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Paper accepted for publication in *Water Resources Management*
https://doi.org/10.1007/s11269-020-02750-x

Full read-only text at https://rdcu.be/cc4DR

A web-based open-source geoinformation tool for regional water resources assessment

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Abstract
To reduce the impact of droughts and increase the resilience of regional water systems, various competing demands, such as hydropower, supply, irrigation and river ecosystems, need to be reconciled. In this perspective, for a sustainable and efficient management of the water resources, planners and practitioners would benefit from using the most recent data and easily accessible analysis tools, that can make hydrological model applications easier to apply. In this paper, a web-based open-source geoinformation tool for estimating Flow Duration Curves (FDCs) in ungauged basins is presented. The FDC estimation derives from a regional statistical model, that relates basin topographic parameters, climatic characteristic and other environmental factors to FDC features via multivariate regression. The software tool has the primary function of simplifying the GIS-intensive application of the multivariate methodology, allowing computation of the necessary basin features through web services. These are developed in compliance with the OGC specifications for geospatial Web Processing Service (WPS), while scripting and model implementation are developed server-side, which ensures the user access to always updated data, and to procedures free from software client compatibility issues. An operational application is available for the North-Western Italy.

Keywords Flow Duration Curve, Water Resources, Web Processing Service (WPS), PyWPS4, Web-GIS tool, Docker

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1 Introduction

Increase in the frequency, duration, and severity of extreme droughts associated with climate change have raised global concern on the need of better management of the available water resources. Several studies have shown how global aridity has increased substantially since 1970, and climate models predict more droughts in the 21st century over many densely populated areas of the world (a complete review can be found in Dai, 2011). In temperate humid climates, management of resources in regional water systems needs to face increasing conflicts of water uses, also due to more strict rules for the preservation of the environment. Tools and methodologies for a systematic assessment of the water availability at large scales are thus required to ensure reliable and harmonized water allocation.

Flow Duration Curves (FDCs) are among the most commonly adopted tools for water resource assessment (see e.g. McMahon 1993). A FDC indicates the percentage of time that a specified discharge in a river section is equaled or exceeded, which is substantially equivalent to drawing a frequency distribution of flow values in a river. A FDC computed for each calendar (or hydrologic) year is called “annual” while, if it includes the observations of all the years merged together, it is referred to as “long-term” or “period-of-record” (see e.g. Berton et al. 2016). This type of information is commonly adopted for hydropower potential assessment and for environmental flow evaluation, but is also a useful support for impact assessment and risk management. Furthermore, the FDC allows to assess minimum flows as the low end of the curve (Ling Lloyd et al., 2015).

For a gauged basin, the empirical FDC is easily built by plotting the sorted observations (usually at the daily scale) versus their exceedance frequency, computed with a plotting position formula (e.g., Weibull). Where gauged data are either limited or not available, regional statistical models for predicting FDCs are commonly adopted (e.g. Nruthya and Srinivas, 2015; Vogel and Fennessey, 1994). In this work we refer to the regional model for FDC prediction in ungauged basins developed by Ganora et al. (2016). It has been initially calibrated for the upper Po river basin in North-Western Italy (Fig. 1) but it can be easily re-calibrated for other regions. The model is one of the products of the RENERFOR project (“Cooperation initiatives for the development of renewable energy sources in the western Alps, energy saving and emissions reduction”) co-funded by EU under the ALCOTRA funding program, primarily focused on the possibility to exploit renewable energy sources.

The Piedmont region has suggested to practitioners to adopt the model proposed by Ganora et al. (2016) when submitting water withdrawal requests for new or revamped hydropower plants. However, practitioners have to face a consistent workload to apply the method, that requires the application of several GIS-based procedures.

