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REMOTE SENSING OF RIVER DISCHARGES – THE CASE OF THE RIONI CATCHMENT

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ABSTRACT

Discharge is a critical parameter *in situ* to calibrate and validate water quantity and quality in rivers flowing into marine environments. Hydrological modelling is a key instrument to complete the quantitative assessment of river catchment ecology and to enumerate the impacts of pollution loads into the sea. Nutrient loads from river catchments are of particular importance for enclosed marine environments such as the Black Sea.

Open-source tools and instruments, promoted for use within several European-supported projects (such as FP7 enviroGRIDS, IASON, and H2020 DOORS),[1] were applied to data-scarce regions around the Black Sea. To mitigate issues with unavailable or low-quality discharge data, determination through satellite remote sensing for the case of the Rioni River is reported in this communication as a proving ground for this novel approach.

In particular, the open-source Soil and Water Assessment Tool (SWAT, ArcSWAT, Arnold et al., 1998) was employed to set up the hydrological model for the Rioni River Basin. Global 30 m resolution land cover, 30 m Global DEM, and FAO soils cover data (complemented with the national soils at 1:500,000 scale), combined with globally available climate datasets in ArcSWAT input format, were applied to set up and run the hydrological model for the Rioni Catchment. Weak quality (and lack of public availability) of hydrological discharge measurements did not allow the calibration and validation of the water quantity model.

To compensate for the lack of quality in *in situ* discharge data, a conceptual validation was performed to apply remote sensing to address the scarcity of discharge data. Due to a satisfactory visual fit of the *in situ* measured and microwave satellite observation data, it was speculated that, instead of the use of a global hydrological model to derive absolute values for river discharge time series from satellite observations, one could combine microwave satellite data (available in relative values; Brakenridge *et al*., 2012) with absolute figures obtained via the 'at-many-stations hydraulic geometry' (AMHG) river-width-based methodology, described in the literature (Gleason and Smith, 2014), in order to recalculate relative values of satellite measurement time series into absolute values for river discharges. It was demonstrated that the high-resolution instruments of the European Sentinel satellite series would allow for the measurement of the required parameters for wide rivers such as the Rioni, thus sensing discharge data remotely, supporting calibration and validation of the hydrological model set-up. This may contribute to resolving environmental governance challenges of river discharge and nutrient loads data availability in the Black Sea Basin.

Keywords: discharge remote sensing, river basin, catchment hydrology, Black Sea.

INTRODUCTION

Need for Catchment Water Quantification in the Black Sea Basin

The Black Sea[2] is an inland sea located between Europe and Asia. The Black Sea system is composed of the central Black Sea Basin and the Sea of Azov. Bulgaria, Georgia,

[1] http://envirogrids.net, http://iason-fp7.eu and https://doorsblacksea.eu.

[2] Main sources for this and next subsections are (Oguz et al., 2008) and (Conides and Papaconstantinou, 2006), as compiled in (Gugushvili *et al*., 2016).

Romania, the Russian Federation, Türkiye, and Ukraine share the Black Sea coastline. The most important rivers that flow into the Black Sea are the Danube and the Dnieper; the Don River flows into the Sea of Azov.

The Ecological Challenge

The Black Sea system is geographically isolated from the open sea, and therefore coastal pollution and outflow from the rivers into the basin are the main driving forces for the environmental quality of the basin and the effects on the resources. Almost a third of the total land area of the European continent drains into the Black Sea through major rivers such as the Danube (2,850 km), Dnieper (2,285 km), and Don (1,969 km) (Fig. 1).

Fig. 1. Catchment area of the Black Sea (http://envirogrids.net)

The Black Sea is nearly landlocked: its only connection to the world's oceans is through the narrow Bosporus. Thus, it takes nature hundreds of years to replenish the Black Sea's bottom waters with fresh seawater. Due in large part to natural conditions, over 90% of the Black Sea is devoid of oxygen. Once-rich biological diversity of the Black Sea has declined dramatically in the past 80 years. Significant nutrient inputs from agriculture, untreated sewage, and other sources have fuelled algal blooms that rob the water of oxygen as plants decompose. Increasing nutrient loads into the Black Sea have created a long-term change in nitrogen and phosphorus concentrations. Nutrients are manifested in the bio-optical 'colour' of the Black Sea observed from satellite sources (Fig. 2).

Significant part of the Black Sea is eutrophic (Mee, 1992). Eutrophication is especially apparent in the north-western shelf area because of the heavy anthropogenic nutrient load carried by the rivers. The indications of eutrophication in the Black and Azov Seas include:

- increased algal blooms.
- gradual basin-wide Secchi disc depth reduction.
- losses of shallow water macrophytes.

- widespread reduction in dissolved oxygen concentrations.
- occasional formation of anoxic benthic layers, distinct from anoxic main basin.
- changes in the food chain.
- severe reductions in fish stocks.

