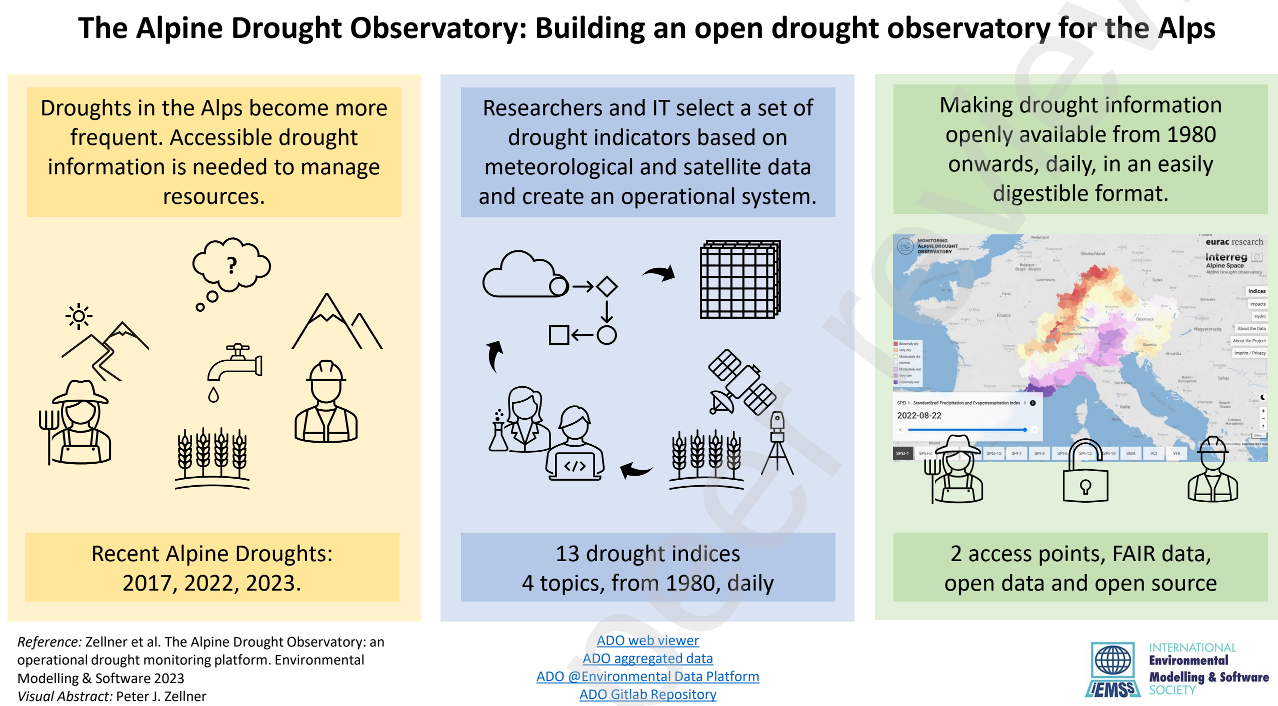
Graphical Abstract

The Alpine Drought Observatory: an operational drought monitoring platform

Peter J. Zellner,Rufai O. Balogun,Konrad Mayer,Thomas Iacopino,Luca Cattani,Mohammad H. Alasawedah,Daniela Quintero,Michele Claus,Bartolomeo Ventura,Andrea Vianello,Alessio Salandin,Elisa Brussolo,Ziva Vlahovic,Christian Ronchi,Bertoldi Giacomo,Mariapina Castelli,Felix Greifeneder,Alexander Jacob



Highlights

The Alpine Drought Observatory: an operational drought monitoring platform

Peter J. Zellner,Rufai O. Balogun,Konrad Mayer,Thomas Iacopino,Luca Cattani,Mohammad H. Alasawedah,Daniela Quintero,Michele Claus,Bartolomeo Ventura,Andrea Vianello,Alessio Salandin,Elisa Brussolo,Ziva Vlahovic,Christian Ronchi,Bertoldi Giacomo,Mariapina Castelli,Felix Greifeneder,Alexander Jacob

- The Alpine Drought Observatory is the first drought observatory dedicated to the Alpine region.
- The Alpine Drought Observatory is an operational platform that is providing drought information on a daily basis easily accessible and analysis ready through interactive web interfaces.
- The Alpine Drought Observatory adheres to open standards wherever possible meaning that the data is following the FAIR principles and the software is open source. Therefore, it serves as a blueprint for other drought observatories and its data is easily integrateble into other platforms.

The Alpine Drought Observatory: an operational drought monitoring platform★

Peter J. Zellner[a,*], Rufai O. Balogun[a], Konrad Mayer[b], Thomas Iacopino[a], Luca Cattani[a], Mohammad H. Alasawedah[a], Daniela Quintero[c], Michele Claus[a], Bartolomeo Ventura[a], Andrea Vianello[a], Alessio Salandin[d], Elisa Brussolo[e], Ziva Vlahovic[f], Christian Ronchi[d], Bertoldi Giacomo[a], Mariapina Castelli[a], Felix Greifeneder[g] and Alexander Jacob[a]

[a]European Research Academy (Eurac Research), Bozen, Viale Druso 1, 39100 Bolzano, Italy
[b]The Central Institute for Meteorology and Geodynamics, Hohe Warte 38, 1190 Vienna
[c]Global Hydrology and Water Resources Research Group, University of Virginia, Thornton Hall, 351 McCormick Road, Charlottesville, VA 22904, USA
[d]Department of Natural and Environmental Risks, Regional Agency of Environmental Protection of Piemonte (Arpa Piemonte), Turin, Italy
[e]Research Center, Societá Metropolitana Acque Torino S.p.A., Turin, Italy
[f]Slovenian Environment Agency, Vojkova 1b, 1000 Ljubljana, Slovenia
[g]Chloris Geospatial, 399 Boylston Street, Suite 600, Boston, MA 02116, USA

ARTICLE INFO

Keywords:
drought monitoring
environmental monitoring
CI/CD
operational platform
near real time
FAIR data
open source

Abstract

The Alpine Drought Observatory (ADO) web platform delivers daily drought data for the Alpine region. Accessible via a user-friendly web interface, it offers interactive maps displaying drought information for NUTS3 regions and hydrological basins. Expert users can access and process raw raster data. ADO covers various drought types, including meteorological, snow, agricultural, and hydrological droughts, initially developed and validated by a multi-disciplinary team. ADO's infrastructure produces drought indices operationally. The pipeline encompasses automated data download, processing, and aggregation, hosts databases, and features online processing tool as well as a web viewing portal. Open standards underpin the technology stack, making data FAIR and software open source wherever possible. ADO's architecture serves as a model for regional drought observatories and easily integrates with other platforms. In summary, ADO delivers daily Alpine drought updates, offers open access, and adheres to open standards, making it a valuable resource for drought monitoring and research.

1. Introduction

1.1. Motivation

The Alps are hosting 170 million people within its 4 major hydrological basins (Po, Rhine, Rhone, Danube) and are considered the water towers of Europe [1, 2]. In the last decade, the water-rich Alpine region has begun to experience a series of severe droughts including snow-drought [3] and other categories of drought events [2, 4]. This growing exposure to persistent and severe drought in the Alpine region and the lowland areas receiving water from the Alps places it at risk of water scarcity [5, 6, 7]. With mountain regions serving as key water suppliers for downstream regions [1], this risk often has far-reaching impacts including disruption in household water supplies, agricultural yield and production, industry manufacturing, and hydro-power generation [5, 8]. In fact, despite being the source of four major European rivers (Po, Rhine, Rhone, Danube) and an annual total precipitation reaching over 3000 mm/year in the wettest parts [9], it is projected that the European Alps will experience frequent and severe drought episodes in the future [10, 11, 12, 13]. Decreasing trends in snow-pack duration and water storage [14, 15] are already impacting alpine rivers' discharge [16, 17] and surrounding plains aquifers recharge [4, 18]. In addition, increasing summer evaporation [19, 20, 21] can amplify the intensity of drought events. On the other side, precipitation variability [22] makes droughts difficult to predict [23, 24, 25].

With its role as a major hydrological buffer the alpine region is at the center of important environmental resources and policy decisions. To foster early response and integrated water resource management, continuous monitoring of drought events and their impacts is necessary. This has been shown by recent extreme events such as the summer 2022 European drought [2]. Terzi et al. documented the impacts of these drought events on different domains such as agriculture, forestry, water quality or industry concluding that the predominant impacts of drought in the alpine region appear in the crucial domains of agriculture and public water supply. This asks for continued monitoring of agricultural and meteorological droughts provided through a drought observatory.

Hence, an Alpine-focused observatory that provides the necessary drought information to drive action in the region is necessary. Although the Alpine countries have developed different country-specific and local operational drought monitoring systems and platforms [26, 27], informing decisions at the scale of the Alps requires more spatial coverage across the region. This region-scale environmental monitoring involves large data processing tasks, requiring automation and scalability to make the generation of information manageable [28, 29].

*Principal corresponding author
ORCID(s): https://orcid.org/0000-0002-3394-9664 (P.J. Zellner)

1.2. Related works on operational drought monitoring

Droughts are complex, multi-domain phenomena, therefore it is often difficult to identify the beginning and ending of an drought episode [5]. Operational drought observatories or monitoring platforms aid to detect droughts by integrating different drought indicators that have proven to be consistent and reliable trackers of dry events. They are able to monitor the evolution of water availability and therefore aid early detection of drought events [27, 30, 31]. Conceptually, operational drought monitoring platforms provide near-real-time information on the evolution of different types of drought events in an integrated manner. At both the regional and the global level, different drought observatories have been developed to provide rich information for meteorological, hydrological, and agricultural droughts [3, 27, 28, 30, 32]. At a national and local scale, within the Alpine countries, several water resource management platforms have embraced a similar methodology [26, 27, 28].

Different drought indices are used in drought monitoring to represent the complexity of the phenomenon. The World Meteorological Organisation (WMO) recommends the Standardized Precipitation Index (SPI) as the primary meteorological drought index to be used by national meteorological and hydrological agencies for tracking meteorological droughts [33, 34]. The SPI quantifies precipitation deficit at multiple aggregation periods such as 3, 6, 12, 24, and 48 months and can be adapted at a weekly or monthly timescale [35]. The SPI addresses the limitation of the Palmer Drought Severity Index (PDSI) by placing the severity of current event into an historical perspective and has since being adapted to develop other standardised indices such as the Standardized Precipitation Evapotranspiration Index (SPEI) [36], which incorporates both evapotranspiration and precipitation.

In snow-dominated areas, the most commonly used index for monitoring spring and summer drought is the Standardized SnowPack Index (SSPI) [37]. It provides information on the relative volume of the snowpack in the catchment on a ten-daily to a seasonal basis in comparison to a reference period, in a similar way as the SPI. To monitor agricultural drought events, anomalies in soil moisture and the fraction of Absorbed Photosynthetically Active Radiation (fAPAR) are commonly used [38, 39]. The Vegetation Condition Index (VCI) and the Temperature Condition Index (TCI) are used to monitor land-surface vegetation and moisture content. The Vegetation Health Index (VHI) combines the VCI and TCI to capture the combined effects of temperature and moisture on vegetation [34, 40]. For hydrological drought monitoring, the most commonly used indices are Streamflow Drought Index (SDI) developed by [41] and the Standardized Streamflow Index (SSI, also called SSFI) [42]. They quantify anomalies in the streamflow based on the long-term observed streamflow mean at a given gauge. To quantify low flow, indices based on the flow duration curve are commonly used, such as the Q347 or the 95 percent quantile [43].

At regional and global levels, the aforementioned indices and indicators are often integrated into a near-real-time operational system that provides reliable and consistent drought information for policymakers. The Global Drought Information System (GDIS), co-developed by WMO and the Group on Earth Observation (GEO), integrates regional and local drought monitors to both monitor and predict meteorological drought events across the globe [32]. In parallel to this, the European Joint Research Center (JRC) developed the European Drought Observatory [31, 44]. This initiative has since inspired the development of other Drought Observatories including the Global Drought Observatory, the South and Central America Drought Observatory and the African Drought Observatory all led by the JRC [30, 45]. All of them provide drought information at near-real time such as a 10-day interval, which often requires the automation of the data generation process.

The development of automated data processing pipelines for environmental modelling is not a new development approach in earth sciences. Notwithstanding, the evolution of effective software engineering methodologies such as DevOps, CI/CD and scalable computing using cloud and on-premises technologies has made the development of reliable and scalable systems possible. DevOps refers to a set of software engineering practices that enables the integration of the work of developers with operations to facilitate collaboration and shared responsibility [46]. One of such practices is Continuous Integration (CI) and Continuous Deployment (CD). CI is the practice of regularly integrating all code changes into the main branch, automatically testing each change, and kicking off a build while CD is the automation of the infrastructure provisioning and application release process. These two are commonly referred to as CI/CD [46].

Santoro, Mazzetti, and Nativi entitled these systems "geoscience digital ecosystems". To create well-architected microservices that allow for quick generation and dissemination of environmental information they leverage important software development frameworks such as containerization, orchestration, and brokering. This evolving paradigm is based on modern tools and concepts such as Continuous Integration and Continuous Deployment [47] Docker [48], Kubernetes [49], Cluster API to produce software leveraging the computing power on multiple processing engines. This paradigm is already being embraced in the development of thematic environmental monitoring software. For instance, Drost et al. developed an event-driven architecture for monitoring the Wupper river (Germany) that uses several modular microservices to generate the final product. In ecological studies, this kind of approach is also used for process improvement such as minimising error rates in ecological data collection by testing code for certain edge cases as part of a CI/CD pipeline [50]. All these new approaches embrace trends in information technology to develop processing chains for earth observation and monitoring [28] and an open-source Digital Earth Twin Hydrology systems [51].

1.3. Objective

The Alpine Drought Observatory (ADO) is the first platform developed to provide near real-time drought information with a homogeneous approach for the whole alpine region, considering a set of indicators to monitor meteorological, nivological, hydrological, and vegetative drought, as well as their impacts. The ADO provides an up-to-date access to a combination of scientifically proven drought indices at 10 days behind real-time.

This paper describes the architectural design of the ADO infrastructure (2), the drought information that is produced operationally and displayed on the ADO web-viewer (3), and a case study showing how the ADO platform can be used in drought management practices (4).

2. The Alpine Drought Observatory infrastructure

2.1. Overview of the ADO infrastructure

The ADO platform is designed as a modular and operational system spanning from raw data download up to web visualisation of drought information. This section describes all components that work together to create the ADO infrastructure including processing pipelines, raster and vector data bases, entry points for user interaction, interactive web visualization, software architecture and the process of making the ADO data FAIR. Figure 1 shows a visual representation of how these components fuse together and the corresponding tools and technologies used to implement them. Each of these components are described more comprehensively in the subsequent sections.