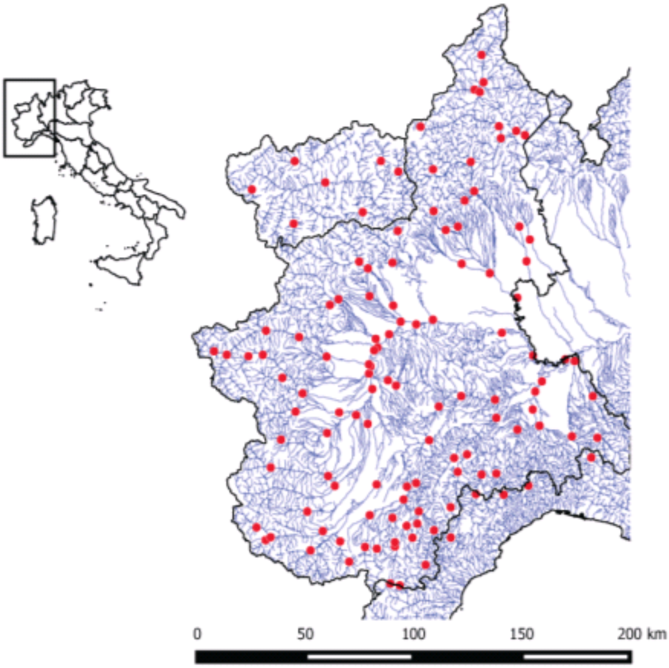


Fig. 1 The case-study area in Northwestern Italy and map of the 129 available gauging stations used in the Alcotra RENERFOR Project. Original source: Ganora et al. 2016

The aim of the present work is to provide different kind of users with an open, scalable and reproducible web GIS procedure for FDC reconstruction over large areas, able to support both institutional regulations and private initiatives of sustainable development of mini-hydropower plants. The underlying scientific objectives are twofold: on one side, to promote a knowledge transfer, by developing an interactive web procedure for reproducing and applying a regional statistical model; on the other side, to assess the robustness of the SSEM model to multiple applications, in order to better check its concrete transferability to other areas.
This paper is organized as follows: in Section 2 we recall the regional methodology to estimate FDCs at ungauged sites; in Section 3, the GIS implications of the procedure are discussed; Section 4 presents the client experience in producing the FDC curve via web-GIS and the details of the free and open-source web platform architecture realized. A conclusion section closes the paper.

2. The SSEM regional statistical analysis for FDC estimation

The regional model for FDC prediction adopted in the RENERFOR Project, fully described by Ganora et al. (2016), is adapted from a spatially-smooth procedure originally developed by Laio et al. (2011) in the flood frequency context. The output of the procedure is the mean annual FDC in analytical form. The

obtained curve can be considered as “natural”, i.e., not affected by possible upstream water abstractions, which should be later accounted for to define the actual water availability. The model is also topological-consistent, being the average annual flow downstream a confluence equal to the sum of the average annual estimates just upstream the confluence.
The practical application of the model in ungauged basins requires a number of steps schematically depicted in Fig. 2. First, the river section of interest is identified, and the corresponding basin boundary is extracted. This task can be performed by several standard GIS procedures; however, we have implemented it as an optional step in our web-based procedure to make it fully reproducible and independent from the user’s software.
Secondly, the basin boundary is used to extract a set of basin-scale descriptors, i.e. morphologic, climatic, soil, vegetation type, land use, etc. characteristics of the basin. These are obtained by clipping a number of maps developed in a regional hydrological atlas (Ganora et al., 2013). In particular, the model uses: *A*, the basin area [km^2]; *MAP*, the mean areal annual precipitation [mm]; z_m and z_{max}, the mean and maximum basin elevation [m a.s.l.]; *fourierB*1 and CV_{rp}, regime parameters for the mean monthly rainfall; *clc*2 and *clc*3, land use parameters (the percentage of the basin area classified as group 2 and group 3 in the Corine Land Cover, see EEA, 2019); *a*75, the 75th percentile of the basin hypsographic curve; and c_{int} and *IDF*a [mm], two extreme-rainfall statistics.
The L-moments of the FDC are then evaluated by a set of linear regression models (Montgomery et al., 2001) based on the basin descriptors previously computed. L-moments are statistics commonly used in hydrology (Hosking and Wallis, 1997) to describe a distribution. The first L-moment μ (m^3/s) is the mean value of the distribution and can be computed as:

$$\mu = \frac{Y \cdot A}{31536} \quad (1)$$

where Y (mm) is equal to

$$Y = -7.3605 \cdot 10^2 + 1.2527 \cdot \mathrm{MAP} + 3.2569 \cdot 10^{-1} \cdot \mathrm{z}_m + 5.2674 \cdot \mathrm{fourierB1} - 6.7185 \cdot \mathrm{clc}. \quad (2)$$

We also estimate the second- and third-order L-moments, respectively τ_2 (or L-CV), which is measure the distribution variability, and τ_3 (or L-skewness), which represents the skewness of the distribution. They read:

$$\tau_2 = -2.896 \cdot 10^{-1} - 2.688 \cdot 10^{-3} \cdot \mathrm{clc3} + 9.643 \cdot 10^{-5} \cdot \mathrm{a75} + 1.688 \cdot 10^{-4} \cdot \mathrm{MAP} + 20.941 \cdot \mathrm{c}_{int} \quad (3)$$
$$\tau_3 = 4.755 \cdot {z_{max}}^{-0.2702} \cdot \mathrm{SD(IDFa)}^{0.06869} \cdot \; \mathrm{CV}_{rp}^{0.2106} \quad (4)$$

Both τ_2 and τ_3 are dimensionless coefficients.
Finally, the L-moments are used to fit the analytical form of the FDC, ultimately represented by a 3-parameter Burr probability distribution (also known as Extended Burr type XII). The quantile function of the Burr distribution reads:

$$Q(P) = \lambda \left[\frac{1-(1-P)^{-k}}{k}\right]^{\frac{1}{c}} \qquad (5)$$

where Q is the discharge value (m^3/s), P is the non-exceedance (also $P = d/(365+1)$ with d the duration expressed in days for year); k and c are the shape parameters and λ is the location parameter. Complete and simplified equations to compute the parameters from the L-moments are discussed in Ganora and Laio (2015). The Burr distribution was chosen among other candidate functions for its performances and its convenient flexibility properties. For some pairs of τ_2 and τ_3 the Burr distribution collapse to the two-parameter Pareto or Weibull (see inset in Fig. 2), which are special cases of the Burr. The location parameter is estimated as a function of k,c and the mean μ.

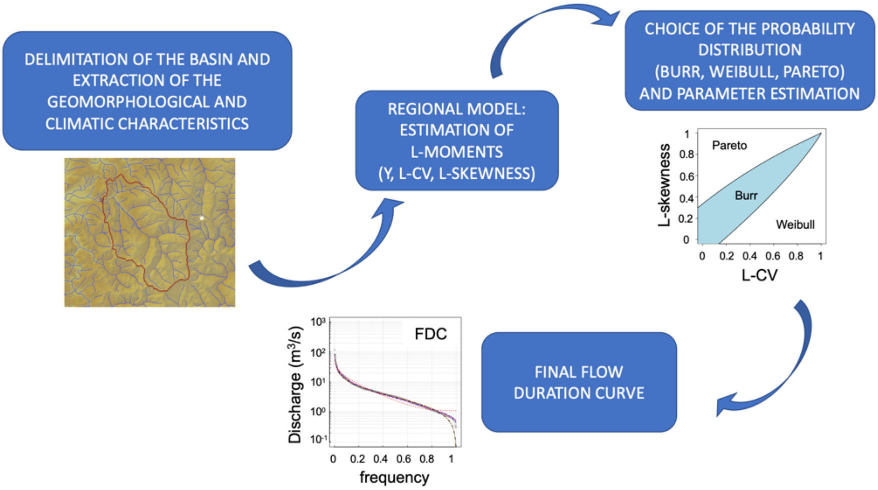


Fig. 2 Flow chart for the estimation process of the mean annual FDC in a generic ungauged basin.

