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AltEx: An open source web application and toolkit for accessing and exploring altimetry datasets

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ABSTRACT

Understanding the spatial and temporal distribution of hydrologic variables, such as streamflow, is important for sustainable development, especially with global population growth and climate variations. Typical monitoring of streamflow is conducted using *in situ* gauging stations; however, stations are costly to setup and maintain, leading to data gaps in regions that cannot afford gauges. Satellite data, including altimetry data, are used to supplement *in situ* observations and in some cases supply information where they are lacking. This study introduces an open-source web application to access and explore altimetry datasets for use in water level monitoring, named the Altimetry Explorer (AltEx). This web application, along with its relevant REST API, facilitates access to altimetry data for analysis, visualization, and impact. The data provided through AltEx is validated using thirteen gauges in the Amazon Basin from 2008 to 2018 with an average Nash-Sutcliffe Coefficient and root mean square error of 0.78 and 1.2 m, respectively. Access to global water level data should be particularly helpful for water resource practitioners and researchers seeking to understand the long-term trends and dynamics of global water level and availability. This work provides an initial framework for a more robust and comprehensive platform to access future altimetry datasets and support research related to global water resources.

1. Introduction

Global population growth, human activities, climate change, and uneven distribution of water supplies (whether being water excess or scarcity) are leading to future water insecurity (Vörösmarty et al., 2010; Tao et al., 2015). Understanding the spatial and temporal distribution of water resources is critical to support sustainable development policies and activities addressing water security (Vörösmarty et al., 2000). Streamflow and river heights in developed nations are actively being monitored since the late nineteenth century for better management and allocation of water resources (Barrow, 1998). While these important hydrologic variables are being monitored in developed countries, *in situ* streamflow monitoring is largely lacking in developing regions, predominantly due to the impractical cost of installation and maintenance of these instruments (Alsdorf et al., 2001). Streamflow and river height information collected by means of *in situ* monitoring can be used to study and understand the impact of climate change on water resources and help understand trends of natural hazards (e.g, flood and drought conditions) (Haritashya et al., 2006; Huntington, 2006; Chen et al., 2014). Given the utility of such data for understanding the hydrologic cycle, these data gaps provide opportunities for innovative solutions to deliver data in data sparse regions, particularly for transboundary river basins (Lakshmi et al., 2018). Satellite-based remote sensing and modeling techniques have been used to fill data gaps and provide vital information for international and transboundary water resources monitoring and management (e.g., Mohammed et al. (2018a), Mohammed et al. (2018b)).

The results of many studies support the use of remotely sensed data for a wide range of water resources applications across the globe. For example, Maswood and Hossain (2016) used satellite data (including altimetry data) as inputs into a hydrologic model in the Ganges, Brahmaputra, and Meghna (GBM) river basins, providing improved river monitoring for flood forecasting applications across the three basins. Additionally, Chang et al. (2019) used the Variable Infiltration

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Capacity (VIC) model with altimetry data to develop a forecasting model in the Mekong Basin, resulting in an improved five-day forecast along the mainstem river. A similar approach to flood forecasting using altimetry data was implemented by Hossain and Bhuiyan (Hossain et al., 2016) for the GBM basins, increasing the flood forecast time to five days. Moreover, Bonnema and Hossain (2017) demonstrated the use of only satellite remote sensing datasets (altimetry and Landsat data) to infer streamflow response to reservoir operations in the Mekong Basin. Other studies have focused solely on using altimetry datasets for monitoring purposes along the in the Yangtze river basin (Chu et al., 2008), the Zambezi River basin (Michailovsky et al., 2012), the Congo River basin (Kim et al., 2019), lakes in Indonesia (Sulistioadi et al., 2015), and more broadly across North America, Africa, and Southeast Asia (Ricko et al., 2012). These studies highlight how a growing number of users are interested in applying remotely sensed water level estimates, and more specifically satellite altimetry, to a wide variety of studies and water resources management challenges related to the hydrologic cycle and climate change.

With the advent of satellite and radar altimetry data, the capability to monitor sea, river, and lake level changes with acceptable accuracy has significantly improved since the early 1990s. Satellite radar altimetry sends radar pulses to the Earth and measures the return time from the reflecting surface to calculate the water level relative to a reference datum along with the satellites altitude. The first major oceanographic research altimeter, TOPEX/Poseidon (Fu et al., 1994), collected the data from 1992 to 2005 paving the way for subsequent satellites, such as the Jason series. Jason-1, -2, and -3 provided data from 2002 to present, creating a long series of available water level measurements. Additional sensors, such as Envisat (operated from 2002 to 2010), SARAL/Altika (operated from 2013 to 2016 in exact repeat-orbit) and Sentinel-3 (currently operating since 2016), have been launched to supplement and continue the water level measurements from the Jason series. Although altimeters were designed primarily for ocean and ice studies, they have been applied to the monitoring of inland water bodies (Lee et al., 2009). In particular, the ability to remotely detect water surface level changes in lakes and inland seas has been demonstrated. Studies have shown that results derived from altimetry data demonstrate how sub-monthly, seasonal, and inter-annual variations in height can be monitored and provide invaluable information in data sparse regions (Bonnema et al., 2016). Despite the use of altimetry data in scientific studies, Gao et al. (2012) concluded that access to water level data has been a major challenge in the global study of reservoirs.

Applications exist to lower the barrier to access and use water level information from altimetry sensors. For example, a GUI-based Jason-2/3 and Sentinel-3A data processing toolbox to generate time series of water level changes over user-defined inland water bodies has been developed based on the automation algorithm by Okeowo et al. (2017). The toolbox has been delivered to stakeholders of developing countries to monitor water level changes over locations of their interest. Furthermore, web applications exist to provide water level information for preprocessed locations such as the Database for Hydrological Time Series of Inland Waters (https://dahiti.dgfi.tum.de/en/), Lakes, Rivers and wetlands Water levels from satellite altimetry (http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/Page_2.html), and Global Reservoirs/Lakes (G-REALM) (https://ipad.fas.usda.gov/cropexplorer/global_reservoir/). Although these desktop and web applications have significantly helped to provide water level measurements with reduced barriers to entry, downloading and processing the altimetry data for multiple sites takes significant time. Moreover, the current web applications are limited to several fixed locations. To date, no service is available that allows users to query the large global altimetry database dynamically to explore data availability and access water level time series information on-the-fly. Here we present a web application, named Altimetry Explorer (AltEx), that allows users to dynamically access historical global water level data derived from satellite altimeters without expert knowledge. The goal of this web application is to provide a free and open-source platform that allows users to access historical and future altimetry data records of river height, decreasing the time spent handling and processing data, allowing more time for analysis, interpretation, and impact. In this paper, we provide a detailed explanation of the altimetry data, processing algorithm, and web applications used to serve global river height information. Furthermore, we validate the results from the application using observed river height data from *in situ* gauges (building on Okeowo et al. (2017)), discuss implications of such an application, and outline future additions to the web application.

2. Materials and methods

2.1. Altimetry data

The Jason satellite mission series, a successor to the TOPEX/Poseidon mission, launched three satellites equipped with altimeters to provide a long time series of surface water level observations. The Ocean Surface Topography Mission (OSTM)/Jason-2 satellite mission was launched in 2008 and has a revisit period of 10 days. The Jason-3 satellite mission was launched in 2016 to further extend the long-term time series of surface water level measurements from Jason-1 and -2, thus has the same orbit, revisit, and sensor characteristics as Jason-2. The Jason-2/3 data are available in 1 Hz and 20 Hz sampling rate; the along track ground distance on the equator between two measurements in the 20 Hz data corresponds to about 330 m on the equator and is suitable for inland water applications (Dumont et al., 2017a, 2017b). Hence, we used the 20 Hz Geophysical Data Record (GDR) height measurements on this web application to generate a water level time series, allowing for the monitoring of water bodies with at least 350 m wide along the satellite ground track.