2.2. Processing Pipelines

To enable automated calculation of drought indices all modules of the processing chain need to be executed in sequence. This is achieved by containerising the different calculation steps into docker containers that encompass the developed scientific code and software. The first step is data download. The online archive Climate Data Store (CDS) [52] is queried via its API to download reanalysis climate variables (ERA5) serving as input for the meteorological drought indices. Likewise, the Land Processes Distributed Active Archive Center (LP DAAC) is queried via its AppEEARS API to download MODIS satellite data serving as input for the satellite based drought indices. In a next step the meteorological data is prepared for analysis. First it is downscaled, then preprocessed to fit the format needed by the SNOWGRID-CL model [53] and finally the snow model is applied, generating a set of snow variables. The meteorological drought indices are based on the output of the downscaling and snowgrid routines, they produce a large set of intermediate data sets (e.g. temperature, precipitation, etc.). They are used for calculating the Standardized Precipitation Index (SPI), the Standardized Precipitation Evapotranspiration Index (SPEI) and Precipitation Anomaly (RR). The Soil Moisture Anomalies (SMA) are calculated using the downloaded soil moisture content from ERA5 directly, since a different downscaling approach is applied. The satellite based drought indices Vegetation Condition Index (VCI), Temperature Condition Index (TCI) and Vegetation Health Index (VHI) use the downloaded and pre-processed satellite data in form of NDVI and Lands Surface Temperature. To produce the list of ADO drought indices seven docker containers created by three research institutes (Eurac Research, Geosphere Austria and National Meteorological Service of Slovenia) are interlinked and run interdependently in sequence. How the indices are calculated in detail is described in section 3. The code and overview of these processing pipelines is openly available in the projects GitLab repository[1]. After the calculation of the drought indices further processing steps are triggered that deal with data storage and publication.

2.3. Databases

The implementation of the ADO project coordinated with 6 international partners across the European Alpine countries requires an effective data management strategy that enables collaboration and data quality assurance. The amount of data covering the alpine region from 1979 up to today is considerable, as well as the different nature of the available information (e.g., raster data, vector data, point data and time series). This involves organizing the collected and processed datasets in a shared storage system, raster databases and vector databases.

2.3.1. Raster databases

The raw drought index files are archived physically on a shared CEPH storage cluster [54]. To facilitate data management and access of multidimensional raster data, dedicated raster databases have been developed. They represent files as virtual multidimensional data cubes by indexing the files in the storage clusters, which allow extraction of arbitrary temporal and spatial regions and promote dedicated processing functionalities, such as aggregation and transformation. This plays an important role for making large volumes of data accessible and actionable by using them as a backend for the openEO API[55, 56] (see section 2.4.2). Two raster databases with different focuses have been set up in the ADO platform – OpenDataCube (ODC) and rasdaman.

2.3.1.1. OpenDataCube

The raster database OpenDataCube (ODC) [57] organises raster data as multidimensional data cubes. Every drought index (and the intermediate products like downscaled meteorological variables) are updated operationally whenever new data is available. The ingestion of new data into ODC is done by automatically updating YAML files containing the current metadata of the new acquisition (e.g. valid pixels, acquisition time, etc.). Consequently, the data cube grows by one date in the temporal dimension every day. ODC has the advantages that it integrates easily with other open source solutions since it is based on the python programming language and is in itself open source software. For raster data manipulation it leverages the well known multidimensional array library xarray [58] and it integrates well with the parallelisation library dask [59]. Additionally, there are ongoing efforts to standardise it as a reusable openEO backend [55][2].

[1] https://gitlab.inf.unibz.it/ado/operational_pipelines
[2] https://github.com/Open-EO/openeo-processes-dask

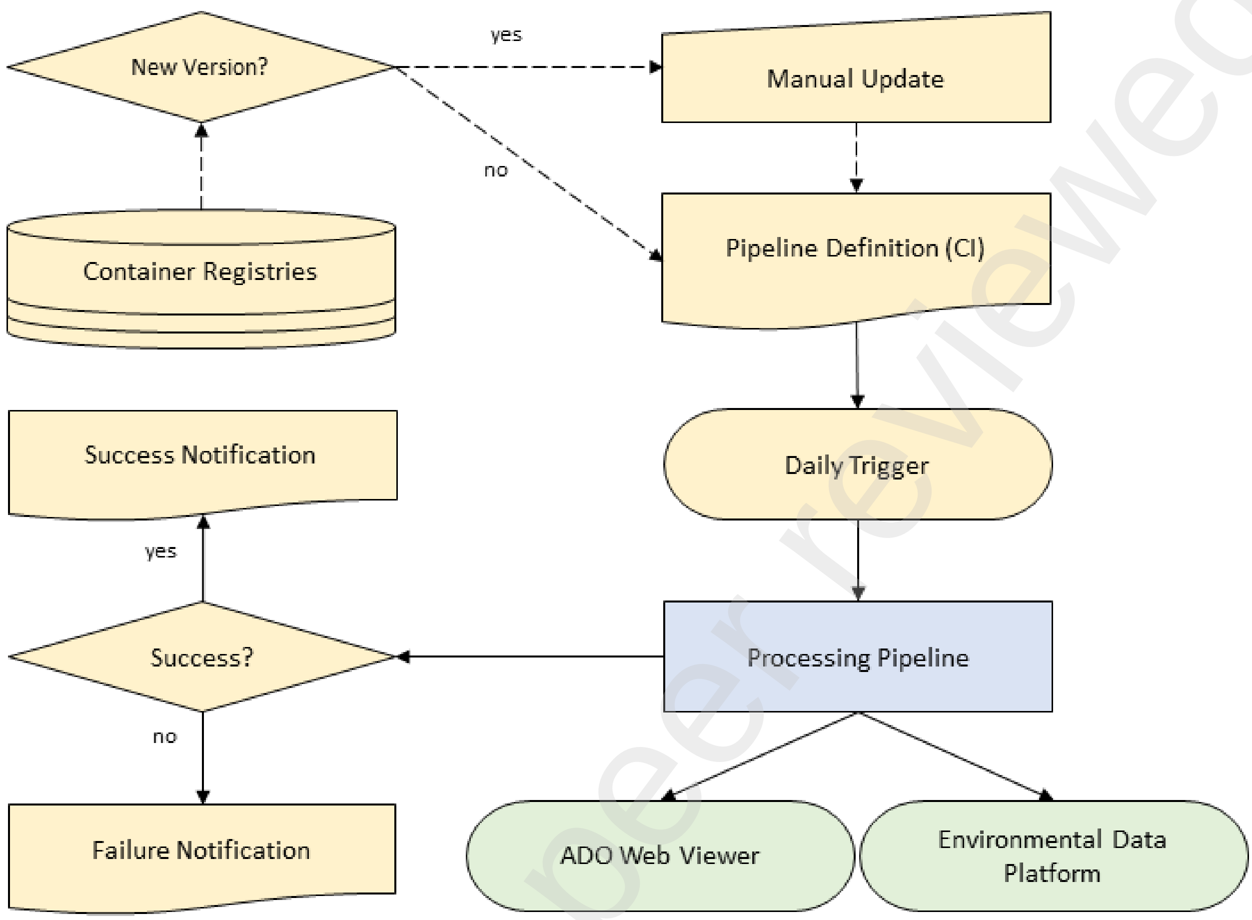


Figure 1: Flowchart diagram of the ADO platform infrastructure. The yellow components represent the workflow management. The dashed lines indicate that the interaction is only triggered if a new version of a pipeline component is available. The blue component represents the processing pipeline (depicted in more detail in figure 2). The green components represent the entry points for users. The technologies used for the workflow management are described in section 1.5 Architecture and Infrastructure.

2.3.1.2. Rasdaman

Rasdaman [60] is the second raster database used in the ADO infrastructure. It is a data cube index database which allows virtual data cube views on disk stored data with a commercial license [60]. It supports fast data access and extraction. Additionally, it potentially supports OGC Web Mapping Services (WMS) for rapid online visualization [60]. Currently, rasdaman is not included in the operational pipelines, which means that the drought indices are not automatically updated here. Nevertheless, the project data is available up to 2021 and can be manually updated if needed.

2.3.2. Vector databases

In addition to the raster databases two vector databases are maintained. The ADO web viewer visualizes the drought indices on different spatial levels (e.g. NUTS3). In order to organise this information a dedicated database is in place holding the aggregated drought indices statistics. Additionally, there is a data base for the hydrological station measurements collected across the Alps.

2.3.2.1. Database for aggregated drought indices

The ADO web viewer visualises the drought information on different spatial levels, i.e. NUTS and hydrological basins. In order to organise this information adequately, a database is put into place. In the first step, the raster data containing information on drought is aggregated into the respective polygons extracting summary statistics, which are saved as polygon attributes in the PostgreSQL database [61]. The database thus contains three spatial levels NUTS2, NUTS3, and hydrological basins. The aggregated value of every drought index is stored per spatial entity on a daily basis. This database structure is suitable for the extraction of time series and enables automatic updates to the ADO web viewer (see table 1). In order to feed the ADO web viewer with the structured GEOJSON files it requires, the database is used to export GEOJSON maps representing each polygon level for each index, as well as time series files representing the time series indices for each polygon level. The database approach is very flexible in changes to the format requirements, which

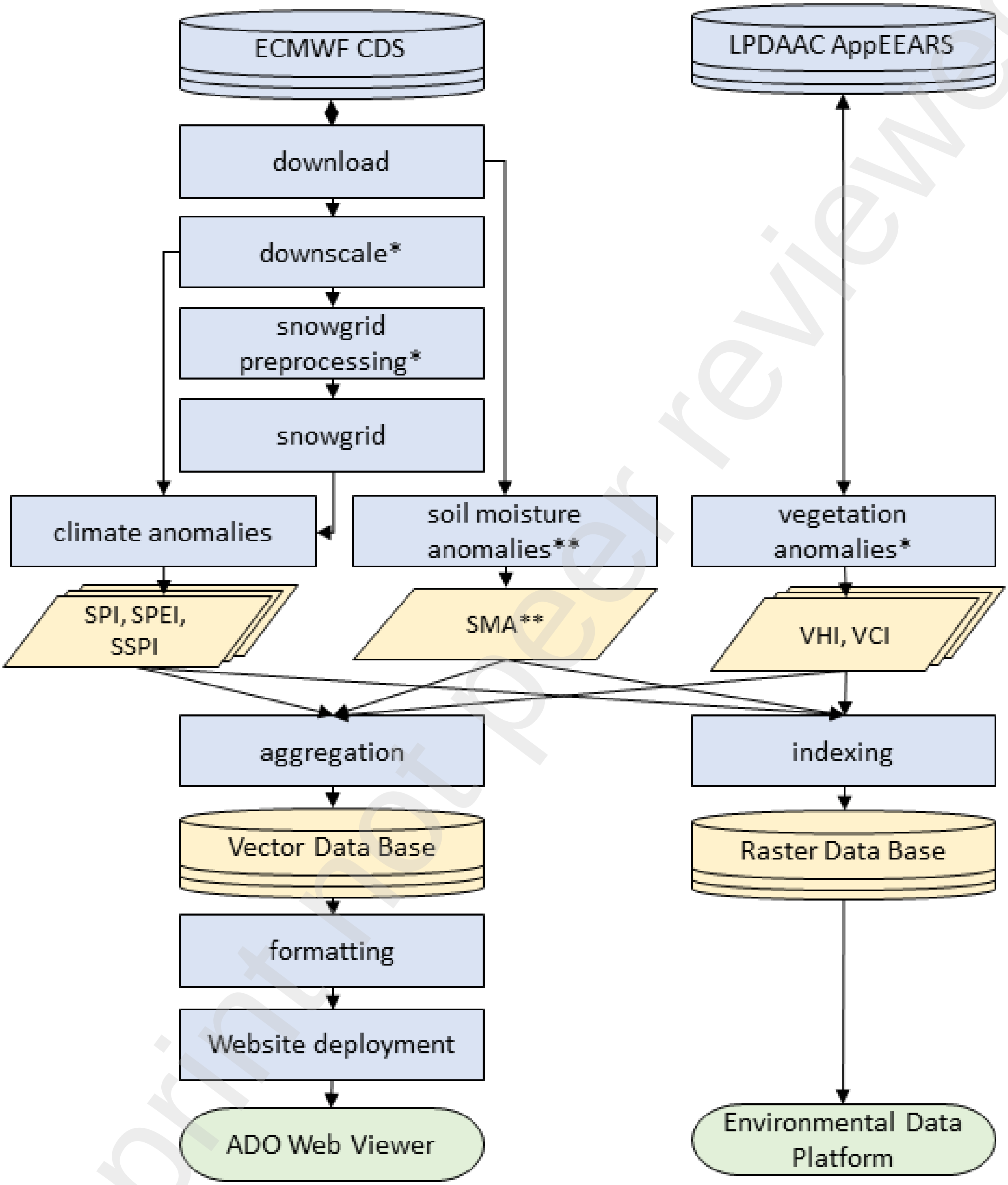


Figure 2: Flowchart diagram of the processing pipeline covering the components that are described in section 1.2 Processing Pipelines (blue components), 1.3 Databases (yellow components) and 1.4 Entry Points (green components). Every process represented by a rectangle is its own GitLab repository and docker container. The used technologies are described in the according sections. *The containers downscale, snowgrid pre-processing, climate anomalies and vegetation anomalies produce additional datasets that are only available on the Environmental Data Platform in order to keep the ADO web viewer concise.**The SMA processing components are currently not operational.

Table 1
Description of the aggregated drought indices database schema (exemplary for the NUTS3 level)

Column name	Description	Data type
Nuts Name	Unique name for each NUTS3 administrative divisions.	Character varying
Nuts ID	Unique codes assigned to each NUTS3 administrative division.	Character varying
Date	format yyyy-mm-dd	date
Index value	Aggregated index value over each NUTS3 division.	numeric

has proven very valuable during the development phase. Exporting the GEOJSON maps and time series files is the last step of the workflow, allowing them to be automatically exported whenever the database is updated with new dates. Finally, the exported files are forwarded to the ADO web viewer public data repository GitHub[3]. The entire process is dockerized for the operational conversion of the ADO indices from raster format to GEOJSON on a daily basis, enabling their use in the ADO web portal.

2.3.2.2. Database for hydrological data

This database contains all the hydrological station measurement datasets collected within the Alpine region by multiple data providers across Austria, France, Germany, Italy, Slovenia, and Switzerland. All the datasets collected by each project partner were integrated into a common open-source object-relational database (PostgreSQL) [62]. The database contains daily observational discharge and water level data for more than 1400 stations starting from the first measurement (which differs for each region) to the present, spanning from 1869 to 2021. A data homogenisation strategy was applied to ensure a common data format, which is necessary because because the measurements have been collected from different authorities. A custom set of Python scripts has been used to homogenize the format of the different data sources[4]. Missing data records were added to have a continuous time series. Currently, the update of this database is not operational. The database contains the following tables:

- **discharge**: daily time series of discharge stations present within the ADO space, obtained from different providers. Is made up of four columns: id station, date, discharge (m^3/s) and the data quality information given by its different providers. For a total of 1436 stations.
- **metadata_discharge**: information for each station site (id_station, country, region, site location, coordinates, start date, end date, watercourse, altitude, catchment area, etc.). All the stations have a record length greater than 10 years, except for Slovenia and the Italian regions Liguria and Friuli-Venezia-Giulia.
- **Water_level**: daily time series of water level stations located within the ADO space, obtained from different providers. Is made up of four columns: id station, date, water_level (m), and data quality information given by its different providers. For a total of 936 stations.
- **Metadata_wtl**: information for each water level station (id_station, country, region, site location, coordinates, start date, end date, watercourse, altitude, catchment area, etc.)
- **catchment_area**: information about the catchment area (m^2) for each gauging station. This information is obtained with a simple algorithm that retrieves the upstream catchment area from the CCM2 hydrological dataset. It can be found here[5]. A description of the latter is available here The geometrical field contains the polygon with the catchment area. The CRS is WGS84 (EPSG:4326).

