processed is narrower than the entire 360° arc. In the present case, as illustrated in figure 9, the geographic transposition can be applied only to waves comprised in the sector 89-352°.

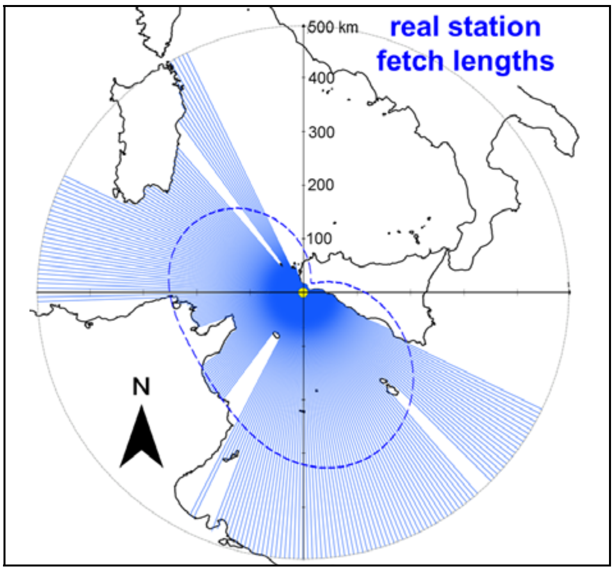

Figure 6. Polar plots of geographic fetches (solid lines) and effective fetches (dashed lines) at the real station

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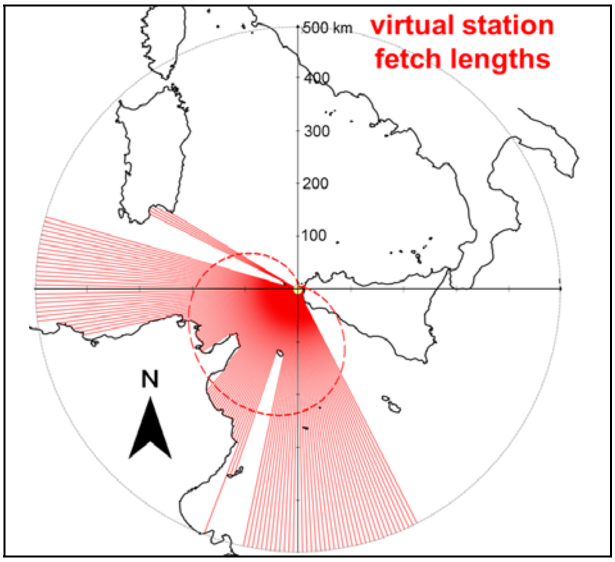

Figure 7. Polar plots of geographic fetches (solid lines) and effective fetches (dashed lines) at the virtual station

The computed transposition coefficients for each wind direction are plotted in figure 10. The values are lower than 1 because, as can be observed from figures 6 and 7, the effective fetches at the virtual station are lower than those computed at the real station. The figure 11 reports a rose plot of the mean wave climate derived from input data. Consistently with the wave exposure of the site, two main directional sectors for prevailing incident waves can be observed, comprising the east by south and the west by north directions, respectively.

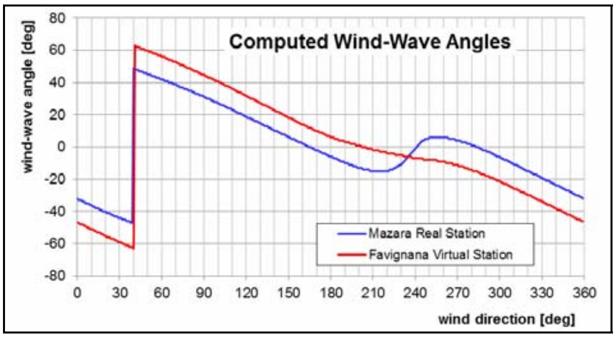

Figure 8. Deviation angle between wind and wave directions

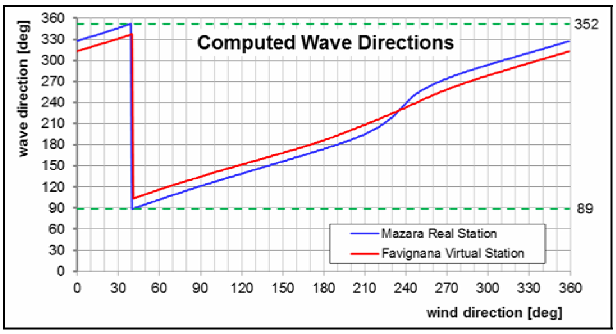

Figure 9. Wave directions for different wind directions, and indication of the directional range in which the geographic transposition method is applicable