On this web application, we use the Jason altimetry data provided by NOAAs National Centres for Environmental Information (NCEI). The GDR product is of scientific quality and has been validated for a range of measurements (Picot et al., 2018); however, the GDR product has latency of 60 days, making it unavailable to near real time applications. The Interim Geophysical Data Record (IGDR) data product is also available in near real time, however, with lower accuracy to facilitate quick distribution. In this study, the OSTM/Jason-2 Level-2 GDR data (Dumont et al., 2017a) was used for Jason-2 due to its data availability and higher quality. Whereas the Jason-3 Level-2 IGDR product (Dumont et al., 2017b) is used initially for Jason-3 to provide near real time observations and switched to the GDR product upon availability; this allows for delivering near real time product through the developed web applications while keeping scientific quality data. The Jason 2/3 altimetry data is downloaded from the NCEI site, compressed, and stored on the server running AltEx.

2.2. Outlier removal algorithm

Satellite altimetry data inherently contain errors, which are due to contamination from the surrounding topography (Berry et al., 2005) when used to monitor inland water bodies. Often, altimetry data are screened for poor-quality measurements using the retracked range quality flags as recommended by Birkett and Beckley (2010). Additional manual removal of these outliers has been implemented in studies (Birkett and Beckley, 2010), but this can be challenging and time

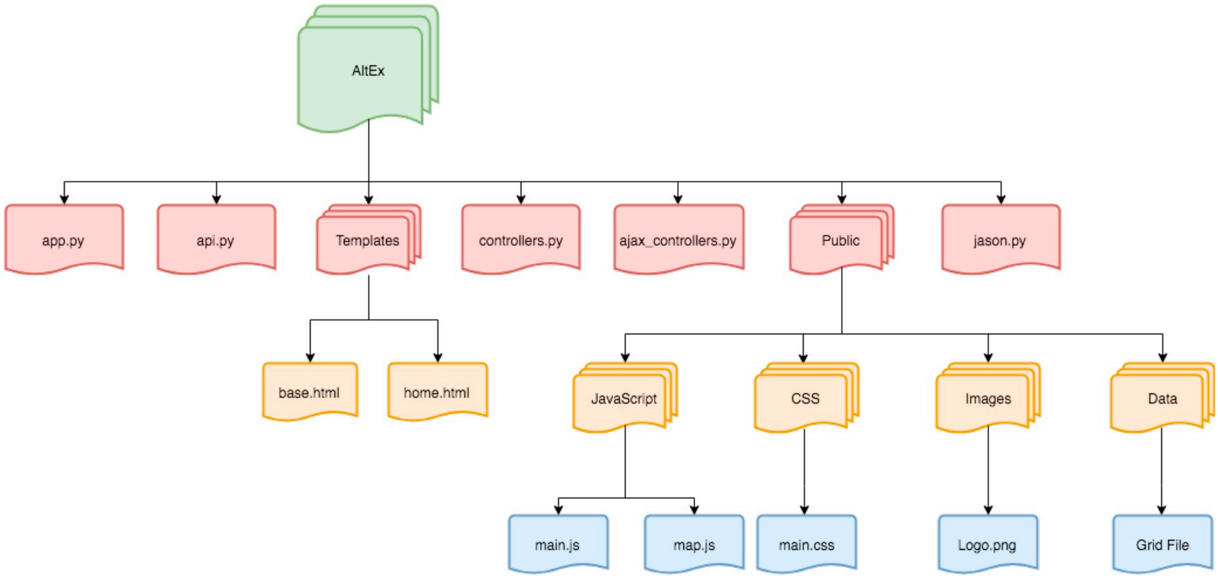

Fig. 1. AltEx web application directory structure.

consuming. Further studies have used automated approaches to remove outliers from the altimetry data using thresholds (Huang et al., 2013), Cauchy and Gaussian distributions to represent observations (Nielsen et al., 2015) and Kalman filters (Schwatke et al., 2015). These outlier removal algorithms require additional datasets or are computationally expensive, making them infeasible for global, on-the-fly processing. Hence, we implemented an outlier detection algorithm that does not require user intervention or ancillary datasets with a short runtime developed by Okeowo et al. (2017) to generate a filtered water level time series from the altimetry datasets.

The outlier removal algorithm developed by Okeowo et al. (2017) is an iterative approach based on a combination of K-means unsupervised clustering and statistical analyses of the height measurements to detect outliers without prior knowledge of the water-body of interest. First, the Interquartile Range (IQR) is calculated and any data outside of the IQR is thrown out. Next, the IQR-filtered data is classified into two classes using the K-Means++ algorithm (Arthur and Vassilvitskii, 2007) and the cluster with class with the least number of observations is thrown out. The K-Means clustering is repeated until the range of values in the resulting good cluster is within a certain threshold, in this case 5 m. The mean value of the cluster is computed, and data points furthest away from the mean are removed until the threshold of inter-class standard deviation is met, in this case 0.3 m. Finally, the resulting data are filtered using the new IQR. This approach is applied to all of the 20 Hz observations from each cycle for the specified distance along the satellites flight path. The algorithm was validated on Envisat and Jason-2 water level retrievals using *in situ* observations over 37 lakes and reservoirs with RMSE values ranging from 0.09 to 1.20 m. According to Okeowo et al. (2017), the algorithm can be extended to process Jason-3 satellite data and also has a potential to be used over rivers and wetlands. For a more detailed explanation of the algorithm and justification for the thresholds used, readers are referred to Okeowo et al. (2017).

The outlier removal algorithm described in Okeowo et al. (2017) for the river height time series is a vital component of the web application and provides users with accurate information without having to manually filter poor data from the altimetry dataset. Additionally, when a user wants to acquire water level information for a select geographic point location, this approach reduces the margin of error in the event a selected point falls outside of a water body. It is suggested that at least 50% of the data points used in the outlier removal algorithm be water retrievals, not noise, or else the algorithm will fail (Schwatke et al., 2015; Okeowo et al., 2017). The AltEx web application attempts to mitigate this problem by constraining users to select river segments at least 350 m wide along satellite ground track to ensure at least one altimetry data point falls within the waterbody in question. It should be noted that the outlier removal algorithm employed in AltEx does not verify whether users have selected points absolutely over water. Employing such a filter based on dynamic user queries is beyond the scope of this study and current application.

2.3. Web application

Tethys (Swain et al., 2015, 2016) is a free and open-source web-development framework developed at Brigham Young University, Provo, Utah. The unique features that Tethys offers helps lower the barrier for developing hydrologic web-applications. The Tethys Platform was selected for developing AltEx given it already comes with several built-in software packages that can be used for the application, enabling a streamlined development process. The Tethys Platform architecture is separated into three major components: Tethys Software Development Kit (SDK), Tethys Portal, and Tethys Software Suite. Tethys web applications are developed with the Python programming language and an SDK. The SDK provides Python module links to each software component of the Tethys Platform, making the functionality of each component easy to incorporate in web applications. In addition, users can access all of the Python modules that they are accustomed to using in their scientific Python scripts to power their web applications.

The Tethys Portal is where developed applications can be published; it provides an application library page for users to access installed applications and includes several tools and functionalities enabling custom features such as user permissions, portal design, and portal settings.