The ADO web viewer shows the 17 outlet stations of the main hydrological basins of the Alps. The complete list of stations is available through direct database access. For an user-friendly visualization of the hydrological discharge time series, the station's location are visible by a spatial layer that can be accessed by a GIS client (or R) to compose maps using the WMS service[6]. The data can be visualized through a web-gis visualization of the station locations including the plots of the time series on a Grafana [63] dashboard[7].

2.4. Entry points

The ADO Platform has been developed with two main user groups in mind: experts, such as researchers or hydrological planners and the general public, such as interested persons and journalists. Their corresponding needs led the team to develop two main entry points for interacting with the ADO drought information. The ADO web platform is the main entry point. It presents the drought information in an easily digestible manner so that all categories of users can access, utilize, and understand the products. The second entry point is the Environmental Data Platform (EDP) [64][8]. It is geared towards an expert audience that requests more detail and control over the data. Therefore, the drought indices (and intermediate products) are available with detailed and standardized metadata (STAC), in their native raster format and resolution and can directly be analyzed using cloud

[3] https://github.com/Eurac-Research/ado-data/tree/main
[4] https://gitlab.inf.unibz.it/ado/hydrology
[5] https://bit.ly/runoff_prediction
[6] https://maps.eurac.edu/geoserver/ows?
[7] https://maps.eurac.edu/maps/85
[8] https://edp-portal.eurac.edu/

data processing tools (openEO). In this section, we provide detailed information on the production of these two entry points to the ADO platform.

2.4.1. Web viewer

The ADO web viewer is designed as a first entry point to the ADO datasets. Therefore, the information is presented in an understandable, responsive, interactive and visually appealing format, allowing the general public to get in touch with drought information. It has been fully developed within the ADO project.

A central theme in the development of geo web visualization platforms is the user accessibility in terms of latency and usability. Many of these platforms are frequently updated with large amounts of data creating a heavy load on database servers. Therefore, it is common that geo web visualization platforms have high latency, which leads to poor user experience. Hence, the objective in the development of the ADO web platform was to establish an informative interactive web viewer with high speed, stability, and usability leveraging our automated data pipelines. In addition, to make sure the platform can be managed and supported by a small team in the long term, the architectural decisions were focused on reducing complexity, and outsourcing labor-intensive infrastructure to external services and automating the others. In turn, this frees up time for conception and work on the web frontend.

Therefore, the web portal was developed using a Serverless, Static and Headless architecture. This implies that (i) the content is managed via CDNs (Content Delivery Networks), so that there is no need for servers, (ii) the frontend components are pre-rendered whenever possible (e.g. static pages), and (iii) frontend and backend are separated, which facilitates maintenance and flexibility. The use of CDNs over services delivers the static pages cached worldwide ensuring that they are fast for users, secure, as there is no direct connection to a backend with databases, and stable, as even high user numbers do not lead to an increased load.

The website itself is a static Next.js[9] app that displays a Mapbox[10] map on which the geojson content is rendered as polygons. Additionally, upon click on a NUTS region time series is displayed. The time series is created with Echarts[11] and goes back to the first observations (e.g. 1980 for the meteorological drought indices). It is possible to interactively add other indices to the time series plots for comparison.

The web viewer is based on two GitHub[12] repositories, the data repository[13] is dedicated to hosting the markdown, geojson, json and html files and the website repository[14] holds the code for the actual Next.js website. The data repository receives its input from a daily process that extracts, formats and pushes drought information from the "Database for aggregated drought indices" (section 2.3.2.1). As soon as new data arrives in the data repository, a push to the website repository is triggered via GitHub Actions. A change to the website repository in turn triggers a deployment of the website to Vercel.com, the CDN and serverless function service. Each push to the repository triggers a deployment to Vercel. If the deployment of the static page with the new data was successful, the cache is automatically purged globally, and the new content is visible everywhere. The page remains cached until the next successful deployment. If a deployment fails for any reason, the page (with the old data) remains online. The core content, i.e., the indices of the NUTS regions, is integrated into the deployment, further information (historical timelines or hydro) is fetched on demand via APIs from the GitHub data repository.

The requirements for speed and stability could be achieved by the chosen architecture. In terms of usability, it is certainly possible to go the last mile and make the site more usable on mobile devices in the future. Notwithstanding, the decision for a Serverless, Static, Headless architecture has been shown to be useful in developing fast and stable geo web visualization platform. The setup is also resource efficient, since neither database nor conventional web servers are constantly running at full speed and consuming energy, but instead only the one-time pre-compiled and cached page is delivered. A visual display of the ADO web portal is shown in Figure **??**.

2.4.2. Environmental Data Platform

The data access via the Environmental Data Platform (EDP) is geared towards an expert audience, such as researchers or hydrological officers. The core services which are covered by the EDP are (i) full metadata access and searchablility, (ii) access to the fully detailed raw raster data sets and (iii) direct cloud processing capabilities to analyse and manipulate the data sets. The EDP has already been available as a service from Eurac Research prior to the ADO project. Its capabilities suit the need for expert users adequately. Consequently, it is used as a component of the ADO infrastructure. To access the processing capabilities of the EDP an account is needed (available upon request). Data discovery is accessible without login.

- **Metadata**: The EDP allows to search datasets by its metadata such as spatial and temporal resolution and extent as well as keywords. The standardized metadata format Spatio Temporal Asset Catalogue (STAC) [65] Specification and Geonetwork [66] are used to store the metadata and to make it searchable. The section 2.6 FAIR data describes this in more detail.
- **Raw data access**: The EDP hosts all data produced operationally through the ADO processing pipelines. This means not only the selected indices displayed on the web platform are available, but also intermediate products such as downscaled meteorological variables. Accessibility to the original data in its native resolution is critical for researchers in order to use it for their own analyses, such as aggregation into different spa-

[9] https://nextjs.org/
[10] https://www.mapbox.com/
[11] https://echarts.apache.org
[12] https://github.com/
[13] https://github.com/Eurac-Research/ado-data
[14] https://github.com/Eurac-Research/ADO/

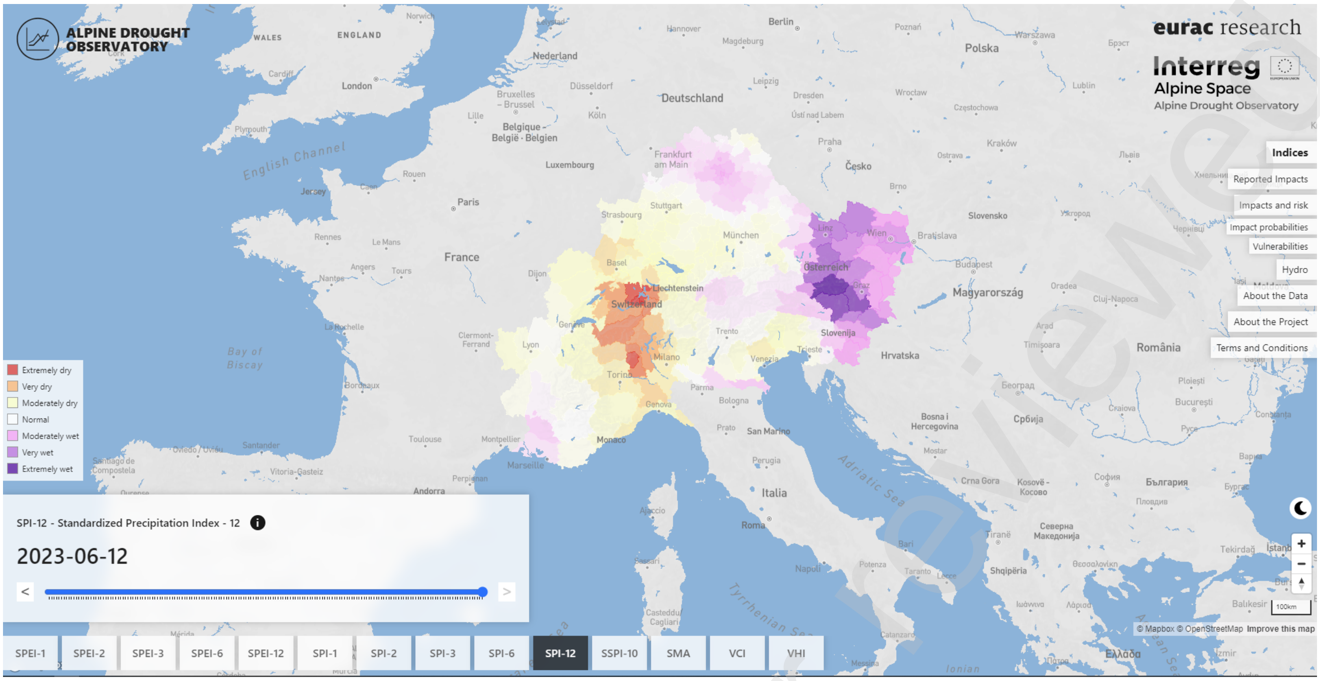


Figure 3: The Alpine Drought Observatory Web Portal: showing the Standardized Precipitation Index at an aggregation period of 12 months across the Alpine countries

tial entities or applying different methods of anomaly calculations to compare to the ADO indices.

- **Cloud processing**: The EDP allows to directly process data in the platform. Therefore, the standardized EO processing API openEO [55, 56] is integrated into the EDP. A Jupyter Hub environment is available for users where the most common geospatial analysis packages for the programming languages R and python are preinstalled and ready to use. Additionally, the openEO web editor allows to build processing workflows by a user friendly drag and drop interface. For the analysis it is possible to select relevant areas and time steps of the vast amount of data to reduce its volume before downloading and to ensure only the relevant data is fetched. Furthermore, direct processing is supported, which enables for example the calculation of statistics or time series analysis. Finally, only the desired information can be downloaded and further processed.

2.5. Architecture and Infrastructure

The previous sections have described the different parts of the ADO platform (see figure 1). It becomes evident that there is a complex relationship between the components that describe a workflow from data download up to web visualization. To manage the interoperability between the modules a common software design strategy and architecture is needed. The ADO Platform was developed following a modular software development approach inspired by the micro-service architecture aiming at high degrees of flexibility, maintainability and portability. Each newly developed component was developed with minimal dependencies on one another in mind.

The components are managed and put into relation using the infrastructure and workflow orchestrator Kubernetes on-premises [49, 67], configured using Rancher [68]. Three small Kubernetes clusters (2 CPUs, 8GB RAM) are spawned in a high availability configuration. In comparison to one large multi-tenants Kubernetes environment, this ensures optimal security and manageability. The storage infrastructure leverages a CEPH-based distributed storage system consisting of 55 servers, 740 disks and reaching a storage capacity of 2.5 petabytes (PB). It is used for physically storing the raw datasets.

2.5.1. *CI/CD*

A recurring topic in the development of operational platforms for environmental monitoring, is the management and coordination of the data pipeline or workflow [28, 29]. A data pipeline is a series of steps that defines the data life cycle from data capture, data transformation, to data visualization or generation of new datasets [69]. The ADO processing pipelines, consisting of 11 docker containers from download to web visualization, are managed through the Eurac Research GitLab and GitHub instances for code hosting, containerization and pipeline definition and Kubernetes on-premises [67] for the execution of the pipeline.

Each of the pipeline components (such as downloading, downscaling, etc.) is hosted separately as a GitLab repository using the GitLab container registry for maintaining and sharing the state of the respective docker container. A GitLab CI (Continuous Integration) trigger is active in each repository, which builds a new version of the docker container as a new tag is added. This containerization mechanism ensures that every step in the pipeline produces the estimated output regardless of where or when it is executed. Additionally, it allows for direct collaboration with the scientific code maintainers, meaning that changes can directly be incorporated and versioned into a new docker container. Currently we have not incorporated the GitLab CD (Continuous Delivery). Code changes are only integrated after manual review to ensure the quality of the updates.

The pipeline is launched daily by a cronjob. It stops itself if a step does not end correctly and sends a result notification to a Microsoft Teams channel to facilitate quality management. Each step of the pipeline is executed on the Kubernetes cluster, which is integrated with Gitlab using tokens. When a job fails due to resource constraints or long execution times, Kubernetes moves those jobs to nodes with extra capacity. Essentially, Kubernetes acts as a queue manager, helping GitLab to keep up with demand by intelligently managing available compute resources. The total computing time for the pipeline is approximately 1 hour 46 minutes per day. This CI/CD pipeline approach ensures the integrity and scalability of the entire development process while minimizing the risk of human errors. The entire process can easily be moved to a cloud environment.

2.5.2. Open source software

The main components of this architecture were implemented using open source tools and platforms, which are now at the center of development of on-premises, hybrid, and cloud-based environmental software architectures [29, 70]. The ADO architecture utilizes different open source tools and technologies to manage its data, infrastructure and access. The pipeline components (e.g. data download, drought index calculation) rely on the programming languages R and python. The data pipelines are managed by Kubernetes, Rancher, Docker and GitLab. The data management is based on CEPH, OpenDataCube, rasdaman and PostgreSQL. For accessing the data via the EDP, STAC, GeoNetwork, openEO are used. The web-viewer is based on Vercel, mapbox, echarts and Next.js. The ADO infrastructure itself is also open source (besides the SNOWGRID-CL Model developed by [53]). Building an infrastructure on-top of an open source software stack allows also to distribute the own developments as open source. An overview with links to the developed components can be found in this Gitlab repository[15]. It can serve as blue print for other regional drought observatories or relevant components can be extracted and integrated into other platforms. The ADO architecture is there to be improved and reused.

2.6. FAIR data

The ADO datasets are produced adhering to the FAIR data principles [71], making them findable, accessible, interoperable and reusable. The FAIR principles provide a set of best practices for sharing data respecting any legal, ethical, or contractual restrictions and thus increasing the impact of the research value. The following sections describe which measures have been taken to comply to any of the FAIR data requirements. Adhering to the FAIR standards has allowed the ADO datasets to be integrated flawlessly into the European Space Agencies Green Transformation Information Factory [72].

2.6.1. Findable

2.6.1.1. STAC GeoNetwork Metadata

Metadata is usually identified as "data about data". Whenever it is possible to find and infer the meaning of a dataset without opening it, the metadata is well-written. In the ADO project, the latest developments in metadata representation are used: Spatio Temporal Asset Catalogue (STAC), and the catalogue application GeoNetwork. STAC is an open specification that evolved from different organizations coming together to increase the interoperability of searching for satellite imagery [65]. GeoNetwork is a catalogue application to manage spatially referenced resources. It provides powerful metadata editing and search functions as well as an interactive web map viewer [66]. Both STAC and GeoNetwork are open-source, and the user can easily interact with the community to suggest improvements and/or contribute new ideas. The STAC specification provides a method to describe a range of geospatial metadata information, so it can more easily be indexed and discovered.