3. GIS implications of the FDC estimation

In the section above we have described to which extent the SSEM procedure relies on GIS analyses. This is consistent with similar approaches (Palla et al, 2016; Sammartano et al., 2019 and references therein) and with the fact that, in recent decades, the use of data obtained by geographic information systems (GIS) has grown rapidly in many sectors and applications. These applications more and more require the use of complex GIS management systems, to collect, integrate, share and display different spatial data and compute geospatial analysis (Land et al., 2010). With the progressive improvement of open geospatial databases, the use of Internet and of the Web technologies have expanded the scale and scope of the GIS domains, moving traditional desktop applications to web mapping solutions and to the global sharing of both spatial data and geoscience models (Fu and Sun, 2011).

In the same time, with the high number of different GIS and WebGIS tools, to

enable software compatibility it is important to provide published data and processing services in line with the already available standards. Based on these considerations, data and procedures are increasingly supplied through geospatial web services by using the Web Processing Service (WPS) standard given by the OGC (Open Geospatial Consortium), that provide easy access and interoperability from heterogeneous platforms and GIS software. This solution has been adopted in our system, as it resolves the technical issues associated with software interoperability, allows users to access calculations independently from the operating system and the installed software and also without specific knowledge of GIS technologies. This can happen since our geospatial analysis and calculations are performed server-side, limiting the data traffic and returning only the expected results to the user. For the WPS service implementation we heve used PyWPS 4 (i.e. the newest version of the server-side implementation of the OGC WPS standard, based on the Python programming language). In addition, the procedures have been set up using a Docker container solution.
It is worth noting that, even if PyWPS provides an effective standard method for web-based geoprocessing, only few applications have actually used it (e.g. Ninsawat et al., 2007, Landa et al., 2017, Hempelmann et al., 2018, Laza, 2018; the National Geoportal of the Italian Ministry of Environment, 2020). A recent implementation of PyWPS 4 (De Sousa et al. 2019) brings new improvements and provides a number of advanced features that present an important leap in the range of modes in which PyWPS can be used and deployed. What we actually propose is a procedure for estimating the mean FDC in a generic watershed through a scalable and reproducible (using a Docker container with Nginx and Gunicorn as WSGI server for a pywps-Flask application) PyWPS 4 server development. The details of the tool developed are presented in the following sections.

4. The geoinformation framework

4.1 The local and web interfaces

The whole procedure for estimating the mean FDC in a generic watershed can be executed via web thanks to the implementation of two customized web processing services that automate the calculations. The services can be accessed from the client side in two ways: directly from the web-mapping application accessible form the project website or from any GIS desktop software that supports the use of WPS protocols. Some software may require external plugins to use WPS capabilities. In both cases, a password is required to access the procedure (see the project website in Fig. 3 and at the link http://www.idrologia.polito.it/piattaformarenerfor). For example, if the open-source desktop software QGIS is used, a WPS plugin is required, and the user can execute the process with reference to a specific watershed layer taken from the list of vector layers available in the QGIS project. After executing the process, the outputs of the procedure are returned into a results console (Fig. 4) and the user can download the FDC's graph as an SVG file. The alternative, and simpler, access to the procedure is reproduced in Fig. 5a, that shows how the user can execute the procedure using the WPS panel specifically developed on the WebGIS page. In both cases the procedure returns an URL that allows to download a complete PDF report. (Fig. 5b).