The Tethys application structure follows the Model-View-Controller (MVC) software architecture, allowing for a simple, readable and reusable code. The MVC structure has three components: 1) Model: The model is responsible for initializing the database and managing the

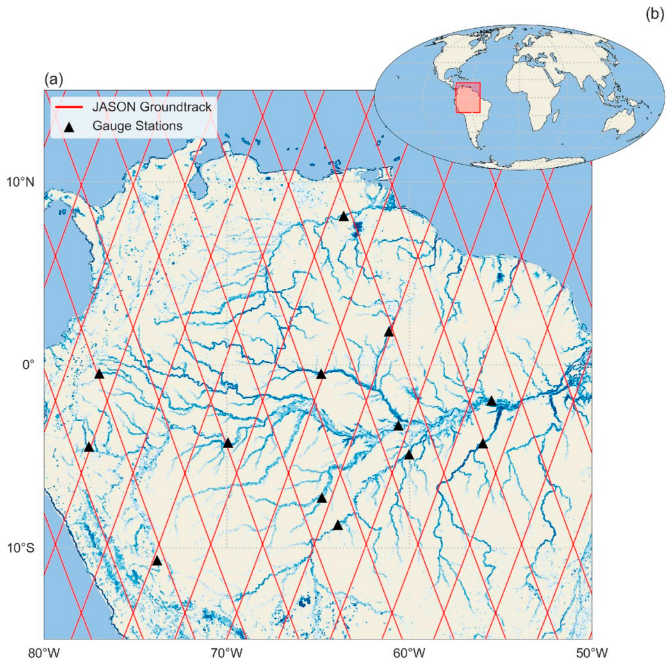

Fig. 2. Study area map show the gauge locations used in this study and altimetry groudtracks (a) along with a reference map (b). The JRC Surface Water occurrence data was used as a background image in (a) to display where water bodies are located.

database structure, 2) View: The views represent the HTML pages that are rendered for the user to see, 3) Controller: The controllers handle the logic in the web application and connect the database (model) to the front end (view). Any data retrieval and presentation is done through the controllers.

The Software Suite contains several tools and packages, such as GeoServer, PostgreSQL, OpenLayers, etc., that are used commonly when developing geospatial web applications. Readers are directed to the Tethys online documentation (http://docs.tethysplatform.org/en/stable/) for a more in-depth description of Tethys and web application development using Tethys.

The Tethys Application folder structure is set up so that it can be easily deployed and replicated. One component within the folder, the application package, contains the source code for executing the Tethys application. Within the application package, there are several different files that come together to create the application. The application directory structure is also shown in Fig. 1. The model.py file initializes the database, and the controllers.py file contains the controller functions that are used throughout the application. The utilities.py file contains common functions that are used throughout the application, and the persistentstore.py file is the database itself. The templates directory contains the HTML pages that are rendered to the front end. The public directory contains resources that are responsible for rendering the HTML content, such as JavaScript, Cascading Style Sheets (CSS), and images; it also contains any external libraries. The original Django application structure has several moving parts, and it is not straightforward for novice developers. However, the Tethys project application structure has the MVC components in one central location, making it easier for first-time web developers to leverage the MVC structure.

The application does not have a database of its own; rather, it relies on the raw satellite data as the database or the Model in the MVC paradigm. The altimetry data is set to download automatically using a CRON job. On download, ancillary data fields are removed from the netCDF datasets reducing the storage size of global data. The data is stored in a flat file system where datasets from individual satellites (i.e. Jason-2 or Jason-3) are stored in their own subdirectory.

The views render information from the controllers to the front end for the users to see. The data from the controllers is passed in the form of context variables, meaning variables that are created every time the application is initiated, thus ensuring that the data returned are dynamic. These variables can be rendered directly through the Django HTML template.

Users interact with the web application by selecting a sensor, the sensors track path on a web map, and dates to process. The AltEx application user interface is designed to be intuitive and extensible. The altimetry track paths of each sensor are published as a layer on the local Tethys GeoServer; once they are published, they are accessible as a Web Mapping Service (WMS) Layer and displayed in the AltEx web map view. To help the users create a cross section over trackpath with water, data from the Joint Research Centres Global Surface Water dataset (Pekel et al., 2016) from Google Earth Engine (Gorelick et al., 2017) is displayed on the web map. This dataset provides surface water occurrence frequency globally from 1984 to 2015 at 30 m spatial resolution. This layer is meant to be a visual aid when users select a track path, helping ensure that the majority of the cross section falls within an area with water, but–as mentioned in the previous section–this does not inhibit the user from wrongfully selecting points along tracks that fall over solid terrain. Any request submitted by the user through the interface is mapped through app.py and is ultimately executed through either controllers.py, ajax_controllers.py or api.py. The controller returns data through the HTML page or as a JSON object, which can be rendered as an HTML object.

A Representational State Transfer (REST) API is enabled for AltEx which allows experienced researchers and application developers to use the data in their own applications and scripts. A HTTP request can be sent to the REST API with the desired parameters (lower latitude, upper latitude, start date, end date, track path and the sensor) and is returned the time series water level data as a JSON object.

2.4. Validation of water level retrievals

To ensure high-quality data are produced through the AltEx application, the results of the outlier removal algorithm server processing were compared with *in situ* water level data. The *in situ* data was collected from the Geodynamical, hydrological and biogeochemical control of erosion/alteration and material transport in the Amazon, Orinoco and Congo basins (SO HYBAM; http://www.ore-hybam.org/) observation service which aims to provide the researchers with high quality scientific data used to understand and model Earth systems and long-term dynamics. For the purpose of this validation, the *in situ* station data from the Amazon Basin were used as they provide a wide range of riverine environments including: the Amazon main channel, tributaries, and floodplains. Each station was manually examined for a corresponding Jason satellite ground track to analyse. Out of the seventeen original *in situ* stations, only thirteen were selected given that availability of data corresponding with satellite overpasses in proximity of the station (Fig. 2).

The AltEx application was used to extract the time series water level data from Jason-2/3 data to compare with the *in situ* data. Temporal filtering was applied to ensure altimeter and *in situ* measurements from the same day were compared. The instantaneous measurements from the altimeters were considered to be the mean value for the entire day to compare with the daily values from the *in situ* stations. Error statistics were calculated for the gauge stations to understand the accuracy of the altimetry data provided through AltEx; the error statistics used include