GeoNetwork offers the possibility to describe data using standards defined by the ISO and OGC community. These specifications don't match. To link these two catalogues an automatic script has been developed to convert STAC metadata entries into GeoNetwork ones. In this way, it is possible to host metadata that can be queried, both, using STAC, and an XML file for a CSW catalogue, compliant with the OGC standards as well as for INSPIRE and ISO-19139 [73]. By adhering to these metadata standards the data available on the EDP is harvested by the Global Earth Observation System of Systems (GEOSS) Portal and is also findable there.

2.6.1.2. Digital Object Identifiers (DOI)

At the same time, it is fundamental to assign a unique and persistent identifier for making and keeping datasets findable. A Digital Object Identifier (DOI) consists of a long-lasting reference to a digital resource. Unlike an URL, which may break, a persistent identifier reliably points to a digital entity managed by specific organisations that guarantee the persistence of the information. DataCite Fabrica offers the service to create, find, connect and track all of your DOIs and metadata [74]. Advantages of the DOI registrations are (i) the increase of credibility through the traceability and reproducibility of research results through the publication of research data, (ii) it enables the citability of scientific contributions such as research data, journal articles, software, videos and grey literature and corresponding citation metrics and (iii) it enables every data or services to be cited properly. Since late 2021, Eurac Research became a DataCite member and it has the possibility to create DOI [74]. Within the ADO project DOIs were created for specific datasets as to profit from the aforementioned benefits.

[15] https://gitlab.inf.unibz.it/ado/operational_pipelines

2.6.2. Accessible

Datasets are accessible if there is no barrier limiting the access to the data. In the ADO Platform, access to the data is secured through the ADO web viewer, an openly reachable web page without any access restrictions. The raw data is available via the EDP where a registration step is needed to secure its processing resources.

2.6.3. Interoperable

Datasets are interoperable if others can integrate them easily into their research. To increase the interoperability of the ADO data sets two main measures have been taken. Every data set that is available on the ADO web viewer has its corresponding fact sheet that summarizes the data properties (e.g. metadata, validation) and how to use the data in a compact and easily understandable format (e.g. how to interpret the values). The other key to interoperability is to use open and community-accepted data formats. The aggregated drought information for the ADO web viewer is openly available as json data[16]. The EDP hosts the ADO collections as virtual data cubes. The data can be extracted into many community standard formats (e.g. tif, netcdf, json, csv, etc.) via the standardized API openEO.

2.6.4. Reusable

The reusability of the data is ensured by assigning an open license to all collections. The ADO collections are published under the Creative Commons License CC-BY-4.0 [75]. It allows to share, copy and redistribute the material in any medium or format and to adapt — remix, transform, and build upon the material for any purpose, even commercially. The only terms of use are correct attribuition. Appropriate credit must be given when using the data, providing a link to the license, and indicating if changes were made.

3. Datasets

This section gives a brief overview of the most important datasets that are produced in the ADO project, presented on the ADO web viewer and are available through the Environmental Data Platform (EDP). Table 2 provides a summary of the spatial and temporal resolutions of the ADO datasets. Every ADO dataset has its dedicated fact sheet summarizing the information on the index. The fact sheets are published on the ADO web viewer[17].

3.1. Precipitation Anomalies - SPI, SPEI and SSPI

Meteorological datasets from the ERA5 reanalysis [52], downloaded via the Copernicus Climate Data Store (CDS) API, serve as the basis for the calculation of the standardized drought indices such as the Standardized Precipitation Index (SPI) [76], Standardized Precipitation Evaporation index (SPEI) [77] and the Standardized Snowpack Index (SSPI) [78]. Data of surface temperature, humidity, solar and thermal radiation, precipitation and wind get resampled to daily aggregates. These are regridded onto the UERRA MESCAN SURFEX grid [79] using bilinear interpolation and bias corrected using quantile mapping. The used quantile mapping approach is based on empirical cumulative distribution functions (ECDF) of regridded ERA5 data and UERRA MESCAN SURFEX data for each day of the year in the reference period 1979-2018. For each value, the probablity from the ERA5-ECDF at the respective day of the year is computed. A correction factor, as the difference of quantile values for the probability at the two reference ECDFs for the respective day of the year is applied [80]. In addition, derived datasets for maximum temperature as well as Penman-Monteith evapotranspiration according to FAO recommendations [81] are computed. Downscaled data are also used to drive the snow model SNOWGRID-CL [53] to derive snow water equivalent (SWE).

For aggregations (1, 2, 3, 6 and 12 months for SPI and SPEI, 10 and 30 days for SSPI) of the data, analytical probability distribution functions (gamma distribution for SPI and SSPI, generalized logistic distribution for SPEI) were fitted for the reference period 1981–2020 and used to transform values to a standard normal distribution. These represent the respective drought index, with positive values for wetter and negative values for dryer than the normal conditions.

For SPI and SPEI validation has been carried out at 15 stations in Slovenia where Penman-Montheith evapotranspiration and precipitation are available with a suitable data record. These stations represent the 15 regions used in the national drought monitoring. The linear regression model between ADO indices SPI-2 and SPEI-2 and the same indices calculated from the station data indicates high correlation, with values of r2 averaging at 0.72 and ranging from 0.62 to 0.79 for both daily index values and monthly mean index values [82]. Additionally, the SPEI has been compared to a yield calibrated grassland model based on station meteorological data in three Slovenian farms. SPEI-2 and SPEI-3 correlated well with the time series of the grassland model output for the chosen variables (drought factor, actual root zone water content, and root dry weight) and managed to identify the three drought years 2003, 2007 and 2017 [83]. The snow height data from the snow model SNOWGRID-CL, which serves as the input for the SSPI, has been validated against the CliRsnow data set, a collection of more than 2900 snow station measurements across the Alps [84]. 2694 stations were considered for the comparison as they share a time series of more than 10 years with the model results. The results show very good agreement of the absolute snow depth below 800 m elevation and in the large valleys. Absolute differences above are mainly caused by the magnitude of modelled snow height, elevation and elevation delta (station location within 5 km grid cell). Some differences due to bias (offset) which may be caused by biased input data (down scaled ERA5 variables) and not modelled redistribution processes (e.g. wind) have been observed. Nevertheless, even if biased, the year to year variation is well covered, thus, the SSPI is of much higher quality than absolute measures [85]. Koehler et al. have used the SSPI in

[16] https://github.com/Eurac-Research/ado-data
[17] https://ado.eurac.edu/md/about-the-data

Table 2
Spatio-temporal resolutions of the ADO datasets. SPI: Standardized Precipitation Index, SSPI: Standardized Snow Pack Index, SPEI: Standardized Precipitation-Evapotranspiration Index, SMA: Soil Moisture Anomaly, VCI: Vegetation Condition Index, VHI: Vegetation Health Index, SDI: Streamflow Drought Index, SSI/SSFI: Standardized Streamflow Index, Q95: Q95 Index

Drought type	Index	Source	Temporal resolution	Temporal coverage	Spatial resolution
Meteorological	SPI	ERA5	Daily	from 1979	5km
	SSPI	ERA5	Daily	from 1979	5km
	SPEI	ERA5	Daily	from 1979	5km
Agricultural	SMA	ERA5	Daily	from 1979	5km
	VCI	MODIS	8 days	from 2001	231 m
	VHI	MODIS	8 days	from 2001	231 m
Hydrological	SDI	Hydr. Offices	Monthly	Station dependent	Point
	SSI/SSFI	Hydr. Offices	Monthly	Station dependent	Point
	Q95	Hydr. Offices	Monthly	Station dependent	Point

a study to describe the 2022 drought in Northern Italy, by determining the snowline elevation, which in 2022 lies several hundred meters over the long term mean. The snow line elevation dynamics derived by optical remote sensing show good agreement (inversely correlated) with the SSPI. The SPI, SPEI and SSPI have been published as openly available data sets [76, 77, 78] with their according fact sheets clarifying how to use the data [86, 87, 88].

3.2. Soil Moisture Anomalies - SMA

The Soil Moisture Anomaly (SMA) [89] is a drought indicator used for determining the start and duration of agricultural drought conditions [90]. Agricultural drought condition is defined as a prolonged period of reduced crop production due to deficit in the availability of soil moisture to plants. In the ADO project, we computed daily SMA with respect to the average conditions of the preceding 10 days (dekad) as anomalies of soil moisture content derived from ERA5 analysis [52] for a reference period of 1981 - 2020. The SMA was calculated using the ERA5 reanalysis dataset at 0.25resolution [52], regridded using bilinear interpolation to 5 km. Numerically, the dekadal SMA can be computed for each grid cell as:

$$SMA = \frac{SM_t - \overline{SM}}{\sigma_{SM}} \tag{1}$$

where SM_t is the dekadal average soil moisture for date t, $\overline{SM}$ is the long-term mean and σ_{SM} is the standard deviation, which are both calculated for each day of the year from a smoothed time series (running mean on a 10 day window) for a baseline period of 1981-2020. Hence, the anomaly values are expressed as units of standard deviation.

The SMA has been compared to in-situ measurements of the soil moisture from three station networks: six stations in Switzerland (SWISSMEX [91]), six stations in the french Alps (SMOSMANIA [92]) and seven stations in the Austrian Kalkalpen national park (WEGERNET [93]). Soil moisture anomalies have been calculated at the station locations and compared to the ADO SMA. The SMA correlations expressed as Pearson correlation coefficient based on the average soil moisture conditions per network is overall 0.73 (0.62, 0.82, 0.75, respectively). The correlation based on every station is overall at 0.62 (0.79, 0.50, 0.59, respectively) [94]. The ADO SMA based on ERA5 describes the general anomalies well on the level of station networks, while the accuracy tends to decrease when looking into the single measurement locations. The SMA has been published as an openly available dataset [89] with an explanatory fact sheet clarifying how to use the data [95]. The SMA product is currently not fully operational on the ADO platform, but is available until April 8, 2022.

3.3. Vegetation Anomalies - VCI and VHI

The vegetation indices computed in the ADO project are based on MODIS satellite data. The spectral reflectances MOD09Q1 [96], are used for computing the Normalized Difference Vegetation Index (NDVI), and MOD11A2 [97], for computing the Land Surface Temperature (LST). These datasets were used to compute the Vegetation Health Index (VHI) [98], which is used for detecting vegetation stress conditions resulting from a shortage of soil moisture to plants. The VHI allows to identify drought impacts on vegetation which correspond to a combination of thermal stress, which is detected as an increase in LST, and a decrease in vegetation greenness, which is identified by lower-than-average values of the Normalized Difference Vegetation Index (NDVI) [40]. In the ADO project, VHI is computed on an 8-day basis and considers the reference period 2000–2020 for calculating extreme values of NDVI and LST. Mathematically, for each location (grid-cell), the VHI is calculated as shown in equation 2

$$VHI = \alpha \times VCI + (1 - \alpha) \times TCI \tag{2}$$

where VCI is the Vegetation Condition Index, TCI is the Thermal Condition Index, and α determines the share of VCI and TCI in the VHI. Since this share depends on location and time and is unknown, the weight of both indices was assumed to be equal, with $\alpha = 0.5$. VCI and TCI are calculated respectively as in equation 3 and 4:

$$VCI = \frac{NDVI_i - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \quad (3)$$

$$TCI = \frac{LST_{max} - LST_i}{LST_{max} - LST_{min}} \quad (4)$$

where $NDVI$ and LST are the smoothed 8 days $NDVI$ and LST, $NDVI_{min}$ and $NDVI_{max}$, and LST_{min} and LST_{max} are the minimum and maximum NDVI and LST values over the reference multiyear period, for the corresponding compositing period. The spatial resolution of the LST (1000 m) is resampled to the spatial resolution of MODIS reflectance (231 m) by the nearest neighbor approach to preserve the original values. Both input products, NDVI and LST, are masked to the highest quality standards using the provided MODIS quality layers. Missing pixel values in the NDVI and LST time series are linearly interpolated up to 2021. Non-vegetated areas are masked using the most recent Corine Land Cover [99] product version for the according year. The final product is re-gridded to the LAEA Projection (EPSG: 3035). The Food and Agricultural Organization (FAO) recommends a classification scheme [100] for identifying the intensity of drought conditions using the VHI, ranging from 0 (extreme vegetation stress) to 100 (very favorable conditions).

The ADO VHI has been analysed on agricultural fields and grassland in Bavaria, Germany between 2001 and 2020 for it's suitability to detect agricultural drought [40]. Kloos et al. found that in summer (July-August), below 800m on agricultural land and grasslands, NDVI and LST show a negative correlation, indicating water as the primary growth-limiting factor. TCI and VHI strongly correlate with soil moisture and yield anomalies, suggesting their potential for detecting agricultural drought in Bavaria. Additionally, the VHI has been compared to grassland model results in Slovenian farms where it showed the potential to identify the targeted drought years 2003, 2007 and 2017 [83]. The VHI and VCI have been published as an openly available data set [98] with an explanatory fact sheet clarifying how to use the data [101].

3.4. Hydrological Anomalies - SDI, SSI and Q95

The hydrological indices in the ADO project were computed on the entire time series collected across 1400 stations from multiple data providers covering Austria, France, Germany, Italy, Slovenia, and Switzerland. Those time series contain observational daily discharge and water level data. The time span of the records is very different and ranges from 1869 to 2021. Only stations with at least 10 years of data have been considered. All time series were converted to a common format and pre-processed by checking for data gaps and discarding out-of-range observations. Lastly, the clean time series were averaged to a daily time-step per station.

For each gauging station, a report was prepared and the Streamflow Drought Index (SDI), the Standardized Streamflow Index (SSI or SSFI), and the Q95 index were computed. These indices were kept as static datasets within the ADO processing chains and are yet to be operational on the ADO platform. The SDI is a measure of the deviation from long-term observed streamflow at a given gauge to show the frequency and severity of hydrological droughts [41]. We computed this index on four different time scales (1, 3, 6, 12 months). The SSI, introduced by Modarres in 2007, is a probability-based index defined as the difference of the streamflow from the mean divided by the standard deviation [102]. The SSI allows for an accurate spatial and temporal comparisons of the hydrological conditions of a stream or a set of streams [42]. It uses the methods of normalizations associated with SPI. The Q95 index also called the Q347 index is the discharge of the watercourse which is reached or exceeded at least for 95% of the time, that is on 347 days in an average year. It is one of the low flow duration indices, which indicates when the river flow rate is below an accepted standard. Although, the Q95 is widely used in government, management and academic literature, it often has problems related to both the measurement of very low discharges and the increasing proportional variability between the natural flow and the net impact of artificial influences [43].

4. ADO case study: Orco river basin drought management

The Orco river basin is located in the Piedmont region, in north-western Italy, and covers approximately 913 km² at 567 m. Figure 4 shows the Orco river basin and its hydrographic characteristics. The climate in the Orco basin, considered as sub-alpine, is characterized by warm summers and mild winters with a classic bimodal monthly rainfall trend with two peaks in spring and autumn. The total annual precipitation and average temperature reached around 1200 mm [103] and 11° C, respectively.

Many municipalities in the mountainous area of the Orco River basin have springs as their only water source for drinking water. The springs are the sources that are most vulnerable to drought phenomena and, in general, to precipitation variability. As a consequence of critical situations, emergency interventions to supply potable water with tanker trucks or mobile reservoirs become necessary. The drought situation in the Orco river basin is monitored by the regional drought monitoring and communication system of the Regional Agency of Environmental Protection of Piemonte (Arpa Piemonte). It is communicated through a monthly hydrological bulletin and during the period from late spring to summer it appears weekly.