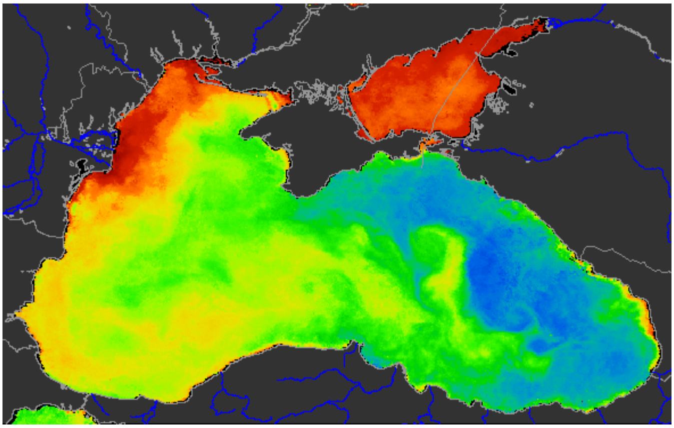


Fig. 2. Typical summer bio-optical remote sensing 'colour' of the Black Sea[3]

The Governance Challenge

The Black Sea is an international water body bordered by six countries. In 1992, the Black Sea countries (Bulgaria, Georgia, Romania, the Russian Federation, Türkiye, and Ukraine) developed the Convention on the Protection of the Black Sea Against Pollution (Bucharest Convention), ratified by all six countries. The Bucharest Convention consists of the framework treaty and four protocols, including the Protocol on the Protection of the Marine Environment of the Black Sea from Land-Based Sources and Activities. The four priority transboundary problems for the Black Sea ecosystem, re-confirmed by the Black Sea Transboundary Diagnostic Analysis (Black Sea Commission, 2007) and by the Strategic Action Plan for the Environmental Protection and Rehabilitation of the Black Sea (Black Sea Commission, 2009), are:

1) Eutrophication and nutrient enrichment.
2) Changes in marine living resources.
3) Chemical pollution (including oil).
4) Biodiversity and habitat changes, including alien species introduction.

As reemphasised in the latest State of the Environment Report of the Black Sea Commission (Oguz *et al*., 2008), the Black Sea ecosystem has been seriously damaged because of large amounts of nutrients carried by the rivers into the sea, leading to a high level of eutrophication. These processes are especially intensive at the north-west coast of the sea, although some eutrophication is evident in coastal waters of the eastern basin as well (Fig. 2).

Eutrophication and nutrient enrichment, perhaps the most challenging problems of the Black Sea Basin, are impossible to address or manage without taking

[3] See detailed treatment on remote sensing of the Black Sea in (Barale and Jaquet, 2006).

quantitative account of water quantity and quality discharging into the basin from its vast catchment. Among efforts applied to quantify nutrient loads into the Black Sea, the most advanced was the European FP7 enviroGRIDS project, which attempted to calibrate and validate a hydrological model for the entire Black Sea catchment area of over 2 million km², covering entirely or partially 23 countries. As documented in the final outputs of this large cooperative project, sharing and/or availability of data to model hydrology – primarily water discharge time series, due to the *in situ* nature of this data – remains the main challenge. One of the key final recommendations of the enviroGRIDS project, with significant policy and economic implications, is to apply model outputs, such as SWAT, to define international targets for controlling diffuse nutrient pollution loads entering the Black Sea (Lehmann *et al*., 2013).

Within the context of this governance challenge (insufficient access to critical water quantity data), as discussed further below, most other datasets required for hydrological model set-up and calibration could, in principle, be obtained from various global sources. Even if all the necessary data is not made available from national sources, the daily discharge time series would remain the major challenge to be addressed in order to introduce a system of equitable quotas for the allocation and management of nutrient loads, shared between coastal and non-coastal countries of the Black Sea Catchment. In addition to data-sharing sensitivities, some countries may have limited or lack entirely the needed quality of historic discharge time series records. An ability to estimate time series discharge data from remote sensing sources would be a paradigm shift in addressing this technical environmental governance challenge of the Black Sea Basin.

The availability and quality of discharge data needed to calibrate the catchment hydrology of the River Rioni Basin are documented elsewhere.[4] It is therefore selected as a test case for the application of discharge remote sensing. This attempt seeks to derive near-daily time series with the assumption that, if successful, similar calculations can be extended to any comparable river basins around the Black Sea, and elsewhere.

MATERIALS AND METHODS

Location of the Rioni River Basin within the Black Sea Catchment of Georgia

The length of the Black Sea coastline of Georgia is 315 km. The territorial waters comprise 6,785 km². The main rivers draining into the Georgian section of the Black Sea are the Chorokhi, Rioni, and Enguri. The Rioni River (Fig. 3) is the largest in Western Georgia, with a length of approximately 330 km and a catchment area of 13,400 km².

Tributaries of the Rioni flow from mountainous areas. The northerly tributaries, Lukhumi, Tskhenistskali, and Tekhuri, drain from the southern slopes of the Greater Caucasus Range, while the southerly tributaries, Kvirila, Dzirula, and Khanistskali, have their sources in the Lesser Caucasus Range. Glaciers also contribute, with over 2 million cubic meters of ice estimated to be in the mountainous regions of the Rioni watershed.

Downstream of Kutaisi, the largest town in the river basin with 125,000 inhabitants (located some 170 km from the source), the river flows onto the Kolkheti

[4] See Rioni River Basin Case Study chapter in (Bektas Balcik et al., 2012).

Lowland and enters the Black Sea near the port city of Poti (population – 40,000). The population of the entire basin is estimated to exceed 500,000.

River flow regimes are controlled by a series of reservoirs located both upstream and downstream of Kutaisi, with several existing and many planned hydropower schemes. In the lower reaches, along the Kolkheti Lowland, the river is mostly diked with 3–5 m high soil berms.