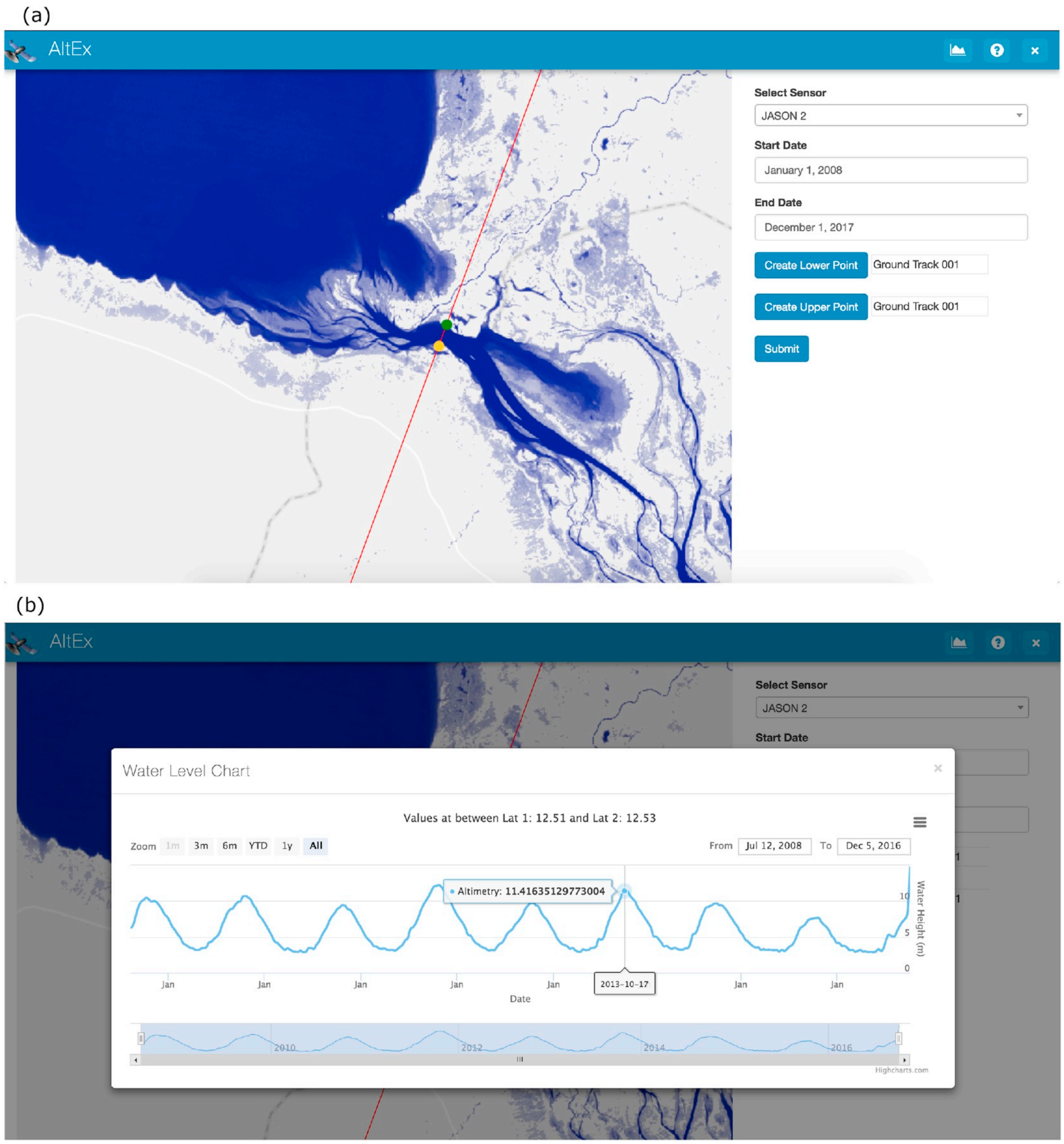

Fig. 3. AltEx Web Application User Interface over Tonle Sap, Cambodia (a) and water level chart as rendered in AltEx Web Application (b).

Nash-Sutcliffe model efficiency coefficient (NSE) (Nash and Sutcliffe, 1970), root-mean square error (RMSE), and correlation coefficient (R).

3. Results and discussion

The source code for AltEx is publicly available on GitHub at https://github.com/SERVIR/AltEx. The application is currently developed to work with Tethys 2.0 and later; it is licensed under the MIT licensing convention. Thus any individual or organization that wishes to use it can download the source code and deploy it on to their own portals without any restrictions. Detailed instructions on deploying the application are available at http://altex.readthedocs.io. The AltEx application is currently deployed on the Tethys Portal at https://tethys.servirglobal.net. The apps on the portal are hosted on the applications page on this website. A user can access the application by clicking on the AltEx application icon on the applications homepage.

3.1. A case study for using AltEx

This section presents a brief case study describing the use of AltEx web application for accessing and visualizing water level near the Tonle Sap Lake in Cambodia. The goal of the case study is to identify trends in water storage changes in Tonle Sap. The case study assumes that the user is using the Web Application available at https://tethys.servirglobal.net/apps/altex. The acquisition and visualization of the data using AltEx is highlighted in this case study.

When the user enters the website, there is a global map with a layer showing the geographic boundaries, Jason 2/3 track path, and JRC Surface Water Occurrence. The user can zoom and pan to the area of interest. Once the user is at the area of interest, they can select an upper and lower point on the track path with water. The JRC Surface Water Layer allows the user to ensure that the cross section that they have selected is within a track path with water. The user can specify the date range of the data.

Table 1
Error statistics for each station used in the validation of the AltEx application.

Station	Lat.	Lon.	NSE [-]	R [-]	RMSE [m]	n Samples
Atalaya Aval	−10.6782°	−73.8179°	0.905	0.957	0.550	263
Borja	−4.47036°	−77.54825°	0.820	0.914	0.615	314
Caracarai	1.82139°	−61.12361°	0.757	0.873	1.043	300
Ciudad Bolivar	8.14319°	−63.60739°	0.906	0.956	1.352	317
Fazenda Vista Alegre	−4.89722°	−60.02528°	0.415	0.779	3.137	324
Francisco de Orellana	−0.4733°	−76.9825°	0.301	0.668	0.551	160
Itaituba	−4.28333°	−55.98333°	0.978	0.990	0.324	325
Labrea	−7.25222°	−64.8°	0.931	0.966	1.587	167
Manacapuru	−3.30833°	−60.60944°	0.933	0.973	1.120	317
Obidos	−1.94722°	−55.51111°	0.594	0.798	1.581	346
Porto Velho	−8.73667°	−63.92028°	0.712	0.871	2.453	324
Serrinha	−0.48194°	−64.82889°	0.980	0.994	0.231	321
Tabatinga	−4.25°	−69.93333°	0.912	0.960	1.079	328
Mean (Std. Dev.)	–	–	0.780 (0.220)	0.900 (0.099)	1.202 (0.845)	–

In this case study, the user selects a cross section near Tonle Sap lake (in Cambodia, approximately 110 km upstream from Phnom Penh) on Track Path 1 as seen in Fig. 3 (a). The user then clicks on the Submit button to retrieve the time series data. The retrieved data are rendered as a time series through the Highcharts JavaScript charting library as seen in Fig. 3b. The user can hover the time series to see the value at the given point. The user can also zoom into a specific data range by clicking and dragging on the chart. The user notices that the water level changes follow a seasonal pattern from 2008 to 2016. The water level reaches the peak around October/November, which are the monsoon months. In the summer months from March to May, there is a significant decrease in the water levels. These values are consistent with historic water levels and seasonality of the Tonle Sap (Kite, 2001). Moreover, the lower-than-normal peak water levels observed by Jason-2 in 2015 and 2016 correspond to some of the regions worst droughts (Guo et al., 2017). To export the data, the user clicks on the chart context menu icon at the top right corner of the chart. The user can then export the data into one of the following formats: PNG, JPEG, PDF, CSV, SVG, XLS. The user can then manipulate or visualize the data in other applications.

Using the API, programmers and researchers can use the time series data in their own statistical packages to further analyse the data. The API currently consists of one method to retrieve time series. The timeseries method in the API requires a lower latitude, upper latitude, start date, end date, track path and the sensor. The full API documentation can be found with the rest of the documentation of the application. The following is an example of a sample REST API call made to the AltEx application:

https://tethys.servirglobal.net/apps/altex/api/timeseries/?lat1=12.508647&lat2=12.523467&start_date=2008-1-1&end_date=2018-12-31&track=001&sensor=jason2.https://tethys.servirglobal.net/apps/altex/api/timeseries/?lat1=12.508647&lat2=12.523467&start_date=2008-1-1&end_date=2018-12-31&track=001&sensor=jason2

The above example returns a JSON object with time series values from the Jason 2 satellite for the above use case. The time series JSON is formatted in UTC Milliseconds and the corresponding value at that time as follows: [1485523207706,1.2400541055837568]. The readers are referred to Appendix A for a full example using Python to programmatically request the time series data from both Jason-2 and Jason-3 for this use case.