This basin was selected as a case study due to: (i) the multiple management of drinking water resources, (ii) the presence of hydro-power abstraction with significant storage capacity upstream and irrigation abstraction downstream, and (iii) the recurrence of summer water deficits.

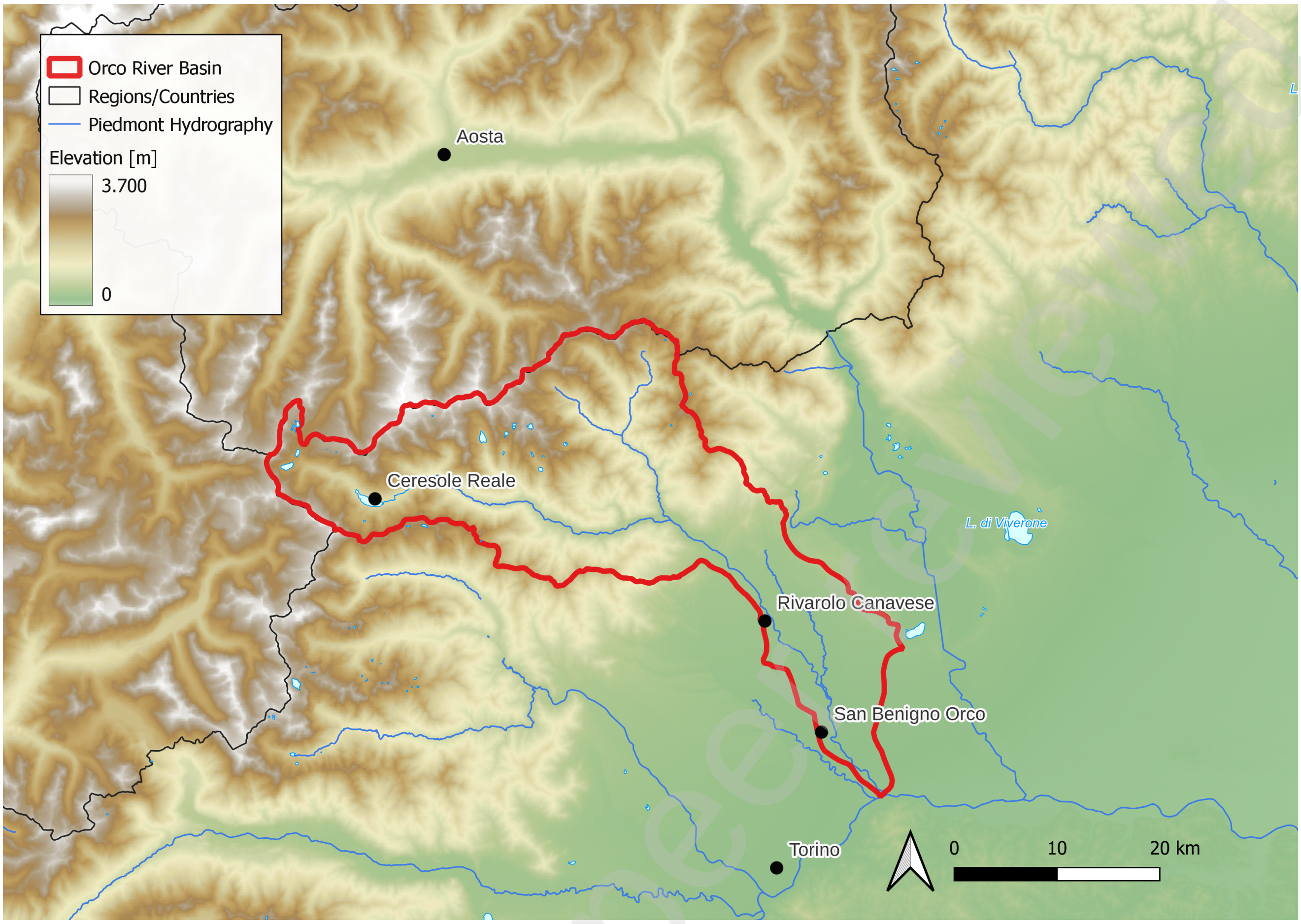


Figure 4: Orco River Basin including the main hydrography of the Piedmont region (EPSG: 32632). The orography is based on a digital elevation model derived from the SRTM project, interpolated at 30m of spatial resolution (processed SRTM data version 4.1, available from `http://srtm.csi.cgiar.org`). The hydrometric station at the end of the basin (San Benigno Orco) is also shown, together with the locations where the ADO products validation was made (Ceresole Reale and Rivarolo Canavese).

4.1. Water availability and drought situation

To assess the drinking water conditions and to update the Piedmont Region's Water Protection Plan, we reconstructed the Water Exploitation Index plus (WEI+). It is the fraction of the difference between water abstractions and returns and the renewable water resources of an area [104]. The WEI+ is an indicator of the level of pressure exerted by human activities on water resources in a territory , i.e. a hydrographic basin or sub-basin. It identifies areas at-risk of water stress. In this study the WEI+ is merely used to describe the water availability in the case studies area of interest, it is not used for the validation procedure. We computed the WEI+ for a time span of 2000-2016, evaluating the water availability deficits in an average year (with reference to the average monthly values) and in a dry year, with reference to the 80th percentile of each month. In an average year, water scarcity occurs in August, while in a dry year, it occurs in July, August, and November. The major water deficits occur at the end of the irrigation season (July-August-September). Overall, the degree of quantitative alteration of the hydrological regime must be considered high due to the high level of water management by the upstream reservoirs.

4.2. Evaluation of ADO products

The SPI and the SPEI, from the ADO platform were evaluated in a case study focusing on the Orco river basin. The ADO indices were compared to the same indices based on the North Western Italy Optimal Interpolation (NWIOI) datasets [105, 106]. NWIOI is a regular gridded dataset based upon more than 400 weather stations spread across the Piedmont Region at 14 km spatial and daily temporal resolution. It contains temperature and precipitation covering the Northwestern part of Italy since 1958. It has been validated and used within ARPA for more than two decades. Therefore, the SPI and SPEI based upon the NWIOI between 1979 and 2021 are chosen as the baseline for the validation. The comparison between the ADO and NWIOI based indices has been made at two locations, for which the indices have been extracted from the respective sources. The chosen locations are Ceresole Reale and Rivarolo Canavese, that represent respectively the top and the bottom part of the valley (see figure 4). We used cross-correlation techniques, scatter plots, and contingency tables to assess the SPI and SPEI indices.

Table 3
SPI3 Contingency tables comparing the SPI3 from NWIOI and ADO for the bottom of the Valley Rivarolo. (Left) Event counts detected using SPI3 < -1 . (Right) The same expressed in percentages. The percentage of disagreement is 12.84 % (5.68 + 7.16; NWIOI NO/ADO YES + NWIOI YES/ADO NO). These are the cases where the two systems don't align.

Drought event counts

	ADO		
NWIOI	YES	NO	Σ
YES	53	34	87
NO	27	361	388
Σ	80	395	475

Percentages

	ADO	
NWIOI	YES (%)	NO (%)
YES (%)	11.16	**7.16**
NO (%)	**5.68**	76.00
Disagreement (%)	**12.84**	

Table 4
Accuracy table of the comparison between NWIOI and ADO. SPI3, SPI6, SPEI3 and SPEI6 are compared at the top and the bottom of Rivarolo Valley. A drought event is counted if an index is smaller -1 (Index < -1). The percentages are retrieved according to the example in Table 3.

	TOP	
Drought Index	Disagreement (%)	No. of events
SPI3	11.58	475
SPI6	11.58	475
SPEI3	11.86	472
SPEI6	11.58	475

	BOTTOM	
Drought Index	Disagreement (%)	No. of events
SPI3	12.84	475
SPI6	10.52	475
SPEI3	13.89	475
SPEI6	10.11	475

4.2.1. Validation of ADO Products

A correlation analysis has been performed between the ADO and NWIOI based indices (SPI and SPEI on a 1, 3, 6 and 12 month aggregation period) extracted at the two locations at the top and bottom of the valley. Overall a strong agreement ($R^2 >= 0.8$) was observed between the two products as shown in Figure 5. Only in some cases in the lower part of the Orco river basin (Rivarolo Canavese downstream) the ADO indices underestimate the drought situation. The good agreement between the ADO and NWIOI SPI index can be seen at all accumulation periods.

Furthermore, the 3(6)-months SPI and SPEI contingency tables have been evaluated for two locations, the top and bottom of the Rivarolo Valley on a monthly basis. We considered the monthly values of the index over the Orco River basin during a timespan from 1979 to 2021 (475 months).Table 3 shows exemplary for SPI3 how the evaluation has been carried out. The number of events where SPI3 is smaller -1 (SPI3 < -1) have been counted in the NWIOI based SPI3 and the ADO SPI3 and compared in a contingency table. The disagreement between the two datasets is expressed in percent. This procedure has been performed for SPI3 and SPI6 at the top and bottom of the Rivarolo Valley. It can be seen that the disagreement between the ADO and NWIOI datasets is at maximum 13.89 % (SPEI3 at the bottom location). On average the disagreement is 11.75 % (Table 4).

4.2.2. Value of the ADO platform in a climatological perspective

The ADO datasets span 40 years starting in 1980 and are thus useful to evaluate the severity of a drought over a long period. This has been tested in the province of Biella, neighbouring the Orco catchment. The ADO platform shows how the 2022 drought was the most extreme since 1980 according to the SPI12 reaching a peak of SPI12 as low as -4, which is an extreme value for SPI (Figure 6).

5. Discussion and Conclusion

5.1. Infrastructure

A cross border drought observatory like the ADO, relying on contributions of many international partners, requires a well-architected design as well as a system that enables collaboration and automation of the processing chains that provide drought information. As typical of most environmental monitoring systems, these steps involve downloading data, pre-processing and processing, validating outputs, and hosting and visualizing results. In an operational setting, these components are chained together in an automated way to minimize maintenance and repeated manual interaction. This way, the results are immediately accessible for deriving higher-level products and information.

In the ADO project, we used a combination of a container orchestration system and a CI tool to manage multiple data processing chains, as well as to integrate the FAIR principles into the data management strategy. The architecture involves: (i) a Kubernetes on-premises container orchestration equally serving as a queue manager, (ii) a GitLab CI framework for automating the respective data pipelines, (iii) a database holding aggregated drought indices to enhance the visualization and sharing of datasets, and (iv) two entry

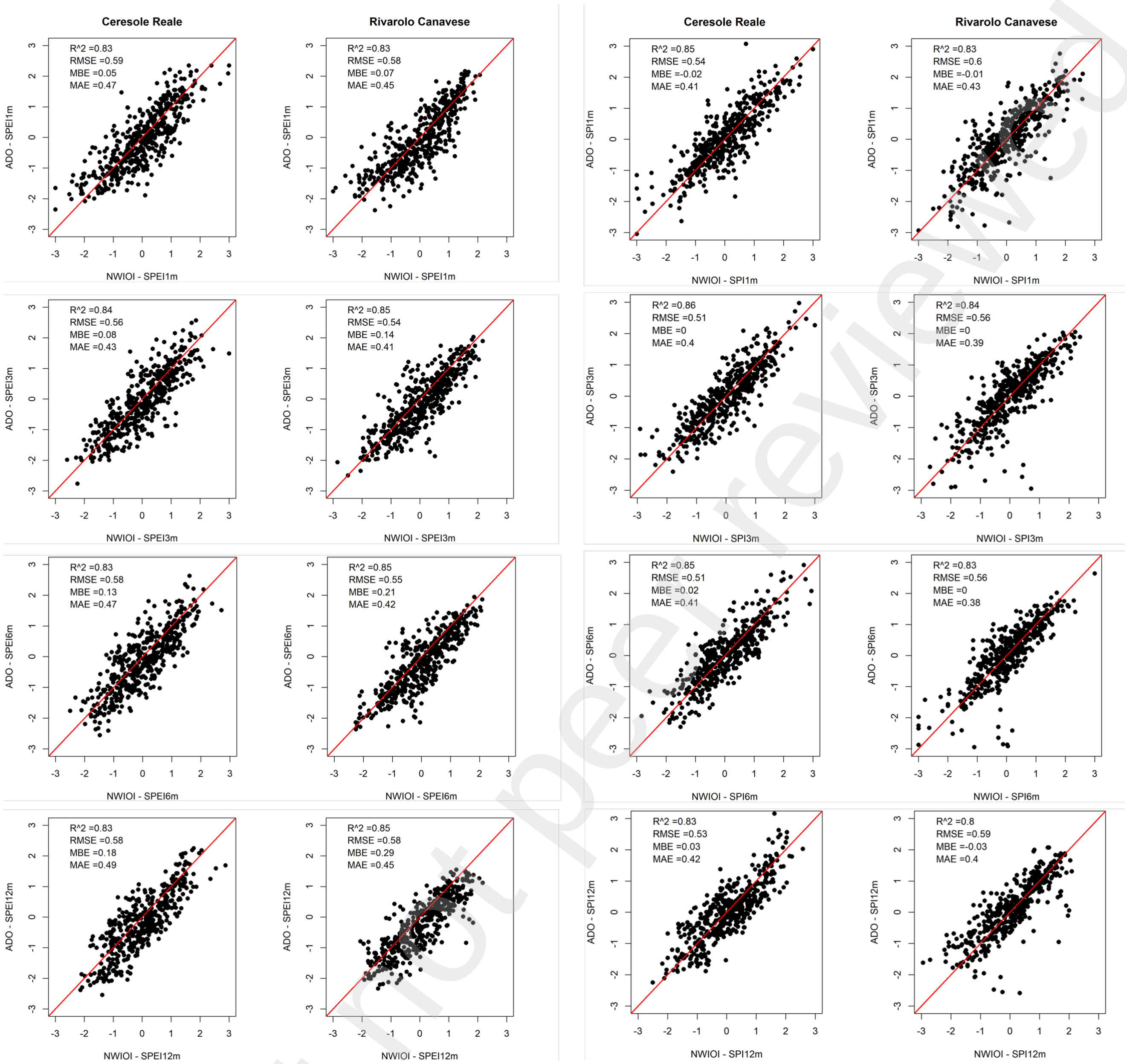


Figure 5: Scatter plots between the 1, 3, 6 and 12 month SPEI (left) and SPI (right) calculated via rainfall data from the Piedmont telemetry network (NWIOI) and ADO data for the locations Ceresole Reale in the upper and Rivarolo Canavese in the lower part of the catchment. The added accuracy metrics are pearson correlation coefficient (R^2), root mean squared error (RMSE), mean bias error (MBA) and mean absolute error (MAE).

points for users (Web Platform and the EDP) for accessing the datasets.

These components form the ADO platform, which serves drought indices on a daily basis with a ten-day time lag from the current day for monitoring drought conditions in the Alps. The ADO platform also hosts semi-automatically updated hydrological indicators, drought vulnerability factors and a drought impact database [107] to further complete drought analysis and management.