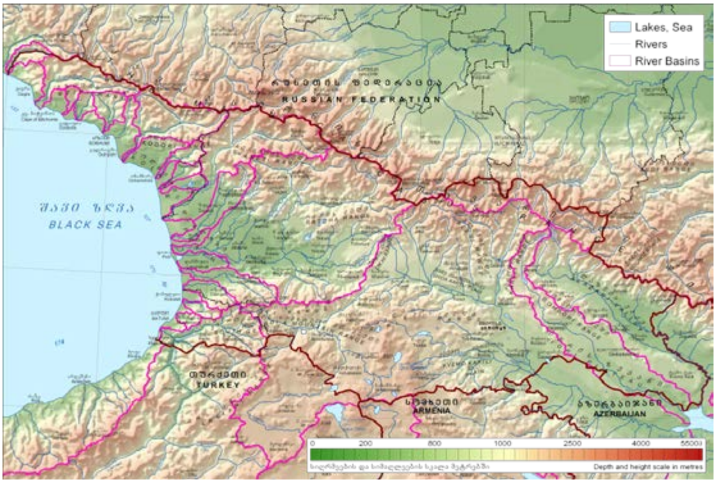


Fig. 3. Location of the Rioni River Basin within the Black Sea Catchment of Georgia

Major flooding events have been recorded every 40–50 years, while relatively small floods are a usual phenomenon and occur every 4–5 years. Deforestation and inappropriate agricultural practices within the catchment are also a source of concern, leading to slope instabilities, soil erosion, and excessive discharges of sediments and pollutants into the Black Sea.

The catchment of the Rioni River is proposed as a test case study for modelling the specific hydrological phenomena occurring in this watershed, due to its similarity to essential issues relevant to the vast Black Sea Catchment. Additional reasons why the catchment should be considered as a test case are:

- Despite its relatively small size, the Rioni Basin topography mimics the hydrological processes of much larger catchments and rivers elsewhere in the Black Sea Catchment. The Rioni Basin flows from high mountainous, glacial-fed areas, and continues with precipitation-fed flows on the lowland prior to joining the sea. The river and catchment processes strongly change character from mountainous areas into the coastal lowland. It is worth mentioning that the edge of the Rioni catchment touches the easternmost boundary of the Black Sea Catchment.

- The rivers in the Western Caucasus are characterized by high sediment loads, which merit specific investigation in terms of the impact on coastal zones and the sea. This is an opportunity to couple remote sensing data on coastal changes with catchment data on land use, soil, vegetation, and hydrology (including glacier mass balance and sediment transport).

- A series of hydropower projects are planned or ongoing both on the Rioni and in its basin, which would drastically alter the hydrology of the entire catchment, making the need for the development of river basin management policies and tools ever more urgent.
- Due to the relatively small area compared to the Black Sea Catchment, the application of remote sensing instruments and testing the sensitivity of hydrological modelling with regard to data from various sensors could be performed before extending the coverage.
- Deforestation and other types of land cover/use changes are apparent in the watershed, and these processes could potentially be detected with remote sensing and coupled with sediment and nutrient loads through hydrological modelling.
- Historic pollution, hydrological, and climate data of variable quality are mostly available (though sharing is an issue), while precipitation and meteorological data collection is available and has recently improved.
- The Rioni, in its downstream reach, is hosting the Global Site 2059 (Area 2050, Rioni, Georgia), depicted in Fig. 7, the only globally monitored site in western Georgia draining to the Black Sea.

The objective of the case analysis is to test the hypothesis of remote sensing estimation of near-daily discharge time series and assess how adequate such data would be for calibration of hydrological models, available under the Black Sea Catchment Observation System (BSC-OS) at http://portal.envirogrids.net. Of particular utility would be the coupling of watershed and coastal processes and issues (Lehmann *et al*., 2009).

Data Sources

The keynote theme for the enviroGRIDS project was how to apply GRID-enabled spatial data infrastructure hydrological modelling to the large Black Sea Catchment and its main sub-catchments. SWAT hydrological model data requirements were kept in mind when developing data specifications for the test case. For a detailed presentation of the SWAT data input/output needs, a reference is made to EnviroGRIDS Deliverable 4.11, Section 4 (Abbaspour and E. Rouholahnejad, 2013). Required datasets need to be identified at the global level (*ex situ*, e.g. through remote sensing), as well as from national sources (*in situ* data such as hydrology, pollution, etc.). Both types of resources are specified below, taking into account applications at the Black Sea Catchment level, as well as for the Rioni and other potential sub-catchment case study sites.

Global Data

The various types of remote sensing data available from global sources can be extracted to run hydrological simulations at case study sites or even for the entire Black Sea Catchment. SWAT data needs can be satisfied with various datasets, as discussed in (Milewski et al., 2009, see also K. Allenbach et al., 2009). Of particular utility is the Tropical Rainfall Monitoring Mission (TRMM) precipitation data.

TRMM (NASA and JAXA) provides global data on rainfall for tropical regions (50°N–50°S) using radar, microwave, and visible-infrared sensors. The spatial and temporal resolution of rainfall estimates is 3 hours and 0.25° × 0.25°. This observation system was launched in 1997 and has provided continuous coverage since 1998. TRMM 3B42.v6 products, with 1998–present and global spatial coverage, can be downloaded from https://daac.gsfc.nasa.gov.