3.2. Validation results

Error statistics for the generated time series extracted from the AltEx application were calculated for the thirteen gauge stations across the Amazon basin (Fig. 2). Table 1 shows the statistics for each station where the reported error statistics are well within acceptable ranges for validation according to Moriasi et al. (2015). The NSE for the water level time series ranges from 0.3 to 0.97 with a mean NSE of 0.78 showing that the altimetry data from AltEx can be used with reasonable accuracy for water level time series. Furthermore, the range of RMSE retrieved from AltEx data is from 0.23 to 3.13 m with a mean of 1.2 m, further adding that the water level time series derived from altimetry data can adequately depict *in situ* water levels.

The majority of the stations show good agreement with the altimetry water level data time series (Fig. 4); however, three stations with marginally satisfactory error statistics show either erroneous values or noise within the time series. For example, stations Fazenda Vista Alegre and Porto Velho (Fig. 4e and (Cont.)k, respectively) have high RMSE errors where the altimetry data do not fit with the observed data. In late 2017 during low flow conditions at the Fazenda Vista Alegre station (Fig. 4e), the Jason-2 data show much higher values than *in situ* measurements. There is an inverse case for Porto Velho (Fig. 4 (Cont.)k) around early-mid 2017 when the Jason-3 data missed a rise, peak, and fall, in water levels. These discrepancies occur when the outlier removal algorithm fails to remove erroneous values cause by excess noise in the retrievals for that day. In the case of the Francisco de Orellana station (Fig. 4f) the NSE is approximately 0.3, where it can be seen that the altimetry water level retrievals are within about 2 m (0.5 RMSE) of the observed data but do not align temporally. This effect is likely due to Francisco de Orellanas being a small tributary at the headwaters of the Amazon and where a small cross-section for the satellite overpass and rapid changes in water level add noise to the altimeter retrievals. Although the data quality flags and outlier removal algorithm are meant to alleviate such errors in the altimetry water level data, these cases present themselves and highlight the need for users to understand and review the systems for which they are applying altimetry data.

The accuracy of water level data provided through AltEx is comparable to other studies that have aimed to provide altimetry datasets to users. For example, Bogning et al. (2018) used the Jason-2/3, ERS-2, ENVISAT, Cryosat-2, SARAL, and Sentinel-3A data to provide water level information in the Ogoou river basin of Gabon, where an RMSE of 0.219–1.05 m was reported at different *in situ* stations. Another application which provided altimetry data across global reservoirs reports an accuracy of a few centimeters to several tens of centimeters (Birkett et al., 2011). While the AltEx system reports errors as high as 3.14 m, the system performs well in most cases and is meant to be used for global applications, thus will have some errors at the local scale.

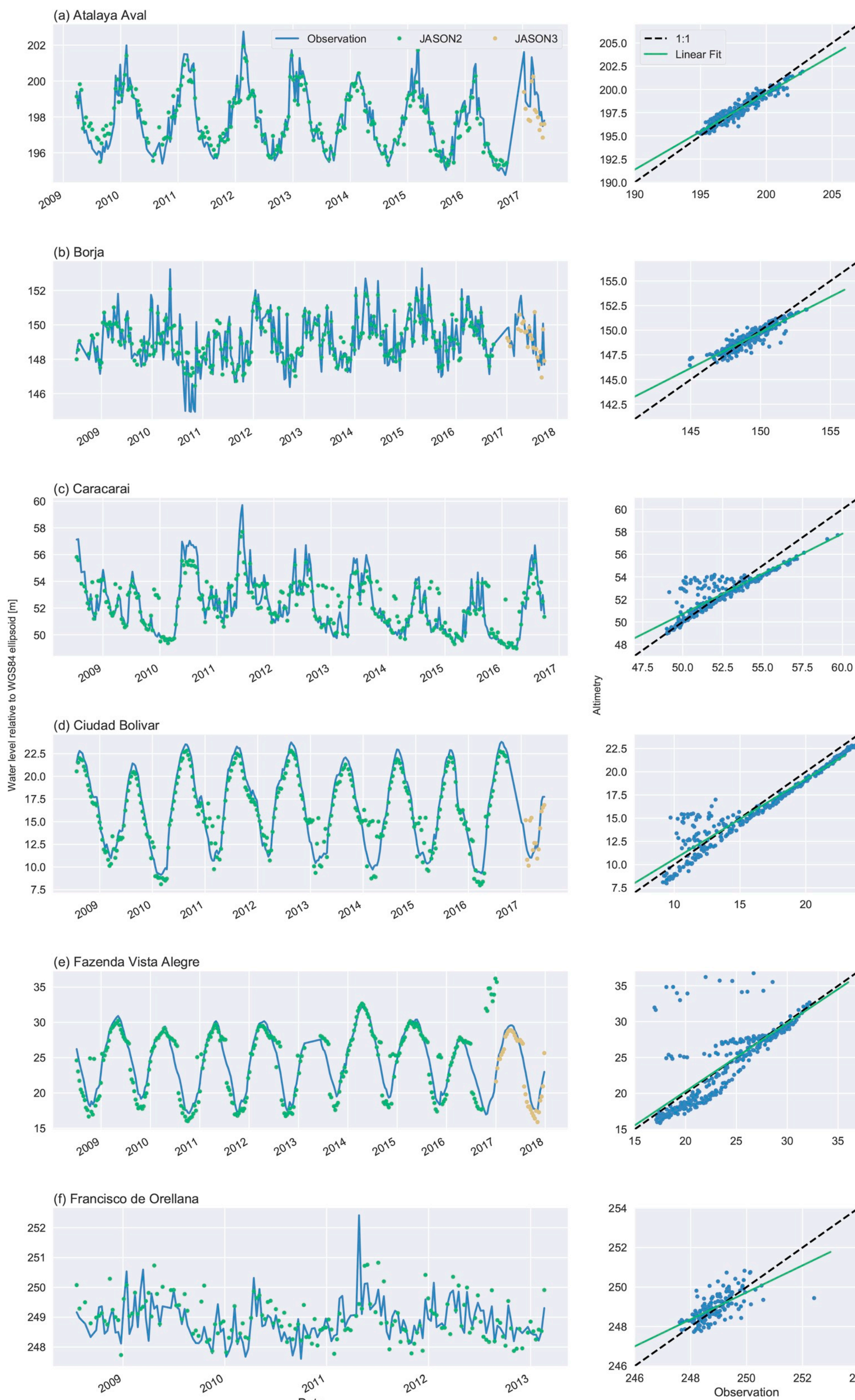

Fig. 4. Time series (left) and scatter plots (right) displaying the observed *in situ* water level (blue) as compared to altimetry derived water levels from Jason-2 (green) and Jason-2 (yellow). Units are in meters above the WGS84 ellipsoid. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