With the ADO platform we provide a blueprint for the development of a drought observatory containing a reproducible template for data and process management, information visualization, and automation of computation. Importantly, it offers a framework for the development of other regional observatories with an open-source repository and open-access to all the datasets under the Creative Commons Attribution (CC-BY 4.0) license. This provides a seamless way of integrating multi-repository projects and working with international teams with different tech stacks to achieve a common goal. Nevertheless, we do not rely on Continuous Deployment (CD). The number of contributors is too high to guarantee the functioning of an highly interdependent system after changes have been made. We recommend to only introduce changes into an operational system after thorough

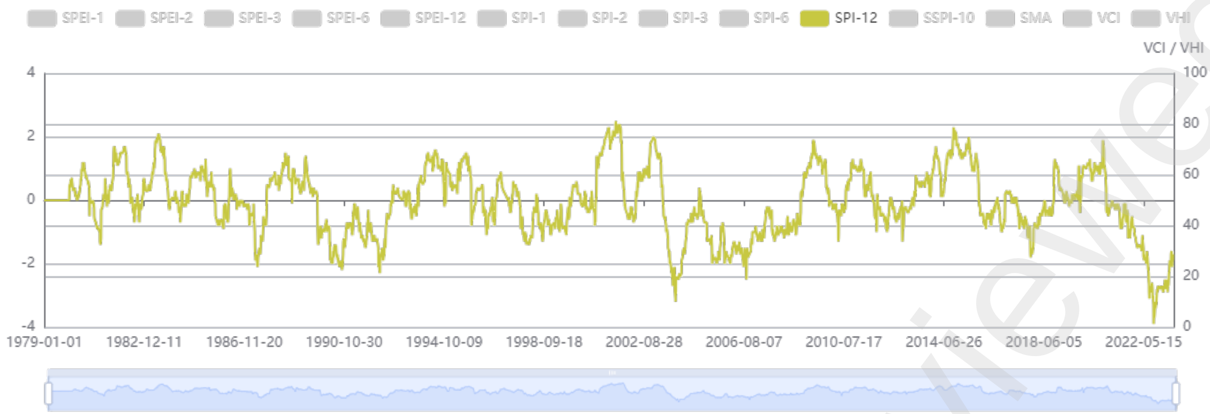


Figure 6: The SPI12 time series in the province of Biella in the interactive time series view on the ADO web platform. The x axis on the left shows the standard deviations for all indices besides the VCI and VHI, which have a secondary x axis ranging from 0 to 100. The blue time selection bar on the bottom allows to select the time range from 1979 up to the most recent date. The lowest value since 1979 has been reached on 06.10.2022.

quality assessment. Overall, this work is in agreement with the proposition of Santoro, Mazzetti, and Nativi for the development of a "geoscience digital ecosystem" leveraging modern cloud technologies. Although the ADO architecture was fully implemented on-premise, the components allow to be easily migrated to cloud resources in an hybrid approach. Hence, this architecture can be adapted for different computational resource types including (i) cloud, (ii) on-premise, (iii) hybrid, and (iv) multi-cloud with only little modification. Central to the implementation of the data strategy is following the FAIR principles including rich metadata (STAC [65] and Geo-Network [66]), data discovery and access points, the use of an open data license (CC-BY 4.0), and registration of DOIs for all datasets.

5.2. Datasets

The ADO datasets have been chosen to capture the variety of droughts (meteorology, soil, vegetation, hydrology). These indicators have proven successful in drought monitoring [39] and their input data is operationally retrievable so that a stable monitoring system can be built. The products are updated on a daily basis, this increases the impact significantly and can be retrieved either at raw raster resolution or in an aggregated form for quick visualization and easy interpretation on the ADO web viewer. The products are freely available and openly accessible for anyone (FAIR) and licensed under CC-BY-4.0 license. A DOI is assigned to them. The SSPI uses snow variables that are produced by the proprietary SNOWGRID model [53], thus the intermediate products like snow depth are not openly available. The vegetation indicators VHI and VCI have higher spatial resolution (231 m) but their temporal resolution is lower (8 days). Their calculation is based on satellite imagery from the MODIS satellite, which is already over its estimated lifetime forcing the developers to search for alternative data sources. The data collection for the hydrological database has manual steps involved. The effort to automize the whole process (i.e. write a web crawler for every Hydrological Office in the Alps) is unfeasible. Unfortunately, there is no standard in data delivery and data description across the different sources. To overcome the different data structures homogenization routines have been established. Finally, work should be invested into the definition and implementation of standards for hydrological dataset descriptions and dissemination.

5.3. ADO compared to other drought monitoring platforms

Drought monitoring tools have diverse requirements and best practices. They fall into two seemingly conflicting categories: user-friendliness with clear information and rich information content. An ideal platform should merge these by providing both ease of use for non-professionals and comprehensive information for all users interested in drought-related data. This section will discuss ADO in comparison to other existing drought observatories.

- **United States Drought Monitor (USDM)**: USDM, operational for over 20 years, stands as a benchmark for drought monitoring tools. It was among the earliest web-based systems designed for decision makers and the public. Falling into the user-friendly category, USDM employs its own drought severity scale. The U.S. Drought Monitor is a weekly assessment of the extent and severity of drought in the United States. It contains a map released every Thursday, showing parts of the U.S. that are in drought, based on various sources of data collected through the previous week. The processing is automated, deriving drought categories objectively from a mix of indicators like PDSI, modeled soil moisture percentiles, SPI, and streamflow percentiles. Despite this, the final map undergoes manual refinement and author signature [108]. The resolution of the ten available data sets in the web viewer varies across regions (approximately NUTS3) in the US and is updated on a weekly basis (table 5). The data is presented in a web GIS which allows to create custom maps. Time series views are available on the homepage. The data is open data. A written drought summary and outlooks are provided. The data can be downloaded from a central repository and via API (table 6).

- **European Drought Observatory (EDO)**: EDO, maintained by the EC's Joint Research Center, focuses on the Combined Drought Indicator (CDI). While the CDI map is initially a static image on the EDO homepage, users can also access an interactive web GIS. Like the USDM, the EDO CDI blends various drought indicators into the categories watch, warning, alert, partial recovery and full recovery [109]. Users can also explore the underlying drought indices, create custom indicators and add additional maps from external servers. The spatial resolution of the ten data sets in the web GIS is 5 km and the temporal resolution is ten daily to monthly (table 5). The web GIS allows for time series views. The data is open data. A written drought summary is provided. The data can be downloaded from a central repository, but there is no API (table 6).

- **drought.ch**: The platform www.drought.ch exemplifies an integrated customer-focused product developed over four years through a participative, science-driven process. The platform is operational since 2014. It showcases successful value addition by integrating and customizing hydro-meteorological data for specific purposes like drought management. Manual refinement and adaptation of the platform's information to user expectations and needs are carried out [110, 111]. Eight indicators are provided on the level of NUTS3 regions. There are more indicators available that do not follow the generally layout or are linked datasets (table 5). The web viewer is mostly static. There is a written summary and outlooks. The data is not available via centralized download and there is no API (table 6).

- **Drought Central - Osservatorio Siccità**: The Institute of BioEconomy of the National Research Council (IBE-CNR) devised a system to deliver a semi-automated, thorough and timely operational service. Initially tailored for the Tuscany Region, this service aids decision-makers, water authorities, researchers, and stakeholders all over Italy [112]. The web viewer contains four indicators at spatial resolutions ranging from 0.1°, 5 km, 1 km to 250 m. The temporal resolution varies between weekly, 16-daily and monthly table 5). The web viewer allows to view the data and retrieve time series upon click. Written drought bulletins and outlooks are available. The infrastructure is well described and based upon open source tools, however there is no link to the source code available. The data can be downloaded from a dedicated catalogue and via API (table 6).

The tables 5 and 6 compare a selection of existing drought observatories. Naturally they aim at different audiences and cover different spatial extents, which may explain many of the design choices of the different observatories. In comparison to the other observatories ADO has no written drought description based on expert knowledge and no outlook into the future. ADO stands out as it is (i) a cross-border platform operating across different countries taking into account a natural region, the Alps, (ii) has a high spatial and temporal resolution and is updated on a daily basis and (iii) relies on a very modern, modular and completely open architecture aimed at users needs (division of web viewer for ease of use and reactivity and a cloud platform for fully configurable expert analysis).

5.4. Showcase

The comparison of ADO products with the current state of the art data set (NWIOI) used by the Hydrological Office of Regione Piemonte is encouraging the use of ADO products and demonstrates that the ADO products tested in this use case, SPI and SPEI, can well represent and monitor the meteorological drought even at a local scale ($R^2 >= 0.8$). Although sometimes the accuracy of the specific local datasets has to be preferred in order to correctly capture the current observed situation. For example in the lower part of the Orco river basin (Rivarolo Canavese downstream) the ADO indices underestimate the drought situation. This might be due to the underestimation of precipitation of the ERA5 input data in this region and is still being investigated. The next steps for integrating ADO products in the hydrological management of the Regione Piemonte will be to replicate the Blended Drought Index which is published in the hydrological bulletin [113] using ADO data. Also, first attempts are being undertaken to relate the interventions of drinking water supply with ADO drought index time series to extract a pattern that allows to identify the onset of a possible intervention following a two step procedure: (i) identifying events that required management measures, such as the intervention of SMAT's Water Emergency Service related to drought phenomena (i.e. liters of water supplied by tanker trucks in a given municipality); (ii) analyzing the meteo-climatic variables and single indices and testing them in relation to the identified events.

5.5. Impact

The operational production and free and open dissemination of the ADO products has led to high impact and uptake of the datasets. The data have been used in articles of major newspapers to illustrate the drought situation for a broad public and underline their statements with data [114, 115]. The ADO SSPI has been used in a study to describe the development of the snow line altitude since 1985 [14]. Stephan et al. have used the indices and related them to the ADO drought impact database in order to describe agriculturally vulnerable regions [107, 116]. Pogačar et al. have analysed grass growth in relation to ADO drought indices [83]. Furthermore, other environmental monitoring platforms are integrating ADO data into their portfolio, for example ESAs

Table 5
Comparison of drought observatories and data sources. N. Indicators stands for the number of operational indices in the web viewer, not counting the aggregation periods. *In Web GIS, more in bulletins. **Prepared for NUTS regions, more information in other representations.

Observatory	Geogr. focus	Geogr. scope	Spat. resolution	Temp. resolution	Earliest data	Type of indicators	Indicators	N. indicators	Comb. drought indicator
ADO	Alps	Region	1km, 250m, NUTS, Hydro. Basins	Daily, weekly	1979	Met, Agr, Hyd	SPEI (1, 3, 6, 12), SPI (1, 3, 6, 12), SSPI-10, SMA, VCI, VHI, (Impacts, Vulnerabilities, Hydro. Stations)	6	no
USDM	USA	Continent	Vector, varies across regions	Weekly	1999	Met, Agr, Hyd	USDM Index, Drought Outlook, Precipitation Outlook, Temperature Outlook, AHPS Precipiation, USGS Streamflow, CoCoRaHS condition monitoring reports, Condition Monitoring Observer, VegDRI, QuickDRI	10*	yes
EDO	Europe	Continent	5km	10-daily, monthly	1979	Met, Agr, Hyd	CDI, SPI, SMA, fAPAR, Low-Flow Index, Heat and Cold Wave Index, Indicator for Forecasting Unusually Wet and Dry Conditions, GRACE Total Water Storage Anomaly, Phenology Masks, Meteorological Drought Tracking	10*	yes
drought.ch	Switzerland	Country	NUTS3	Daily	NA	Met, Agr, Hyd	Runoff, Precipitation, Evaporation, Soil Moisture, Snow Water Equivalent, Litter Moisture, Water Level Surface Water, Water Temperature	8**	yes
Drought Central	Italy	Country	0.1°, 5km, 1km, 250m	16-daily, weekly, monthly	1979	Met, Agr	SPI (1, 3, 6, 24), VHI, TCI, VCI, (E-VCI, E-VHI, ESI)	4*	yes

Table 6
Comparison of data access mechanisms on different drought observatories. Data access mechanism is classified as web GIS in contrast to web viewer if it supports more features than viewing spatial data and time series.

Observatory	Data access mechanism	FAIR data	Open source	Written summary	Time series	Outlook	API	Central download
ADO	Web Viewer, Cloud Platform	yes	yes	no	yes	no	yes	yes
USDM	Web GIS	yes	no	yes	yes	yes	yes	yes
EDO	Web GIS	yes	no	yes	yes	no	no	yes
drought.ch	Web Viewer	-	no	yes	no	yes	no	no
Drought Central	Web Viewer, Data Catalogue	yes	no	yes	yes	yes	yes	yes

Green Transition Information Factory [117] and the United Nations space4water portal [118]. In future projects it is planned to build on top of the existing infrastructure to offer data sets with higher spatial resolution and to explore forecasting methods. The importance of providing data on a regular basis, adhering to community standards and open science practices and disseminating the results freely cannot be overestimated. The ADO portal gives a blueprint of how modern earth system science platforms can be set-up to increase their impact.

Data and Software availability

Datasets

The datasets produced in the ADO project include:

a) Slovenian Environment Agency, & Central Institution for Meteorology and Geodynamics. (2022). Standardised Precipitation Index - ERA5_QM SPI-1 (Version 1.0) [Data set]. Eurac Research. https://doi.org/10.48784/15abe686-534a-11ec-b9ef-02000a08f41d

b) Slovenian Environment Agency, & Central Institution for Meteorology and Geodynamics. (2022). Standardised Precipitation-Evapotranspiration Index - ERA5_QM SPEI-1 (Version 1.0) [Data set]. Eurac Research. https://doi.org/10.48784/166e51ee-534a-11ec-9143-02000a08f41d

c) Slovenian Environment Agency, & Central Institution for Meteorology and Geodynamics. (2022). Standardised Snow Pack Index - ERA5_QM SSPI-10 (Version 1.0) [Data set]. Eurac Research. https://doi.org/10.48784/0ca021a6-7942-11ec-a314-02000a08f41d

d) Greifeneder, F. (2022). Soil Moisture Anomalies - ERA5 _QM (Version v1) [Data set]. Eurac Research. https://doi.org/10.48784/ea665ca2-0ceb-11ed-86c5-02000a08f4e5

e) Zellner, P., Castelli, M. (2022). Vegetation Health Index - 231 m 8 days (Version 1.0) [Data set]. Eurac Research. https://doi.org/10.48784/161b3496-534a-11ec-b78a-02000a08f41d

ADO entry points

ADO datasets are openly available via the

a) ADO Webviewer: https://ado.eurac.edu/
b) Environmental Data Platform: https://edp-portal.eurac.edu/

Code repositories

The code that is used for creating the ado data and setting up the ADO production pipelines is maintained here

a) Overview of data pipelines: https://gitlab.inf.unibz.it/ado/operational_pipelines
b) ADO Data repository: https://github.com/Eurac-Research/ado-data
c) ADO Webviewer deployment: https://github.com/Eurac-Research/ADO

Acknowledgements

This work was funded by the Interreg Alpine Space Programme within the project ADO [grant number ASP940] and the RETURN Extended Partnership from the European Union Next-Generation EU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005). The authors wish to acknowledge support from partners within the ADO project, whose contribution led to the successful implementation of the platform. We also wish to acknowledge the staff and researchers at the European Research Academy, Bozen/Bolzano from the Institute for Earth Observation, Institute for Alpine Environment, Center for Sensing Solutions, Communications and ICT.