Fig. 3 Homepage of the Project website where visitor can access to the registration and documentation pages of the offered services

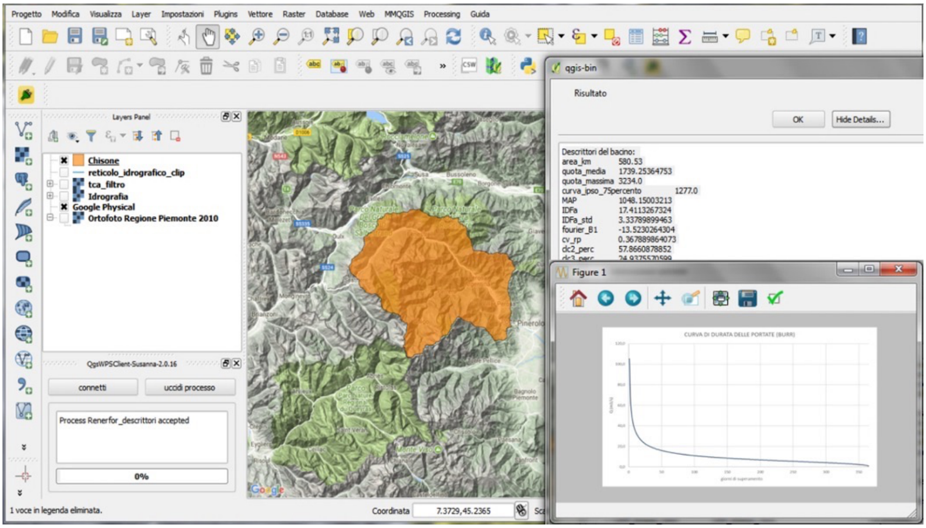
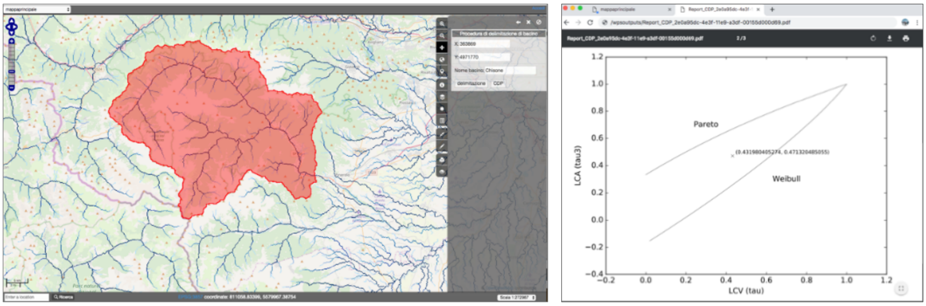


Fig. 4 Result of the procedure called up from QGIS using a WPS plugin.



(a) (b)

Fig. 5 Access by web browser to the procedure from (a) the web-mapping application (b) and to the PDF reporting the results obtained from the Estimation of the analytical FDC procedure.

4.2. The Platform Architecture

In this sub-section we describe the elements that form the structure of the software platform. Detailed explanations of the meaning of each specific part are provided in the appendix.

The remote application of the geospatial analyses required for the estimation of the FDC is realized on a "WPS server", that uses PyWPS 4 (4.2.8 version) on the top of GRASS GIS (7.8.2 version) as backend to access all the geoprocessing functionalities. PyWPS is deployed using Nginx and Gunicorn inside a Docker container, i.e. a solution that isolates portion of code from the interaction with most of the requests from the users. The complete project source code to setting up the containerized WPS server is hosted into the open platform GitHub at the address: https://github.com/SusannaGr/POLITO_PyWPS_Docker. Documentation also

contains the scripts that reproduce the results of the model, as reported above. The second pillar of the procedure, that allows to deploy the mapping contents from a WebGIS application (accessible through client browsers), is a web platform. It has been developed with free and open-source software, using GISClient3 as the web mapping tool, Apache2 (2.4.18 version) as web server, Ubuntu 16.04.4 LTS as Server OS.
To illustrate the architecture of the software system, we have depicted all parts in the sketch of Fig. 6.