TRMM can be accessed and downloaded through TOVAS (TRMM Online Visualization and Analysis System, https://disc.gsfc.nasa.gov/precipitation/tovas). Certain straightforward pre-processing steps are required to generate location-bound time series in the format required for SWAT input, i.e. as an ASCII file prefixed with the start date and continuing with a precipitation series in mm/day for as many points as determined by the time interval. Fig. 4a depicts the TRMM precipitation time series grid points falling within the Rioni Basin.

Global climate data in ArcSWAT format can also be sourced from http://globalweather.tamu.edu .

The following datasets can also be used to define the land-related part of the ArcSWAT input:

- GlobCover land classification (layer based on 300 m resolution Envisat MERIS).
- Land cover resolution can be improved with 30 m data available for 2000 and 2010 (Chen, 2015), even 10 m with annual global coverage for year 2020 and beyond.[5]
- Food and Agriculture Organization (FAO) global soil cover.
- SRTM (90 m) was used as the DEM grid.

National Data

The *in situ* data resources available for hydrological modelling included the following tabular time series datasets (source: National Environmental Agency of Georgia).

Hydrology: daily discharge time series for Alpana (1996–2009) and Namokhvani (1996–2005) hydrological stations, as well as monthly multi-year average data for Chaladidi (1990–1993, 1995–1998, 2008–2009).

Meteorology: 3-hour meteorological data for Oni (1998–2000), Kutaisi (1998–2009), and Poti (1998–2009).

Soils: national map at scale 1:500,000 (Urushadze, 1999), available in geospatial format as well.[6] Fig. 4b depicts operational hydrology and meteorological stations within the Rioni Basin.

SWAT Modelling

R Project statistical computing codes, developed by Rahman, K.,[7] were used to run SWAT, as well as MATLAB code to calibrate the hydrological model. Both were utilized to calibrate simulated discharge against measured discharge time series.

[5] https://land.copernicus.eu/en/products/global-dynamic-land-cover/land-cover-2020-raster-10-m-global-annual.
[6] https://sustainable-caucasus.unepgrid.ch/catalogue/#/dataset/38.
[7] http://nil-pipraen.blogspot.com/p/codes.html

Global sources of data mainly were used for the set-up, run, and calibration of the model. Simulation results for the Rioni River are reproduced below (Fig. 5).

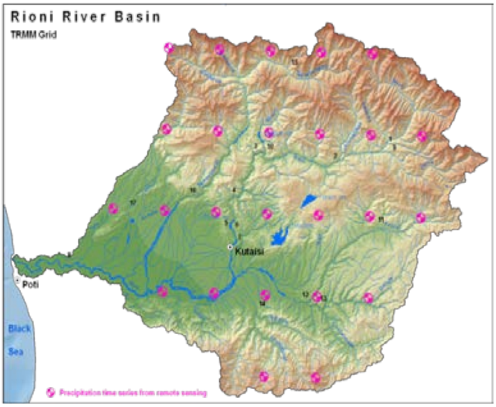


Fig. 4a. TRMM precipitation time series 0.25° × 0.25° grid points falling within Rioni Basin

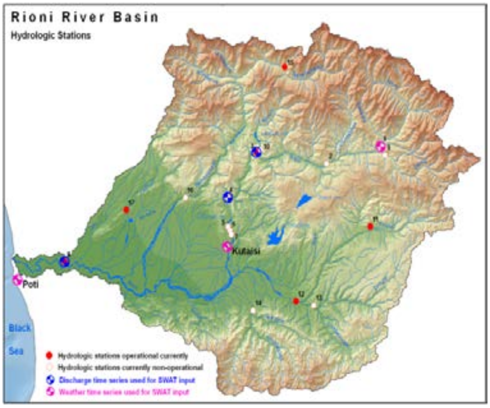


Fig. 4b Hydrological and meteorological stations in the Rioni Basin

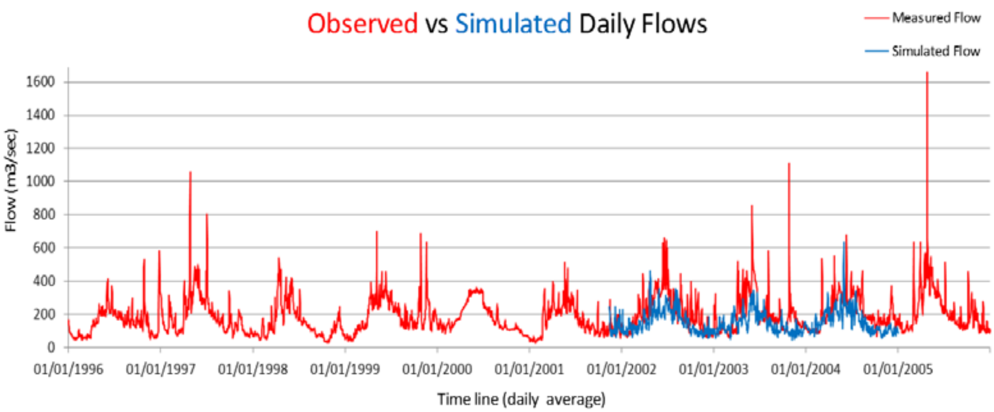


Fig. 5. Observed versus SWAT-simulated daily flow for the Rioni River (calibration period). Red line represents measured discharge, and the blue line represents the SWAT model output

Despite numerous assumptions and approximations made – such as the lack of detailed local data and the use of global sources of input data (rainfall in particular) – a visual check of the results shown in Fig. 5 is surprisingly positive. However, satisfactory statistical values, such as Nash–Sutcliffe Efficiency (NSE) could not be achieved, most likely due to issues with the quality of discharge measurements and river depth-to-flow rating curve approximations.