Credit authorship contribution statement

Peter J. Zellner: Conceptualization, Supervision, Software, Data Curation, Writing - Original Draft, Writing - Review & Editing, Project administration. **Rufai O. Balogun:** Writing - Original Draft, Investigation, Software, Data Curation, Visualization. **Konrad Mayer:** Software, Writing - Original Draft. **Thomas Iacopino:** Conceptualization, Software, Writing - Original Draft. **Luca Cattani:** Conceptualization, Software, Writing - Original Draft. **Mohammad H. Alasawedah:** Software, Data Curation, Writing - Original Draft. **Daniela Quintero:** Software. **Michele Claus:** Software, Writing - Original Draft. **Bartolomeo Ventura:** Data Curation, Writing - Original Draft. **Andrea Vianello:** Software. **Alessio Salandin:** Validation, Writing - Original Draft. **Elisa Brussolo:** Validation, Writing - Review & Editing. **Ziva Vlahovic:** Software. **Christian Ronchi:** Supervision, Validation, Writing - Review & Editing. **Bertoldi Giacomo:** Supervision, Data Curation, Writing - Original Draft, Writing - Review & Editing. **Mariapina Castelli:** Writing - Review & Editing. **Felix Greifeneder:** Conceptualization, Project administration, Funding acquisition. **Alexander Jacob:** Conceptualization, Project administration, Funding acquisition, Writing - Review & Editing.

References

[1] W. W. Immerzeel et al. "Importance and vulnerability of the world's water towers". In: *Nature* 577.7790 (Jan. 2020), pp. 364–369. ISSN: 0028-0836. DOI: 10.1038/s41586-019-1822-y.

[2] Andrea Toreti. "Drought in Europe July 2022". In: *Publications Office of the European Union* (2022). DOI: 10.2760/014884. URL: doi:10.2760/014884.

[3] C. Cammalleri, P. Barbosa, and J. V. Vogt. "Testing remote sensing estimates of snow water equivalent in the framework of the European Drought Observatory". In: *Journal of Applied Remote Sensing* 16(1) (2022), pp. 014509–13. DOI: https://doi.org/10.1117/1.JRS.16.014509.

[4] Elisa Brussolo et al. "Aquifer recharge in the Piedmont Alpine zone: historical trends and future scenarios". In: *Hydrology and Earth System Sciences* 26.2 (2021), pp. 407–427. DOI: 10.5194/hess-26-407-2022.

[5] S. Terzi et al. "Alpine drought impact chains for sector-based climate-risk assessments". In: European Geosciences Union. 2020. DOI: https://doi.org/10.5194/egusphere-egu21-205.

[6] A. J. Teuling. "A hot future for European droughts". In: *Nature Climate Change* 8 (2018), pp. 364–365. DOI: https://doi.org/10.1038/s41558-018-0154-5.

[7] R. Weingartner, D. Viviroli, and B. Schadler. "Water resources in mountain regions: a methodological approach to assess the water balance in a highland-lowland system". In: *Hydrological Processes* 21 (2007), pp. 578–585. DOI: https://doi.org/10.1002/hyp.6268.

[8] Y. Tramblay et al. "Challenges for drought assessment in the Mediterranean region under future climate scenarios". In: *Earth-Science Reviews* 210 (2020). DOI: https://doi.org/10.1016/j.earscirev.2020.103348.

[9] Francesco a. Isotta et al. "The climate of daily precipitation in the Alps: development and analysis of a high-resolution grid dataset from pan-Alpine rain-gauge data". In: *International Journal of Climatology* 34.5 (2013). ISSN: 08998418. DOI: 10.1002/joc.3794. URL: http://doi.wiley.com/10.1002/joc.3794.

[10] A. Baronetti et al. "Future Droughts in Northern Italy: High-resolution projections using EURO-CORDEX and MED-CORDEX Ensembles". In: *Climatic Change* 172 (2022). DOI: https://doi.org/10.1007/s10584-022-03370-7.

[11] A. Böhnisch et al. "Hot Spots and Climate Trends of Meteorological Droughts in Europe–Assessing the Percent of Normal Index in a Single-Model Initial-Condition Large Ensemble". In: *Frontiers in Water* 3 (2021). DOI: https://doi.org/10.3389/frwa.2021.716621.

[12] J. Spinoni et al. "Will drought events become more frequent and severe in Europe?" In: *International Journal of Climatology* 38 (2017), pp. 1718–1736. DOI: https://doi.org/10.1002/joc.5291.

[13] The Alpine Convention. *Facing droughts in the Alpine region - experiences, approaches and common challenges*. Alpine Convention 2018. Online, Accessed on March 27, 2023. 2018. URL: https://www.alpconv.org/fileadmin/user_upload/Organisation/TWB/Water/Facing_droughts_in_the_Alpine_region.pdf.

[14] Jonas Koehler et al. "Drought in Northern Italy: Long Earth Observation Time Series Reveal Snow Line Elevation to Be Several Hundred Meters Above Long-Term Average in 2022". In: *Remote Sensing* 14.23 (2022), p. 6091. DOI: https://doi.org/10.3390/rs14236091.

[15] Michael Matiu et al. "Observed snow depth trends in the European Alps: 1971 to 2019". In: *The Cryosphere* 15.3 (2021), pp. 1343–1382. DOI: 10.5194/tc-15-1343-2021.

[16] Andrea Blahušiaková et al. "Snow and climate trends and their impact on seasonal runoff and hydrological drought types in selected mountain catchments in Central Europe". In: *Hydrological Sciences Journal* 65.12 (Sept. 2020), pp. 2083–2096. ISSN: 0262-6667. DOI: 10.1080/02626667.2020.1784900.

[17] Klaus Haslinger et al. "Changing summer precipitation variability in the Alpine region: on the role of scale dependent atmospheric drivers". In: *Climate Dynamics* 57.3-4 (2021), pp. 1009–1021. ISSN: 0930-7575. DOI: 10.1007/s00382-021-05753-5.

[18] Julian Xanke and Tanja Liesch. "Quantification and possible causes of declining groundwater resources in the Euro-Mediterranean region from 2003 to 2020". In: *Hydrogeology Journal* 30.2 (2022), pp. 379–400. ISSN: 1431-2174. DOI: 10.1007/s10040-021-02448-3.

[19] M. Castelli. "Evapotranspiration Changes over the European Alps: Consistency of Trends and Their Drivers between the MOD16 and SSEBop Algorithms". In: *Remote Sensing* 13 (2021). DOI: https://doi.org/10.3390/rs13214316.

[20] T. Mastrotheodoros et al. "More green and less blue water in the Alps during warmer summers". In: *Nature Climate Change* 10 (2020), pp. 155–161. DOI: https://doi.org/10.1038/s41558-019-0676-52020.

[21] Christian Massari et al. "Evaporation enhancement drives the European water-budget deficit during multi-year droughts". In: *Hydrology and Earth System Sciences* 26.6 (2022), pp. 1527–1543. DOI: 10.5194/hess-26-1527-2022.

[22] Klaus Haslinger et al. "Exploring the link between meteorological drought and streamflow: Effects of climate-catchment interaction". In: *Water Resources Research* 50.3 (2014), pp. 2468–2487. ISSN: 1944-7973. DOI: 10.1002/2013wr015051.

[23] Ben Livneh and Andrew M. Badger. "Drought less predictable under declining future snowpack". In: *Nature Climate Change* 10.5 (2020), pp. 452–458. ISSN: 1758-678X. DOI: 10.1038/s41558-020-0754-8.

[24] Klaus Haslinger et al. "Contradictory signal in future surface water availability in Austria: increase on average vs. higher probability of droughts". In: *EGUsphere* 2022 (2022), pp. 1–28. DOI: 10.5194/egusphere-2022-191.

[25] Oldrich Rakovec et al. "The 2018–2020 Multi-Year Drought Sets a New Benchmark in Europe". In: *Earth's Future* 10.3 (2022). ISSN: 2328-4277. DOI: 10.1029/2021ef002394.

[26] R. Kiese et al. "The TERENO Pre-Alpine Observatory: Integrating Meteorological, Hydrological, and Biogeochemical Measurements and Modeling". In: *Vadose Zone Journal* 1 (2018), p. 15391663. DOI: https://doi.org/10.2136/vzj2018.03.0060.

[27] R. Magno et al. "Semi-Automatic operational service for Drought Monitoring and Forecasting in the Tuscany Region". In: *Geosciences* 8 (2018), p. 49. DOI: https://doi.org/10.3390/geosciences8020049.

[28] S. Drost et al. "WaCoDis: Automated Earth Observation data processing within an event-driven architecture for water monitoring". In: *Computers and Geosciences* 159 (2022), p. 105003. DOI: https://doi.org/10.1016/j.cageo.2021.105003.

[29] M. Santoro, P. Mazzetti, and S. Nativi. "Virtual earth cloud: a multi-cloud framework for enabling geosciences digital ecosystems". In: *International Journal of Digital Earth* 16 (2023), pp. 43–65. DOI: https://doi.org/10.1080/17538947.2022.2162986.

[30] C. Cammalleri, P. Barbosa, and J. V. Vogt. "Evaluating simulated daily discharge for operational hydrological drought monitoring in the Global Drought Observatory". In: *Hydrological Sciences Journal* 65 (2020), pp. 1316–1325. DOI: https://doi.org/10.1080/02626667.2020.1747623.

[31] C. Cammalleri, J. V. Vogt, and P. Salamon. "Development of an operational low-flow index for hydrological drought monitoring over Europe". In: *Hydrological Sciences Journal* 62 (2017), pp. 346–358. DOI: https://doi.org/10.1080/02626667.2016.1240869.

[32] R. R. Heim and M. J. Brewer. "The Global Drought Monitor Portal: The Foundation for a Global Drought Information System". In: *Earth Interactions* 16 (2012), p. 15. DOI: https://doi.org/10.1175/2012EI000446.1.

[33] C. Cammalleri et al. "The effects of non-stationarity on SPI for operational drought monitoring in Europe". In: *International Journal of Climatology* 42 (2022), pp. 3418–3430. DOI: https://doi.org/10.1002/joc.7424.

[34] M. J. Hayes et al. "Drought Monitoring: Historical and Current Perspectives". In: *Drought Mitigation Center Faculty Publications* 94 (2012). URL: https://core.ac.uk/download/pdf/188138949.pdf.

[35] T. B. McKee, N. J. Doesken, and J. Kleist. *The relationship of drought frequency and duration to time scales*. Eighth Conference on Applied Climatology. 1993. URL: https://www.droughtmanagement.info/literature/AMS_Relationship_Drought_Frequency_Duration_Time_Scales_1993.pdf.

[36] S.M. Vincente-Serano, S. Begueria, and J. I. Lopez-Moreno. "A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index". In: *Journal of Climate* 23 (2010). DOI: https://doi.org/10.1175/2009JCLI2909.1.

[37] Andrea Toreti. *Standardized precipitation index (SPI) - factsheet*. 2020. URL: https://edo.jrc.ec.europa.eu/documents/factsheets/factsheet_spi.pdf.

[38] NOAA. *What is Drought: Drought basics*. Online, Accessed on April 17, 2023. 2023. URL: https://www.drought.gov/what-is-drought/drought-basics.

[39] Copernius Emergency Management Service. *Drought Indicators*. Online; Accessed on June 26, 2023. URL: https://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1010.

[40] S. Kloos et al. "Agricultural Drought Detection with MODIS Based Vegetation Health Indices in Southeast Germany". In: *Remote Sensing* 13 (2021). DOI: https://doi.org/10.3390/rs13193907.

[41] I. Nalbantis and G. Tsakiris. "Assessment of Hydrological Drought Revisited". In: *Water Resources Management* 23.5 (July 2008), pp. 881–897. DOI: 10.1007/s11269-008-9305-1. URL: https://doi.org/10.1007/s11269-008-9305-1.

[42] Luciano Telesca et al. "Investigation of scaling properties in monthly streamflow and Standardized Streamflow Index (SSI) time series in the Ebro basin (Spain)". In: *Physica A: Statistical Mechanics and its Applications* 391.4 (Feb. 2012), pp. 1662–1678. DOI: 10.1016/j.physa.2011.10.023.

[43] R.S. Pyrce. *Hydrological Low Flow Indices and their Uses*. Tech. rep. WSC Report No.04-2004. Watershed Science Centre, Peterborough, Ontario, 2004, p. 33. URL: https://1916f56da6.clvaw-cdnwnd.com/2b98f99fedb4f35c0fc97694c27253ba/200004594-b3995b5902/LowFlowOntRpt2004.pdf.

[44] C. Cammalleri et al. "A revision of the Combined Drought Indicator (CDI) as part of the European Drought Observatory". Natural Hazards and Earth System Sciences. 2020. DOI: https://doi.org/10.5194/nhess-21-481-2021.

[45] JRC. *Global Drought Observatory*. Online, Accessed on April 21, 2023. 2021. URL: https://edo.jrc.ec.europa.eu/gdo/php/index.php?id=2000.

[46] *What is DevOps?* Online; Accessed on July 26, 2023. URL: https://about.gitlab.com/topics/devops/#how-is-dev-ops-and-ci-cd-related.

[47] Red Hat. *What is CI/CD?* https://www.redhat.com/en/topics/devops/what-is-ci-cd. Accessed 2023-06-13. 2022.

[48] Docker. *Docker overview*. https://docs.docker.com/get-started/overview/. Online, Accessed on June 13, 2023. 2023.

[49] Kubernetes. *Overview*. https://kubernetes.io/docs/concepts/overview/. Online, Accessed on June 12, 2023. 2023.

[50] A. Y. Kim et al. "Implementing GitHub Actions continuous integration to reduce error rates in ecological data collection". In: *Methods in Ecology and Evolution* 13 (2022), pp. 2572–2585. DOI: https://doi.org/10.1111/2041-210X.13982.

[51] Riccardo Rigon et al. "HESS Opinions: Participatory Digital eARth Twin Hydrology systems (DARTHs) for everyone – a blueprint for hydrologists". In: *Hydrology and Earth System Sciences* 26.18 (2022), pp. 4773–4800. DOI: 10.5194/hess-26-4773-2022.

[52] Hans Hersbach et al. "The ERA5 global reanalysis". In: *Quarterly Journal of the Royal Meteorological Society* 146.730 (2020), pp. 1999–2049. ISSN: 1477-870X. DOI: 10.1002/qj.3803. (Visited on 06/09/2021).

[53] Marc Olefs et al. "Changes in Snow Depth, Snow Cover Duration, and Potential Snowmaking Conditions in Austria, 1961–2020—A Model Based Approach". In: *Atmosphere* 11.12 (Dec. 2020), p. 1330. DOI: 10.3390/atmos11121330.

[54] CEPH. *Intro to CEPH*. Online, Accessed on June 12, 2023. 2023. URL: https://docs.ceph.com/en/latest/start/intro/.

[55] M. Claus and A. Vianello. *Eurac Research - OpenEO Backend*. 2023. DOI: https://doi.org/10.25504/FAIRsharing.f9de28. (Visited on 06/10/2023).