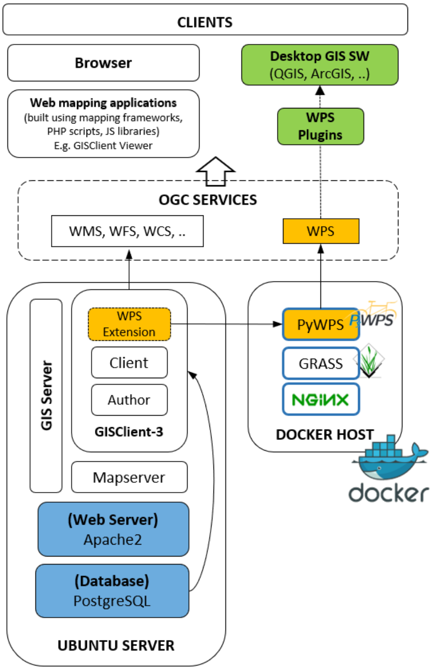


Fig. 6 Project architecture where the PyWPS server is realized using the Docker technology (the container is build up with GRASS GIS support, Gunicorn and Nginx) and a WebGIS Platform is implemented on a Linux Server to test the usability by browser of the web processing services.

4.2. Input data and implementation of the procedure

The basin boundary delimitation and the computation of catchment descriptors described in Sect. 2 require the input dataset containing (raster and vector) maps used in the RENERFOR project. The most important input map is the digital elevation model (DEM), which allows to delimit the catchment area and to compute the average slope and the hypsographic curve. We used the NASA SRTM (Shuttle Radar Topography Mission) DEM, locally corrected to obtain an accurate flow drainage network). All the required geospatial input data (e.g. Corine Land Cover vector maps, regime rainfall parameters raster maps) were set up in the GRASS GIS database.

The whole procedure is divided into two different PyWPS scripts: The *Basin Boundary Extraction* and The *Estimation of the analytical naturalized FDC*.
The first one represents an optional procedure (as the basin boundary can be also uploaded independently, using any GIS software) aimed at extracting the basin boundary from the DEM. This operation requires that the outlet section coordinates strictly belong to the drainage network generated from the RENERFOR DEM. The network is provided in the online geodatabase. Using the GRASS algorithm *r.water.outlet*, the WPS procedure returns the watershed boundary from the drainage direction map (also available in the database) starting from the outlet coordinates given by the user.
The second procedure, aimed to estimate the FDC curve, operates in three steps:

1. Using a PyWPS-GRASS-bridge, the basin boundary is imported into a GRASS session, where the spatial averages of the basin descriptors layers are computed from pre-determined raster maps using *r.univar* and *r.stats* GRASS algorithms.
2. The regional L-moments for the given basin are estimated using equations (1)-(4); the correct probability distribution is selected and the distribution's parameters are computed from the L-moments values.
3. The whole average FDC curve is computed using eq. (5) and its plot is produced with the *Matplotlib* library.

Once the process is completed, the server-side procedure provides an *URL* pointing to the location of a PDF file that summarizes the results, i.e. the basin descriptors, the estimated regional L-moments, the distribution parameters, the FDC curve. If the procedure is called by a GIS software (i.e., not using the web browser), the results are directly reported also in text format together with the SVG graph of the FDC.

6. Conclusions

The estimation of Flow Duration Curves in ungauged basins is related to several key activities in water resources and water systems management. Nowadays, extensive FDC assessment is possible in large areas, and this can valuably support responses to the Water Framework Directive (2000/60/EU) planning requirements. The regional model developed within the RENERFOR-ALCOTRA Project, for the North-Western Italy, represents a common and useful guidance for practitioners to evaluate FDC's. Its application requires spatial data analysis and is not straightforward to apply. To make the application of this procedure easier, a WPS service has been built, based on the PyWPS using GRASS for geoprocessing operations. The tool allows the computation of the average FDC in any basin within the North-Western Italy region by providing an outlet section location, encompassing an area of more than 25000 km^2.
A server-side scripting has been used in the software design, with the great advantage that users can access data and calculations in real time and

independently of the underlying software, also reducing the time required for the analysis and the risk of miscalculations. A pdf reporting procedure is also implemented, which provides the results of the analysis, i.e. a summary of the numerical results of the descriptors, L-moments, parameters and the graphical representation of the FDC. The system has been set up with a versatile modular structure, aimed at making it easily reproducible in other spatial domains and other WPS server implementation.