The latter aspect again raises the issue of the availability and quality of critical *in situ* data, such as daily discharge time series, warranting the exploration of the possibility and feasibility of estimating river discharges through remote sensing.

RESULTS AND DISCUSSION

Recent Advances in River Discharge Remote Sensing

Several methodologies have been proposed in recent years in the field of remote sensing to estimate river discharge values with various spatial and temporal variabilities. For the purposes of this communication, two such approaches are briefly characterised in this subsection. The first approach involves applying microwave radar measurements to estimate, in relative values, near-daily flow rates of major rivers globally, while the second approach involves applying a new hydrological paradigm to estimate near-monthly discharges in absolute values through calculations based on river width time series at specific locations, obtained through remote sensing measurements.

Microwave

In (Brakenridge *et al*., 2012), and in a series of previous works by these authors, it was demonstrated that orbital passive microwave instruments (such as AMSR-E[8] – out of operation since 2011 – and TMI[9]) have the capability to measure river discharge variation (in relative values) on a daily basis. The orbital passive microwave data that directly monitors discharge can be coupled with the global hydrology model (WBM)-based 'rating curves'. This allows for the needed gauging of the remote sensing signal into river discharge units (m³/s). The authors developed an algorithm to automatically calibrate discharge units to microwave remote sensing over thousands of river measurement sites. The microwave brightness temperature satellite image sites measured are ~10 km single-pixel square river reaches, generating daily updated, 4-day forward running mean water/no-water signals per each pixel. At river measurement sites where optical remote sensing detects surface water area variation within the site reaches (10 km in length), near-daily time series of passive microwave signals have been obtained and archived for each site since July 1, 2002, and are available as Global Flood Detection System (GFDS) sites at the Global Disaster Alert and Coordination System portal at http://www.gdacs.org/flooddetection.

AMHG

In (Gleason and Smith, 2014) and (Gleason *et al*., 2014), it is shown that estimates of absolute river discharge (in m³/s units) may be derived solely from satellite images, with no need for ground-based or *a priori* information. The approach is based on the discovery of a scaling law unique to natural rivers, termed by the authors as At-Many-Stations Hydraulic Geometry (AMHG). AMHG effectively halves the number of parameters required by traditional river hydraulic geometry, thus paving the way for remote estimation of a single remaining parameter – and thus river discharge – through repeated satellite image observations along a river course, measuring its width (detectable through remote sensing), rather than depth (generally not detectable from remote observations). A demonstration based solely on repeated Landsat TM satellite measurements of varying instantaneous river flow widths over geographic space and

[8] Advanced Microwave Scanning Radiometer for EOS, see https://aqua.nasa.gov/amsr-e.

[9] TRMM Microwave Imager (TMI), see https://gpm.nasa.gov/missions/TRMM/satellite/TMI.

time yielded absolute discharges agreeing to within around 20–30% of traditional *in situ* gauging station measurements. This breakthrough opens up opportunities for quantifying river resources globally through repeat imaging, both retrospectively and prospectively, without relying on expensive and cumbersome ground-based information, such as gauge measurements, bathymetric surveys, and/or calibrated hydrology models. Time-wise updates are limited to the bi-monthly interval of cloud-free Landsat scene observations.

Conceptual Validation Scenario for Remote Discharge Estimation

The two discharge estimation methodologies described above have certain limitations. Microwave time series measurements from space produce results in relative values, and calibrated models are required to obtain results in absolute values, implying the availability of some ground-based data. AMHG, on the other hand, can estimate discharge in absolute values, but bi-monthly observation rates make the repeat interval too coarse for application in hydrological model calibration, where near-daily time series are much more desirable.

Fig. 6 below illustrates successful fitting of microwave measurements with the *in situ* discharge data for the Rioni River case (Gvilava, 2016). The results are strikingly similar to the results of the calibration of the hydrological model as demonstrated in Fig. 5 above. This leads to the formulation of the hypothesis regarding the usability of microwave-derived time series for actual calibration, provided that the time series can be converted into absolute values by combining the approaches proposed in the two methodologies described above.

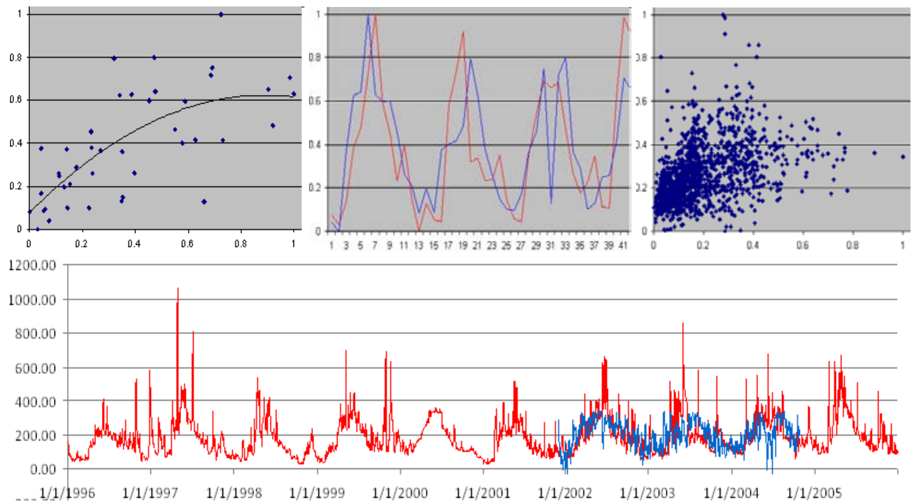


Fig. 6. Visual exploratory calibration of Rioni River discharge using GFDS passive microwave data. The satellite-derived relative flow index (blue line) has been scaled to match the magnitude of observed discharge (red line), showing good agreement in timing and pattern