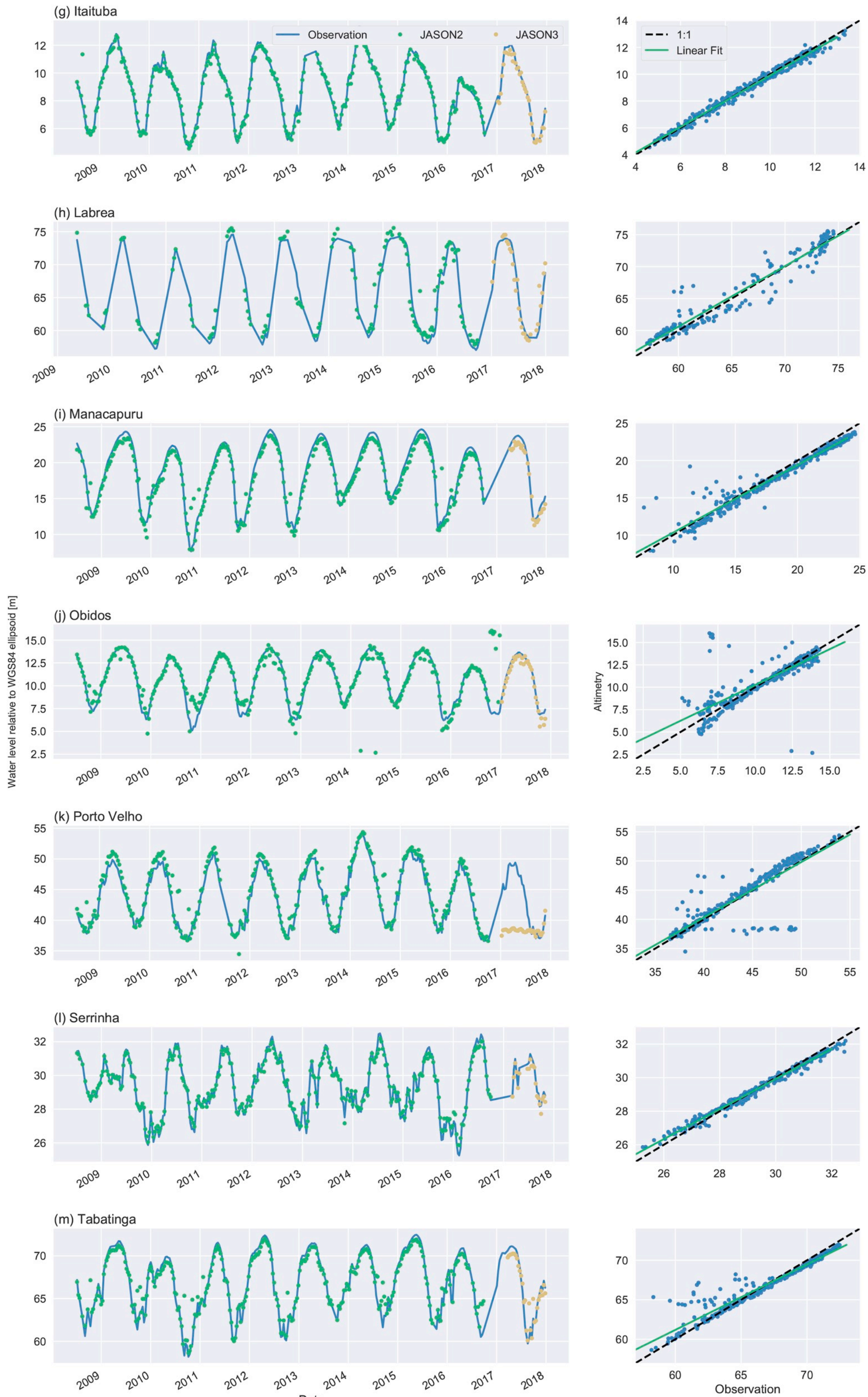

Fig. 4. (*continued*)

3.3. Future work

Due to the modular design of the application, the workflow for adding a new altimetry sensors into the system is as simple as creating a new controller or a processing script, followed by the creation of the relevant HTML elements and JavaScript to interact with that controller. This approach keeps the barrier low for developing new functions and algorithms, since the existing structure can seamlessly integrate with any new datasets. Currently, AltEx has Jason-2 and Jason-3 processing available, and it is planned to include additional altimetry datasets (i.e. SARAL, EnviSat, Sentinel-3, and potentially the forthcoming Surface Water Ocean Topography (SWOT) mission) in the application.

Many scientists and practitioners representing a broad community have expressed demand for more satellite altimetry data that are timely, easy to access and interpret, and relevant to a plethora of applications for societal benefit (Hossain et al., 2017). Additional studies will be completed to highlight use cases of AltEx for research and water resources management applications. When including additional datasets it is important to validate the results, further validation will be performed in data sparse regions, such as the Mekong Basin, to further highlight the application of such a tool in such regions. Application use cases could be conducted using AltEx API for data assimilation, climatology trends, estimating water availability/flooding, and impacts of dams on hydrologic systems (e.g., Arias et al. (2012); Arias et al. (2014); Kummu and Sarkkula (2008)). Any additional features needed to assist researchers and practitioners in using altimetry data at a global scale will be considered to improve availability and use of altimetry data.

4. Conclusion

This article describes the design, development and implementation of a web-based application for extracting and visualizing time-series data from altimetry datasets. This work builds on existing research efforts to provide accurate water level time series from altimetry datasets. The valuable contributions of this study are: 1) AltEx provides a modular framework for accessing and visualizing time-series values of water level heights from various altimetry datasets, 2) the AltEx web application provides an intuitive user-interface and an API access to researchers, students and decision makers working with hydrologic data, 3) the use of open-source technologies for developing the application help promote a potential user and developer community for further improvements and enhancements.

Other studies have provided altimetry data for particular use cases. AltEx provides access to global water level data, where water resource managers can monitor water levels at rivers and reservoirs without expensive *in situ* monitoring stations. Building on prior validation work, this study shows that AltEx performs well when compared to *in situ* observations across the Amazon Basin. The results from AltEx can be used to fill in gaps and monitor water levels in areas with no physical infrastructure. This is a novel contribution to the field of hydrology by providing open-source resources to access accurate water level retrievals anywhere across the globe without expert knowledge. Ultimately, this service aims to reduce time needed to acquire, process, and visualize alimtery data, thus availing users to spend more time to developing meaningful use cases and applications.

The AltEx web app is under continuous development, and new features will be added to the source code repository and push to the development server after testing. Feature requests, comments, and contributions are welcome at the public software repository.

Software Availability

Name of software AltEx (Altimetry Explorer)
Developers Kel N. Markert and Sarva T. Pulla
Contact km0033@uah.edu
Software required Linux OS, Python 3, Tethys Platform 2.0 + , NumPy, SciPy, netCDF4
Program language Python 3
Software availability Source code at https://github.com/SERVIR/AltEx
Documentation Detailed documentation for required software and application installation can be found at https://altex.readthedocs.io/en/latest/
Data required For local installation and use of AltEx, users will need to have the Jason-2 and Jason-3 data locally available. Altimetry data can be accessed at ftp://ftp.nodc.noaa.gov/pub/data.nodc/jason2/ or ftp://ftp.nodc.noaa.gov/pub/data.nodc/jason3/

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2019.03.021.