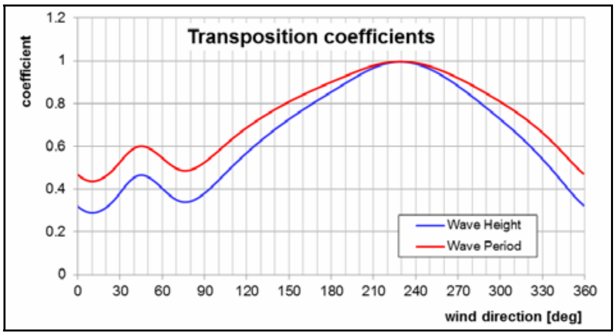

Figure 10. Transposition coefficients for wave parameters

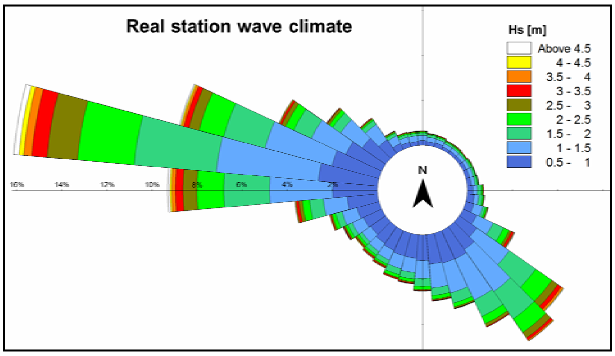

Figure 11. Rose plot of mean wave climate derived from input data at real gauging station

The figure 12 illustrates the QWaveTransposition user interface during the model run. A display label and a progress bar indicate the current process, (e.g. fetch calculation, estimation of wind-wave angles, performing transposition). The directional wave range in which transposition can be performed is displayed in the special labels above the progress bar.

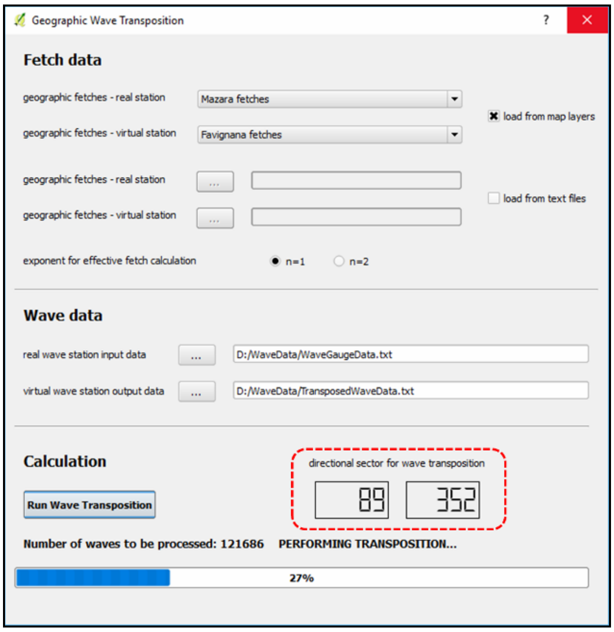

Figure 12. A view of the user interface during the model run

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The labels in the red rectangle (figure 12) display the limits of the directional sector where the geographic transposition method is applicable in the present case.

The final results are illustrated in figure 13, reporting a rose plot of the mean wave climate at virtual station derived from transposed wave data.

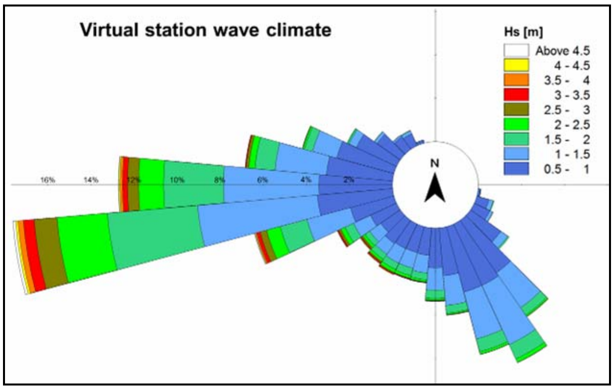

Figure 13. Rose plot of mean wave climate derived from output data transposed at virtual gauging station

Comparing figures 11 and 13, some differences can be observed between real and virtual station that are consistent with different geographic positions and wave exposures of the two sites.

In particular, a general reduction of wave heights at virtual station compared to the real station can be observed, as a consequence of the lower extensions of fetches. Moreover, a less pronounced influence of the waves coming from the northern directions can be noticed, due to the sheltering effect of Favignana and Marettimo islands north of the virtual station (figure 5).

Finally, the graph in figure 13 clearly shows the limitations to the range of wave directions for which the transposition method is applicable. It can be observed, however, that the excluded directions are characterized by the lowest values of fetch lengths.

5. CONCLUSIONS

The original QGIS plugin QWaveTrasposition was developed to perform the geographic transposition of wave gauge data for offshore wave hindcasting originally proposed by Contini and De Girolamo (1998).

QWaveTransposition is currently at a testing stage. However, a general agreement was found between the model output of the present example application and the results of a previous study (Pasanisi et al., 2015), in which the geographic transposition was performed using a spreadsheet and different semi-automated procedures.

Further testing applications to different sites are planned for validation purposes. Based on the user experience, further implementations of the algorithm and numerical procedures, as well as modifications to the user interface or input/output format will also be possibly performed.

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