Based on the positive outcome of the visual exploratory calibration (manual fit) demonstrated above, a conceptual validation scenario was proposed to explore the feasibility of discharge remote sensing using the Rioni case as an example.
This could be achieved by gauging microwave-derived relative value data, acquired through the web portal http://www.gdacs.org/flooddetection, using the AMHG methodology to convert microwave data into absolute discharge values, without resorting to a global hydrology model or any ground-based data in producing rating curves. This hypothesis is explained and put to the test in the following subsection for the GFDS site at the Rioni (Fig. 7).[10]

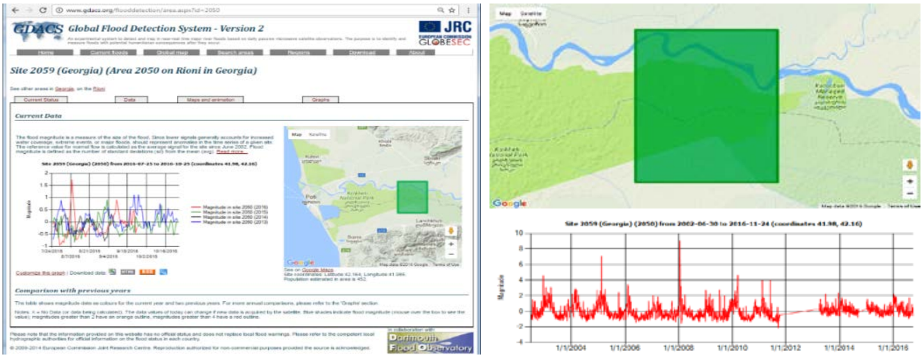


Fig. 7. AMHG test case area – Global Flood Detection System (GFDS) Site 2059 (Area 2050) on the Rioni River, Georgia. The images show the 10 km river reach (green outline) used for both microwave monitoring time series (red line) and Sentinel-1 width measurements *(source: GDACS Flood Detection System portal http://www.gdacs.org/flooddetection)*

Applying Sentinel for Discharge Remote Sensing

Due to a satisfactory visual fit of the *in situ* measured and microwave satellite observation data, it is speculated that, instead of using a global hydrological model to derive absolute values for river discharge time series from satellite observations, one could combine microwave satellite data (available in relative values) with absolute figures obtained via the at-many-stations hydraulic geometry river-width-based methodology, as described in Gleason and Smith (2014), in order to recalculate relative values of satellite measurement time series into absolute values for daily discharges.

As microwave data has a sufficient timespan for hydrological model calibration (at least 10 years of daily time series data is usually required), it does not seem necessary to resort solely to 30 m resolution Landsat data. Therefore, the most recent Sentinel-1A and -1B Synthetic Aperture Radar (SAR) sensors,[11] available in various resolutions – such as ~20 m, as applied in this work – are expected to allow for the required river width measurements and AMHG calculations. Other advantages of using SAR include its inherent cloud-free capability, availability in 6-day repeat intervals (Sentinel-1A and -1B, when the latter was operational), and its ability to produce

[10] http://www.gdacs.org/flooddetection/area.aspx?id=2050
[11] https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar

water/no-water masks with relatively straightforward processing, as characterized below.

The methodology for Sentinel-1 SAR image processing follows the one described at the UN-SPIDER Knowledge Portal, [12] which contains step-by-step instructions on applying the ESA SNAP tool.[13] Therefore, workflow steps are only listed below, with typical results illustrated in Fig. 8:

- Downloading, importing, and subsetting Sentinel-1 GRD HR product (~20 m).
- Radiometric Calibration.
- Speckle Filtering.
- Binarisation math processing to derive water/no-water image.
- Geometric Terrain Correction.
- Exporting to GeoTIFF for visualisation and further processing.