The easy accessibility to a free service, which does not require special programming skills or computational resources, can offer significant incentives for cooperation between the scientific community and the end-users in tackling water resources related issues. The application case illustrated for the North-Western Italy, can thus act as a guideline for similar implementations in other regions of the world.

The project source code referred to WPS server implementation is accessible online on GitHub at https://github.com/SusannaGr/POLITO_PyWPS_Docker; while the user documentation and a WebGIS platform to access online the WPS services is available at http://www.idrologia.polito.it/piattaformarenerfor.

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Declarations

Funding not applicable

Conflicts of interest/Competing interests Authors declare no conflicts of interest

Availability of data and material Data are available from the RENERFOR Project

Code availability The web-based tool is built with open source software described in the article text

Authors' contributions All authors contributed to the study conception and design. SG developed the web platform and wrote the first draft of the manuscript. All authors contributed to the revised version, read and approved the final manuscript.

Appendix: Glossary of the main components of the WPS Platform

A brief description of the individual tools making up the system is presented hereafter.

DOCKER is an open-source software designed to create, deploy, and run applications by using container technology. Docker provides repeatable development, test and production environments that allows developers to pack up different applications in independent and isolated way. Briefly, a Docker container consists of a *Docker image*, an execution environment, and a standard set of build instructions. Multiple containers can share the access to the same *image* and make container-specific changes on a writable layer. A *Docker image* can be built by reading the instructions from a *Docker file* that usually consists of commands to install packages, calls to customed scripts, setting environmental variables and permissions. Building up a container and deploy it into any other system where Docker is running, is easy enough.

Containerization improves encapsulation, scalability, reproducibility, portability, maintainability and offers new possibilities concerning execution security and isolation of resources but, in contrast to virtual machines, faces the issues of high overhead due to hardware emulation obtaining better performance in sharing the host OS kernel.

The use of this technology makes development process more agile and responsive and makes hassle-free the code reuse (Docker, 2020).

Web Processing Service (WPS) is one of the OGC (OGC WPS, 2020) specifications to provide access to GIS data or functionality over the internet in a standardized way, on the basis of XML/GML communication encoding, used for serving and executing geospatial processes, algorithms, and calculations. WPS standard defines how a client can request the execution of a process, and how the output from the process is handled. The data that the process uses can be delivered through the network or made available at the server level and can include vector or image formats such as GeoTIFF, GML, KML etc. Client applications work with a WPS service by appending parameters to the service's URL. The *Request* may be made as a HTTP GET, or a HTTP POST with an

XML request document. The inputs and outputs required depend on the process being executed. *Response* is delivered as an XML document. **GRASS** (Geographic Resources Analysis Support System) is a free and open-source desktop GIS software (GRASS, 2020). It can handle all geospatial data format such as: raster, vector, image, tabular data, etc. Furthermore, GRASS offers many spatial modeling algorithms focused on hydrological analysis. This software has an intuitive graphical user interface but can also be used through the system command line, so it can be easily integrated in other services through designated scripts.

PyWPS is a Python-based WPS implementation. It provides a native support for many geospatial tools like GRASS GIS, R-Project and GDAL. Python is recognized as the most geo-positive scripting language currently available: therefore GIS software are evolving more and more to take advantage of it. Initially started in 2006, PyWPS version 3 has been completely re-written to PyWPS-4 in order to provide new and useful features. The current version implements the WPS 1.0 standard (PyWPS 2020).

GISCLIENT3 is an open source software, offered by the Italian company GisWeb s.a.s., written in AJAX, Javascript, PHP/MapScript that offers an innovative way to manage complex GIS projects. It is composed by two components: *GisClient Author*, a component that allows administrators to build and manage data and GIS projects and *GisClient Viewer*, a Web-GIS interface, based on OpenLayers, which allows the typical client-side mapping operation and execution.