Appendix B. Example API request workflow using Python

Here Python code is provided to illustrate how the AltEx API can be used programatically. The requests highlighted are for the Jason-2 and Jason-3 time series data for the Tonle Sap Lake case. The code is provided as in a Jupyter Notebook using IPython syntax, users may need to modify the code slightly to create functional Python scripts.

```python
import requests
import pandas as pd
import seaborn as sns

%pylab inline

# set plotting styling
sns.set()
sns.set_context("notebook")

# function to convert API json response to Pandas df
def response_to_series(json,name='Altimetry'):
    # unpack the date and water level data
    dates, hgts = list(zip(*json['values']))
    # scale the date timestamp to correct pandas units
    dates = list(map(lambda x: x*1e6,dates))
    # create a pandas Series from the water level data
    ts = pd.Series(hgts,index=pd.to_datetime(dates),name=name)
    return ts

# specify REST API URL
url = "https://tethys.servirglobal.net/apps/altex/api/timeseries/?"

# define parameters to pass into URL for Jason-2


j2_params = dict(
    lat1 = '12.508647',
    lat2 = '12.523467',
    start_date ='2008-1-1',
    end_date = '2018-12-31',
    track = '001',
    sensor = 'jason2',
)

# send request to AltEx API URL with the parameters
j2_response = requests.get(url,params=j2_params,verify=False)

# load the reponse in json format
j2_data = j2_response.json()

# get data into series format
j2_series = response_to_series(j2_data,name='Jason2')

# define parameters to pass into URL for Jason-3
j3_params = j2_params
j3_params['sensor'] = 'jason3'

# send request to AltEx API URL with the parameters
j3_response = requests.get(url,params=j3_params,verify=False)

# load the reponse in json format
j3_data = j3_response.json()

j3_series = response_to_series(j3_data,name='Jason3')

# plot the data for visualization
fig = plt.figure(figsize=(10,5))

ax = j2_series.plot(label='Jason2')
j3_series.plot(ax=ax,label='Jason3')
ax.set_ylabel('Water Level [m]')

plt.legend(frameon=True)

plt.show()
```

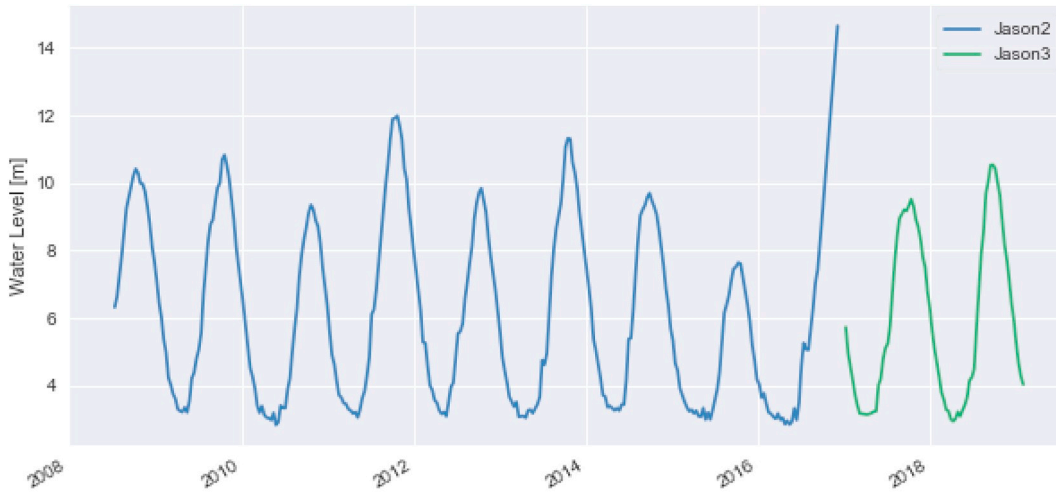

Fig. A1. Plot of example water level data as requested from the AltEx Web Application for the Tonle Sap case study.

References

Alsdorf, D., Birkett, C., Dunne, T., Melack, J., Hess, L., 2001. Water level changes in a large amazon lake measured with spaceborne radar interferometry and altimetry. Geophys. Res. Lett. 28, 2671–2674.

Arias, M.E., Cochrane, T.A., Piman, T., Kummu, M., Caruso, B.S., Killeen, T.J., 2012. Quantifying changes in flooding and habitats in the tonle sap lake (Cambodia) caused by water infrastructure development and climate change in the mekong basin. J. Environ. Manag. 112, 53–66.

Arias, M.E., Piman, T., Lauri, H., Cochrane, T.A., Kummu, M., 2014. Dams on mekong tributaries as significant contributors of hydrological alterations to the tonle sap floodplain in Cambodia. Hydrol. Earth Syst. Sci. 18, 5303–5315.

Arthur, D., Vassilvitskii, S., 2007. K-means++: the advantages of careful seeding. Proceedings of the Eighteenth Annual ACM-SIAM Symposium on Discrete Algorithms, SODA '07. Society for Industrial and Applied Mathematics, Philadelphia, PA, USA, pp. 1027–1035.

Barrow, C.J., 1998. River basin development planning and management: a critical review. World Dev. 26, 171–186.

Berry, P.A.M., Garlick, J.D., Freeman, J.A., Mathers, E.L., 2005. Global inland water monitoring from multi-mission altimetry. Geophys. Res. Lett. 32.

Birkett, C.M., Beckley, B., 2010. Investigating the performance of the jason-2/ostm radar altimeter over lakes and reservoirs. Mar. Geodes. 33, 204–238.

Birkett, C., Reynolds, C., Beckley, B., Doorn, B., 2011. From research to operations: the usda global reservoir and lake monitor. In: Vignudelli, S., Kostianoy, A.G., Cipollini, P., Benveniste, J. (Eds.), Coastal Altimetry. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 19–50.

Bogning, S., Frappart, F., Blarel, F., Nio, F., Mah, G., Bricquet, J.-P., Seyler, F., Ongun, R., Etam, J., Paiz, M.-C., Braun, J.-J., 2018. Monitoring water levels and discharges using radar altimetry in an ungauged river basin: the case of the ogoou. Rem. Sens. 10.

Bonnema, M., Hossain, F., 2017. Inferring reservoir operating patterns across the mekong basin using only space observations. Water Resour. Res. 53, 3791–3810.

Bonnema, M., Sikder, S., Miao, Y., Chen, X., Hossain, F., Ara Pervin, I., Mahbubur Rahman, S.M., Lee, H., 2016. Understanding satellite-based monthly-to-seasonal reservoir outflow estimation as a function of hydrologic controls. Water Resour. Res. 52, 4095–4115.

Chang, C.-H., Lee, H., Hossain, F., Basnayake, S., Jayasinghe, S., Chishtie, F., Saah, D., Yu, H., Sothea, K., Bui, D.D., 2019. A model-aided satellite-altimetry-based flood forecasting system for the mekong river. Environ. Model. Softw 112, 112–127.

Chen, X., Hao, Z., Devineni, N., Lall, U., 2014. Climate information based streamflow and rainfall forecasts for huai river basin using hierarchical bayesian modeling. Hydrol. Earth Syst. Sci. 18, 1539–1548.

Chu, Y.P., Li, J., Jiang, W., Zou, X., Fan, C., Xu, X., Dadzie, I., 2008. Monitoring level fluctuations of the lakes in the yangtze river basin from radar altimetry. Terr. Atmos. Ocean Sci. 19, 63–70.

Dumont, J., Rosmorduc, V., Carrere, L., Picot, N., Bronner, E., Couhert, A., Desai, S., Bonekamp, H., Scharroo, R., Leuliette, E., 2017a. OSTM/Jason-2 Products Handbook, Technical Report. National Centers for Environmental Information, NOAA, USA.

Dumont, J., Rosmorduc, V., Carrere, L., Picot, N., Bronner, E., Couhert, A., Guillot, A., Desai, S., Bonekamp, H., Figa, J., Scharroo, R., Lillibridge, J., 2017b. Jason-3 Products Handbook, Technical Report. National Centers for Environmental Information, NOAA, USA.