[56] Matthias Schramm et al. "The openeo api–harmonising the use of earth observation cloud services using virtual data cube functionalities". In: *Remote Sensing* 13.6 (2021), p. 1125. DOI: https://doi.org/10.3390/rs13061125.

[57] Brian Killough. "Overview of the Open Data Cube Initiative". In: IGARSS 2018 - 2018 IEEE International Geoscience and Remote Sensing Symposium. 2018, pp. 8629–8632. DOI: 10.1109/IGARSS.2018.8517694.

[58] S. Hoyer and J. Hamman. "xarray: N-D labeled arrays and datasets in Python". In: *Journal of Open Research Software* 5.1 (2017). DOI: 10.5334/jors.148. URL: https://doi.org/10.5334/jors.148.

[59] Matthew Rocklin. "Dask: Parallel computation with blocked algorithms and task scheduling". In: *Proceedings of the 14th python in science conference*. 130-136. Citeseer. 2015. DOI: http://dx.doi.org/10.25080/Majora-7b98e3ed-013.

[60] P. Baumann et al. "The Multidimensional Database System RasDaMan". In: *SIGMOD Rec.* 27.2 (June 1998), pp. 575–577. ISSN: 0163-5808. DOI: 10.1145/276305.276386. URL: https://doi.org/10.1145/276305.276386.

[61] PostGIS Project Steering Committee et al. *PostGIS, spatial and geographic objects for postgreSQL*. Online; Accessed on July 26, 2023. 2018. URL: https://postgis.net.

[62] M.R. Stonebraker and L.A. Rowe. "The design of POSTGRES". In: *Association for Computing Machinery* 15 (2 1986), pp. 340–355. DOI: https://doi.org/10.1145/16856.16888.

[63] Grafana Labs. *Grafana Documentation*. 2018. URL: https://grafana.com/docs/ (visited on 07/25/2019).

[64] A. Vianello. *Maps - Environmental Data Platform*. 2021. DOI: https://doi.org/10.25504/FAIRsharing.8ee7f1.

[65] *STAC: SpatioTemporal Asset Catalogs*. Online, Accessed on June 14, 2023. 2023. URL: https://stacspec.org/en.

[66] OSGeo. *GeoNetwork:Open Source*. Accessed on June 15, 2023. 2023. URL: https://geonetwork-opensource.org/.

[67] Platform9. *Kubernetes on-premises: why and how*. Online, Accessed on June 09, 2023. 2023. URL: https://platform9.com/blog/kubernetes-on-premises-why-and-how/ (visited on 06/09/2023).

[68] Rancher. *Why Rancher?* Online, Accessed on June 09, 2023. 2023. URL: https://www.rancher.com/why-rancher (visited on 06/09/2023).

[69] Patrick Alexander. *What Data Pipeline Architecture should I use?* Online, Accessed on June 09, 2023. 2023. URL: https://cloud.google.com/blog/topics/developers-practitioners/what-data-pipeline-architecture-should-i-use (visited on 06/09/2023).

[70] M. M. Billah et al. "Using a data grid to automate data preparation pipelines required for regional-scale hydrologic modeling". In: *Environmental Modelling and Software* 78 (2016), pp. 31–39. DOI: http://dx.doi.org/10.1016/j.envsoft.2015.12.010.

[71] Mark D. Wilkinson et al. "The FAIR Guiding Principles for scientific data management and stewardship". In: *Scientific Data* 3 (2016). DOI: 10.1038/sdata.2016.18. URL: https://www.nature.com/articles/sdata201618.

[72] European Space Agency. *Green Transformation Information Factory*. Online, Accessed on June 23, 2023. 2023. URL: https://gtif.esa.int/.

[73] Roberto Roncella et al. "Publishing Eurac Research data on the GEOSS Platform". In: *Big Earth Data* 0.0 (2023), pp. 1–23. DOI: 10.1080/20964471.2023.2187659.

[74] DataCite. *DataCite Members*. Online, Accessed on May 23, 2023. 2023. URL: https://datacite.org/members.html.

[75] Creative Commons. *Attribution 4.0 International (CC BY 4.0)*. Online, Accessed on June 23, 2023. 2023. URL: https://creativecommons.org/licenses/by/4.0/.

[76] Central Institution for Meteorology Slovenian Environment Agency and Geodynamics. *Standardized Precipitation Index - ERA5*$_Q MSPI-1(Version1.0)[Dataset]$. Type: [Dataset. 2022. DOI: https://doi.org/10.48784/15abe686-534a-11ec-b9ef-02000a08f41d.

[77] Central Institution for Meteorology Slovenian Environment Agency and Geodynamics. *Standardized Precipitation Evapotranspiration Index - ERA5*$_Q MSPEI-1(Version1.0)[Dataset]$. Type: [Dataset]. 2022. DOI: https://doi.org/10.48784/166e51ee-534a-11ec-9143-02000a08f41d.

[78] Central Institution for Meteorology Slovenian Environment Agency and Geodynamics. *Standardized Snow Pack Index - ERA5*$_Q MSSPI-10(Version1.0)[Dataset]$. Type: [Dataset]. 2022. DOI: https://doi.org/10.48784/0ca021a6-7942-11ec-a314-02000a08f41d.

[79] Angel Lopez. *Complete UERRA regional reanalysis for Europe from 1961 to 2019*. Type: [Dataset]. 2019. DOI: 10.24381/CDS.DD7C6D66.

[80] Matthias Jakob Themeßl, Andreas Gobiet, and Georg Heinrich. "Empirical-statistical downscaling and error correction of regional climate models and its impact on the climate change signal". In: *Climatic Change* 112.2 (May 2012), pp. 449–468. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-011-0224-4.

[81] R. G. Allen and Food and Agriculture Organization of the United Nations, eds. *Crop evapotranspiration: guidelines for computing crop water requirements*. FAO irrigation and drainage paper 56. Rome: Food and Agriculture Organization of the United Nations, 1998. ISBN: 978-92-5-104219-9.

[82] Ž. Vlahović. *A validation of ADO drought indices SPI and SPEI in Slovenia.* Tech. rep. Slovenian Environment Agency, 2023. DOI: 10.48784/11568050-56FD-44E9-B1E8-2BF7649153A4.

[83] Tjaša Pogačar et al. "Grassland Model Based Evaluation of Drought Indices: A Case Study from the Slovenian Alpine Region". In: *Agronomy* 12.4 (2022). ISSN: 2073-4395. DOI: 10.3390/agronomy12040936.

[84] Michael Matiu et al. *Snow cover in the European Alps: Station observations of snow depth and depth of snowfall*. Version v1.3. Zenodo, July 2021. DOI: 10.5281/zenodo.5109574.

[85] K. Mayer and K. Haslinger. *ADO SNOWGRID CL Validation Report.* Tech. rep. Geosphere Austria, 2023. DOI: 10.48784/37D82FEE-1217-45B0-9F2B-12B66E1EB7D4.

[86] Slovenian Environment Agency. *ADO Factsheet: Standardized Precipitation Index (SPI)*. Tech. rep. Slovenian Environment Agency, 2023. DOI: 10.48784/2f51d416-d73d-4c87-80b6-c4673b4f6ce1.

[87] Slovenian Environment Agency. *ADO Factsheet: Standardized Precipitation-Evapotranspiration Index (SPEI)*. Tech. rep. Slovenian Environment Agency, 2023. DOI: 10.48784/b36d76a8-cc57-4c6f-a1b5-6d12c860d104.

[88] Slovenian Environment Agency. *ADO Factsheet: Standardized Snowpack Index (SSPI)*. Tech. rep. Slovenian Environment Agency, 2023. DOI: 10.48784/b7db0a55-31ac-4339-bf60-a6124fb45915.

[89] Felix Greifeneder. *Soil Moisture Anomalies - ERA5*$_O M(Version v1)$. Type: [Data set]. 2022. DOI: https://doi.org/10.48784/ea665ca2-0ceb-11ed-86c5-02000a08f4e5.

[90] Joint Research Centre. *European Drought Observatory Factsheet - Soil Moisture Anomaly*. Tech. rep. Joint Research Centre, 2020. URL: https://edo.jrc.ec.europa.eu/documents/factsheets/factsheet_soilmoisture.pdf.

[91] H. Mittelbach and S. I. Seneviratne. "A new perspective on the spatio-temporal variability of soil moisture: temporal dynamics versus time-invariant contributions". In: *Hydrology and Earth System Sciences* 16.7 (2012), pp. 2169–2179. DOI: 10.5194/hess-16-2169-2012. URL: https://hess.copernicus.org/articles/16/2169/2012/.

[92] Jean-Christophe Calvet et al. "In situ soil moisture observations for the CAL/VAL of SMOS: the SMOSMANIA network". In: *2007 IEEE International Geoscience and Remote Sensing Symposium*. 2007, pp. 1196–1199. DOI: 10.1109/IGARSS.2007.4423019.

[93] Gottfried Kirchengast et al. "WegenerNet: A Pioneering High-Resolution Network for Monitoring Weather and Climate". In: *Bulletin of the American Meteorological Society* 95.2 (2014), pp. 227–242. DOI: 10.1175/BAMS-D-11-00161.1. URL: https://journals.ametsoc.org/view/journals/bams/95/2/bams-d-11-00161.1.xml.

[94] Felix Greifeneder. *ADO Soil Moisture Validation Report.* Tech. rep. Eurac Research, 2023. DOI: 10.48784/37D82FEE-1217-45B0-9F2B-12B66E1EB7D4.

[95] Eurac Research. *ADO Factsheet: Soil Moisture Anomalies (SMA)*. Tech. rep. Eurac Research, 2023. DOI: 10.48784/5b9d5fd4-0aee-4f18-bb51-1503339cf07a.

[96] Vermonte Eric. *MODIS/Terra Surface Reflectance 8-Day L3 Global 250m SIN Grid V061 [Dataset]*. 2021. DOI: https://doi.org/10.5067/MODIS/MOD09Q1.061.

[97] Z. Wan, S. Hook, and G Hulley. *MODIS/Terra Land Surface Temperature/Emissivity 8-Day L3 Global 1km SIN Grid v061 [Dataset]*. 2021. DOI: https://doi.org/10.5067/MODIS/MOD11A2.061.

[98] P. Zellner and M. Castelli. *Vegetation Health Index -231m 8 days (Version 1.0) [Data set]*. Type: [Dataset]. 2022. DOI: https://doi.org/10.48784/161b3496-534a-11ec-b78a-02000a08f41d.

[99] EEA. *Corine Land Cover, European Union, Copernicus Land Monitoring Service[Dataset]*. https://land.copernicus.eu/. Online, Accessed on June 12, 2023. 2018.

[100] FAO. *Brief Guidelines to the Global Information and Early Warning System's (GIEWS) Earth Observation Website*. FAO Publications, 2018.

[101] Eurac Research. *ADO Factsheet: Vegetation Health Index (VHI) and Vegetation Condition Index (VCI)*. Tech. rep. Eurac Research, 2023. DOI: 10.48784/d125c506-8144-4eda-bfc1-80b7bac6727c.

[102] Reza Modarres. "Streamflow drought time series forecasting". In: *Stochastic Environmental Research and Risk Assessment* 21 (2007), pp. 223–233. DOI: 10.1007/s00477-006-0058-1.

[103] ARPA. *Bilancio Idrico Regionale Delle Acque Superficiali*. IL SISTEMA DI GESTIONE QUALITÀ È' CERTIFICATO, 2021.

[104] H. Faergemann. *Update on Water Scarcity and Droughts indicator development*. 2012. URL: https://circabc.europa.eu/sd/a/c676bfc6-e1c3-41df-8d31-38ad6341cbf9/1_Update%20on%20Water%20Scarcity%20and%20Droughts%20indicator%20development%20May%202012.doc.

[105] ARPA. *AAVV: Cinquant'anni di dati meteo-climatici in Piemonte, Arpa*. Online; Accessed on April 23, 2013 (in Italian). 2011. URL: http://rsaonline.arpa.piemonte.it/meteoclima50/intro.htm.

[106] C Ronchi et al. *Development of a daily gridded climatological air temperature dataset based on a optimal interpolation of ERA-40 reanalysis downscaling and a local high resolution thermometers network*. 2008. URL: https://www.arpa.piemonte.it/export/sites/default/pubblicazioni/clima/poster/EMS2008.pdf.

[107] Ruth Stephan et al. "An Alpine Drought Impact Inventory to explore past droughts in a mountain region". In: *Natural Hazards and Earth System Sciences Discussions* 2021 (2021), pp. 1–25. DOI: 10.5194/nhess-2021-24.

[108] National Drought Mitigation Center University of Nebraska-Lincoln. *U.S. Drought Monitor*. Online; Accessed on February 26, 2024. URL: https://droughtmonitor.unl.edu/.

[109] Joint Research Centre. *European Drought Observatory Factsheet - Combined Drought Indicator*. Tech. rep. Joint Research Centre, 2019. URL: https://edo.jrc.ec.europa.eu/documents/factsheets/factsheet_combinedDroughtIndicator.pdf.

[110] M. Zappa et al. "A prototype platform for water resources monitoring and early recognition of critical droughts in Switzerland". In: *Proceedings of the International Association of Hydrological Sciences* 364 (2014), pp. 492–498. DOI: 10.5194/piahs-364-492-2014. URL: https://piahs.copernicus.org/articles/364/492/2014/.

[111] Schnee und Landschaft WSL Die Eidgenössische Forschungsanstalt für Wald. *drought.ch*. Online; Accessed on February 26, 2024. URL: https://drought.ch/de/index.html.

[112] Consiglio Nationale della Ricerca CNR. *droughtcentral.it*. Online; Accessed on February 26, 2024. URL: https://droughtcentral.it/.

[113] Arpa Piemonte. "Bolletino Idrologico Mensile Marzo 2023". In: *Bolletino Idrologico Mensile* 03/2023 (2023), pp. 1–10.

[114] Oliver Schnuck. "Wo der Winter besonders schneearm war". In: *Süddeutsche Zeitung* (Apr. 19, 2023). Online, Accessed on September 11, 2023. URL: https://www.sueddeutsche.de/projekte/artikel/wissen/schnee-alpen-winter-2022-23-regionen-klimakrise-e319485/?reduced=true.

[115] Guido Gluschitsch et al. “Die Trockenheit in Ostösterreich verwandelt Schotterteiche in Kiesgruben”. In: *Der Standard* (Apr. 2, 2023). Online, Accessed on September 11, 2023. URL: https://www.derstandard.at/story/2000145091342/die-trockenheit-in-ostoesterreich-verwandelt-schotterteiche-in-kiesgruben?ref=rec.

[116] Ruth Stephan et al. “Assessing agriculture’s vulnerability to drought in European pre-Alpine regions”. In: *Natural Hazards and Earth System Sciences* 23 (Jan. 2023), pp. 45–64. DOI: 10.5194/nhess-23-45-2023.

[117] ESA. *Green Transition Information Factory*. Online; Accessed on September 11, 2023. 2022. URL: https://gtif.esa.int/explore?x=1827282.06773&y=5981374.26177&z=7.08155&poi=AT-ADO.

[118] United Nations - Office for Outer Space Affairs. *Space4Water Portal*. Online; Accessed on December 05, 2023. 2023. URL: https://www.space4water.org/project-mission-initiative-community-portal/alpine-drought-observatory.