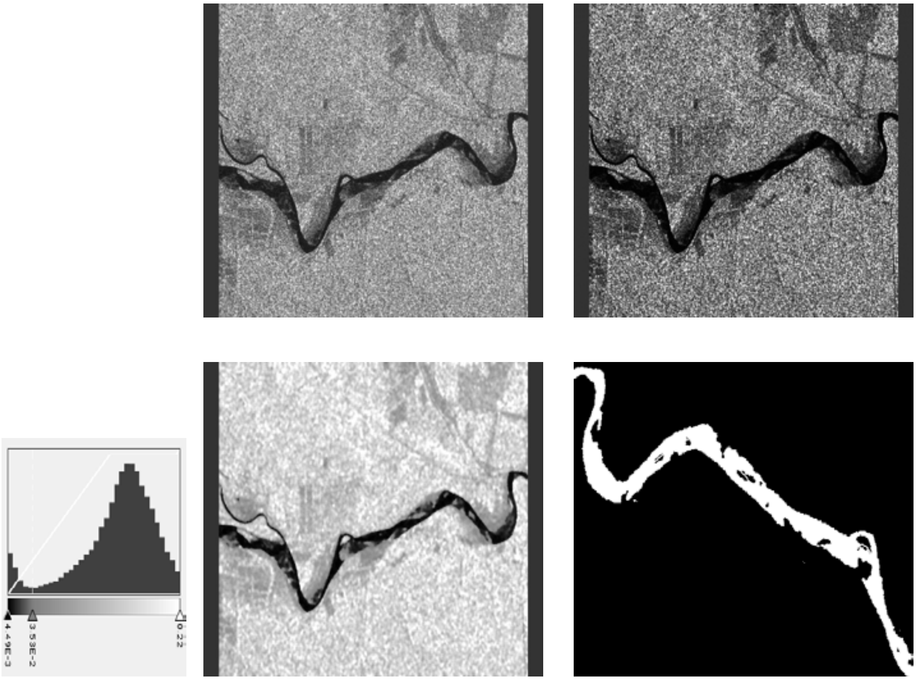


Fig. 8. Illustration of Sentinel-1 SAR image processing workflow and typical end results

The subsequent processing included the following steps and specific calculations performed under each step:

- River width measurements using Geographic Information System software (ArcGIS):

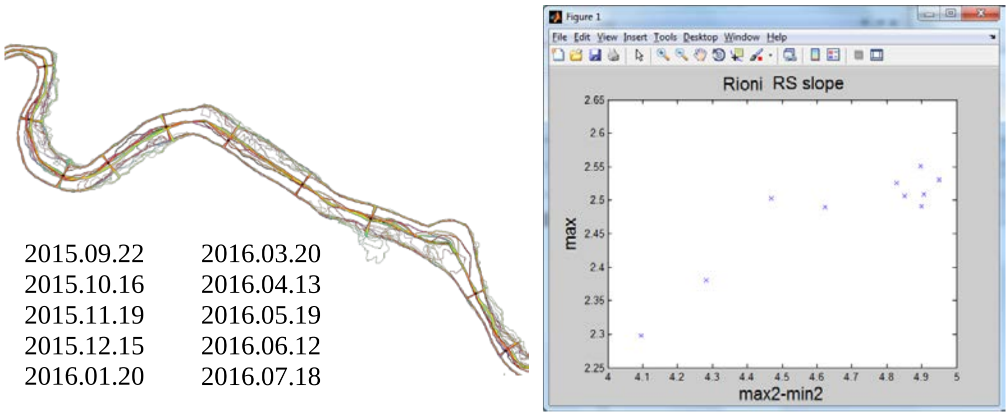
- SAR imagery, imported and subsetted to the Rioni case site (within a bounding box of 42.23 north, 41.94 west, 42.16 south, and 42.03 east), was processed into projected water/no-water images for 12-time instances, covering the period from

[12] http://www.un-spider.org/advisory-support/recommended-practices/recommended-practice-flood-mapping/step-by-step
[13] http://step.esa.int/main/toolboxes/snap

September 2015 to September 2016, with an average monthly interval between imagery dates. A 10-km stretch of the Rioni Global GFDS Site 2050 area was selected, and 10 cross-section points were defined at approximately 1 km intervals to measure river widths within ArcGIS for each of the 12 images, with monthly intervals between image timestamps. Each timestamp of the SAR image dates is listed, and the 12 water/no-water contours are all shown overlaid in Fig. 9, together with the 10 cross-sections used for width measurements for each of the 12 river contours applied in the AMHG calculations.

AMHG processing to estimate river discharges in absolute values at respective dates:

MATLAB source code (Gleason, personal communication), provided by the main author of the AMHG methodology (Gleason *et al.*, 2014), was applied to calculate river discharge values for each of the image timestamps. The AMHG log-linear slope chart, produced by the software code, is also reproduced in Fig. 9, with the consistent linear pattern indicating the applicability of the AMHG algorithm. In addition to the RS slope chart, the algorithm code calculated river discharge estimates for each input Landsat scene timestamp.



$$Max\,(w_{x1;x2;\ldots;xn}) = p\,Max\,(w_{x1;x2;\ldots;xn}{}^2 - Min\,w_{x1;x2;\ldots;xn}{}^2)^y$$

Fig. 9. River width measurement and AMHG discharge computation for the Rioni. (Left) Locations of 10 cross-sections along the ~10 km study reach, overlaid on all 12 extracted water masks from Sep 2015–Sep 2016. (Right) Log–linear plot of the AMHG relationship derived from the width measurements, showing a consistent linear fit (indicating the applicability of the AMHG method)

- Derivation of the rating curve using AMHG-estimated and downloaded microwave data:

Microwave data was downloaded from the GDACS web portal for the one-year period starting on September 1, 2016. One year of daily microwave data was coupled with 12 AMHG-estimated discharge values, and through straightforward data scatter and linear fit analysis using Microsoft Excel, a linear 'rating curve' formula was derived (in a manner similar to Brakenridge *et al*., 2012, but this time without resorting to a global hydrology model), which is provided on the left part of Fig. 10.

- Application of the rating curve to microware daily time series data:

In order to convert relative values of daily microwave data into an absolute river discharge hydrograph, the rating curve derived in the previous step was applied to the entire daily time series of the respective time interval. The main result of the paper is depicted on the right side of Fig. 10 (thin blue lines), overlaid with the AMHG discharge estimate data used for the 'rating curve' production (thick red lines).