Fu, L.-L., Christensen, E.J., Yamarone Jr., C.A., Lefebvre, M., Mnard, Y., Dorrer, M., Escudier, P., 1994. Topex/poseidon mission overview. J. Geophys. Res.: Oceans 99, 24369–24381.

Gao, H., Birkett, C., Lettenmaier, D.P., 2012. Global monitoring of large reservoir storage from satellite remote sensing. Water Resour. Res. 48.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017. Google earth engine: planetary-scale geospatial analysis for everyone. Remote Sens. Environ. 202, 18–27 (Big Remotely Sensed Data: tools, applications and experiences).

Guo, H., Bao, A., Liu, T., Ndayisaba, F., He, D., Kurban, A., De Maeyer, P., 2017. Meteorological drought analysis in the lower mekong basin using satellite-based long-term chirps product. Sustainability 9.

Haritashya, U.K., Singh, P., Kumar, N., Singh, Y., 2006. Hydrological importance of an unusual hazard in a mountainous basin: flood and landslide. Hydrol. Process. 20, 3147–3154.

Hossain, A., Arifuzzaman Bhuiyan, M., 2016. Application of satellite radar altimeter data in operational flood forecasting of Bangladesh. In: Hossain, F. (Ed.), Earth Science Satellite Applications: Current and Future Prospects. Springer International Publishing, Cham, pp. 269–284.

Hossain, F., Srinivasan, M., Peterson, C., Andral, A., Beighley, E., Anderson, E., Amini, R., Birkett, C., Bjerklie, D., Blain, C.A., Cherchali, S., David, C.H., Doorn, B., Escurra, J., Fu, L.-L., Frans, C., Fulton, J., Gangopadhay, S., Ghosh, S., Gleason, C., Gosset, M., Hausman, J., Jacobs, G., Jones, J., Kaheil, Y., Laignel, B., Le Moigne, P., Li, L., Lefvre, F., Mason, R., Mehta, A., Mukherjee, A., Nguy-Robertson, A., Ricci, S., Paris, A., Pavelsky, T., Picot, N., Schumann, G., Shrestha, S., Le Traon, P.-Y., Trehubenko, E., 2017. Engaging the user community for advancing societal applications of the surface water ocean topography mission. Bull. Am. Meteorol. Soc. 98, ES285–ES290.

Huang, X., Xie, H., Zhang, G., Liang, T., 2013. A novel solution for outlier removal of icesat altimetry data: a case study in the yili watershed, China. Front. Earth Sci. 7, 217–226.

Huntington, T.G., 2006. Evidence for intensification of the global water cycle: review and synthesis. J. Hydrol. 319, 83–95.

Kim, D., Yu, H., Lee, H., Beighley, E., Durand, M., Alsdorf, D.E., Hwang, E., 2019. Ensemble learning regression for estimating river discharges using satellite altimetry data: Central Congo river as a test-bed. Remote Sens. Environ. 221, 741–755.

Kite, G., 2001. Modelling the mekong: hydrological simulation for environmental impact studies. J. Hydrol. 253, 1–13.

Kummu, M., Sarkkula, J., 2008. Impact of the mekong river flow alteration on the tonle sap flood pulse. Ambio 37, 185–192.

Lakshmi, V., Fayne, J., Bolten, J., 2018. A comparative study of available water in the major river basins of the world. J. Hydrol. 567, 510–532.

Lee, H., Shum, C.K., Yi, Y., Ibaraki, M., Kim, J.-W., Braun, A., Kuo, C.-Y., Lu, Z., 2009. Louisiana wetland water level monitoring using retracked topex/poseidon altimetry. Mar. Geodes. 32, 284–302.

Maswood, M., Hossain, F., 2016. Advancing river modelling in ungauged basins using satellite remote sensing: the case of the gangesbrahmaputrameghna basin. Int. J. River Basin Manag. 14, 103–117.

Michailovsky, C.I., McEnnis, S., Berry, P.A.M., Smith, R., Bauer-Gottwein, P., 2012. River monitoring from satellite radar altimetry in the zambezi river basin. Hydrol. Earth Syst. Sci. 16, 2181–2192.

Mohammed, I.N., Bolten, J.D., Srinivasan, R., Lakshmi, V., 2018a. Improved hydrological decision support system for the lower mekong river basin using satellite-based earth observations. Rem. Sens. 10.

Mohammed, I.N., Bolten, J.D., Srinivasan, R., Lakshmi, V., 2018b. Satellite observations and modeling to understand the lower mekong river basin streamflow variability. J. Hydrol. 564, 559–573.

Moriasi, D.N., Gitau, M.W., Pai, N., Daggupati, P., 2015. Hydrologic and water quality models: performance measures and evaluation criteria. Transactions of the ASABE 58, 1763–1785.

Nash, J., Sutcliffe, J., 1970. River flow forecasting through conceptual models part i a discussion of principles. J. Hydrol. 10, 282–290.

Nielsen, K., Stenseng, L., Andersen, O.B., Villadsen, H., Knudsen, P., 2015. Validation of cryosat-2 sar mode based lake levels. Remote Sens. Environ. 171, 162–170.

Okeowo, M.A., Lee, H., Hossain, F., Getirana, A., 2017. Automated generation of lakes and reservoirs water elevation changes from satellite radar altimetry. IEEE Journal of

Selected Topics in Applied Earth Observations and Remote Sensing 10, 3465–3481.
Pekel, J.-F., Cottam, A., Gorelick, N., Belward, A.S., 2016. High-resolution mapping of global surface water and its long-term changes. Nature 540, 418 EP.
Picot, N., Marechal, C., Couthert, A., Desai, S., Scharroo, R., Egido, A., 2018. Jason-3 Products Handbook, Technical Report. Office of Satellite and Product Operations, NOAA, USA.
Ricko, M., Carton, J.A., Birkett, C.M., Cretaux, J.-F., 2012. Intercomparison and validation of continental water level products derived from satellite radar altimetry. J. Appl. Remote Sens. 6, 6 6 – 24.
Schwatke, C., Dettmering, D., Bosch, W., Seitz, F., 2015. Dahiti an innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry. Hydrol. Earth Syst. Sci. 19, 4345–4364.
Sulistioadi, Y.B., Tseng, K.-H., Shum, C.K., Hidayat, H., Sumaryono, M., Suhardiman, A., Setiawan, F., Sunarso, S., 2015. Satellite radar altimetry for monitoring small rivers and lakes in Indonesia. Hydrol. Earth Syst. Sci. 19, 341–359.
Swain, N.R., Latu, K., Christensen, S.D., Jones, N.L., Nelson, E.J., Ames, D.P., Williams, G.P., 2015. A review of open source software solutions for developing water resources web applications. Environ. Model. Softw 67, 108–117.
Swain, N.R., Christensen, S.D., Snow, A.D., Dolder, H., Espinoza-Dvalos, G., Goharian, E., Jones, N.L., Nelson, E.J., Ames, D.P., Burian, S.J., 2016. A new open source platform for lowering the barrier for environmental web app development. Environ. Model. Softw 85, 11–26.
Tao, S., Fang, J., Zhao, X., Zhao, S., Shen, H., Hu, H., Tang, Z., Wang, Z., Guo, Q., 2015. Rapid loss of lakes on the Mongolian plateau. Proc. Natl. Acad. Sci. Unit. States Am. 112, 2281–2286.
Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. Science 289, 284–288.
Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R., Davies, P.M., 2010. Global threats to human water security and river biodiversity. Nature 467, 555 EP.