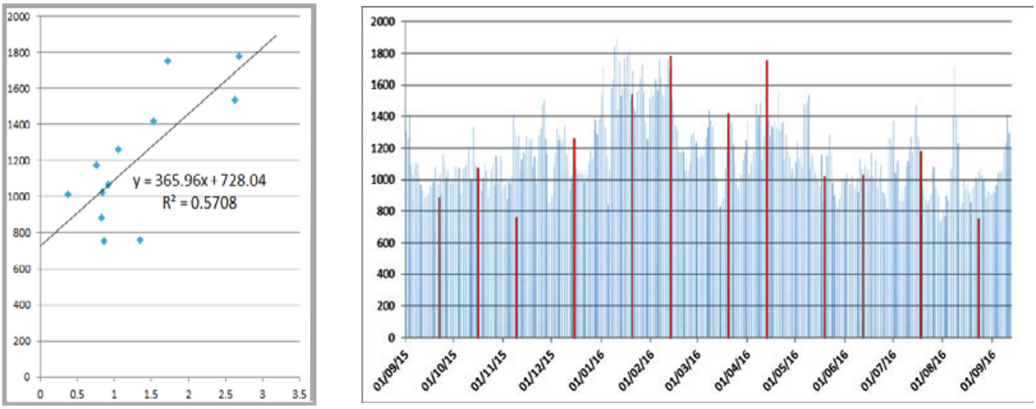


Fig. 10. Rating curve calibration and remote-sensed discharge hydrograph for the Rioni River. (Left) Thick points show the discharge values obtained from AMHG (from Fig. 9) plotted against the GFDS microwave index for the matching dates; the fitted line is the rating curve used for calibration. (Right) Thin blue lines show the resulting continuous daily discharge estimate for Sep 2015–Sep 2016 after applying the rating curve (visualised with thick red lines) to the entire microwave time series. (*Note:* R^2 = 0.5708 on left figure quantifies the rating-curve regression between AMHG discharge snapshots and the GFDS microwave index (n = 12). It does **not** represent overall hydrograph accuracy or SWAT model performance.)

A linear regression between AMHG-derived discharges and the coincident GFDS microwave index (n = 12) yielded R^2 = 0.57, indicating a moderate linear relationship sufficient to calibrate the relative microwave signal into discharge units. Given the heterogeneous error sources (SAR width extraction, AMHG assumptions, microwave footprint effects), this level of fit is consistent with expectations for mixed-sensor calibration and supports applying the rating curve to reconstruct daily flows.

To integrate the various components of this study, a step-by-step workflow was developed. Fig. 11 illustrates the overall methodology, beginning with the acquisition of satellite data and ending with the production of a continuous discharge time series. Data from two remote sensing sources – (1) passive microwave daily signals and (2) high-resolution Sentinel-1 SAR images – are first gathered for the river of interest.

These datasets undergo preprocessing (using tools such as ESA SNAP for SAR and GIS for spatial analysis) to derive useful measures: notably, the river's width at selected cross-sections from each SAR scene. Next, an AMHG discharge estimation is performed on the width data to yield a set of absolute discharge values on the dates of SAR observations.

In parallel, the passive microwave time series (which reflects relative changes in river flow) is analysed. A rating curve derivation step then uses the SAR/AMHG-derived discharge snapshots to calibrate the microwave relative values into actual discharge units. Finally, this calibration is applied to the full microwave record to compute a daily discharge estimation over the entire period of interest.

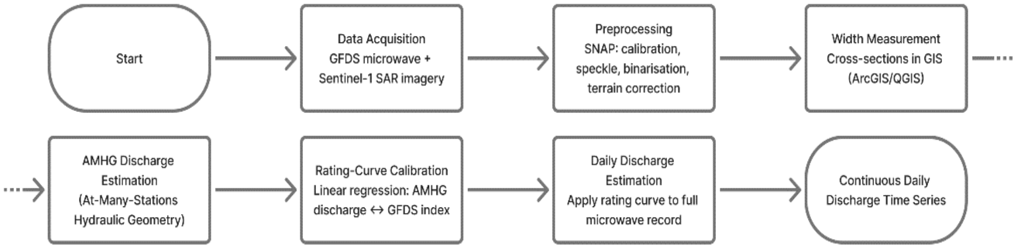


Fig. 11. Workflow of the methodology for remote sensing-based river discharge estimation.

The above results highlight both the challenges and opportunities in river discharge estimation for data-scarce regions. The SWAT model calibration for the Rioni, based largely on globally available inputs, achieved only limited success. Despite numerous modelling assumptions and approximations – such as using coarse-resolution rainfall data – the visual agreement between simulated and observed flows was encouraging, but truly satisfactory statistical performance (e.g., a high NSE) could not be reached. This is most likely due to issues with input data quality and with the observed discharge records themselves, as discussed. In essence, if the foundational data (precipitation, gauge flows) are unreliable, even a well-structured hydrological model will struggle to calibrate. This underscores a broader point: the availability and quality of in situ data (particularly continuous discharge time series) remain a bottleneck for hydrological analysis in many regions. Our findings in the Rioni case reaffirm the need for alternative approaches to obtain flow information when ground data are missing or suspect.

Remote sensing offers a promising path forward to address this need. In this study, we implemented a novel combination of two remote sensing techniques and demonstrated that it is possible to derive an absolute daily discharge time series using no ground measurements beyond basic river geometry acquired through remote sensing. The two methods we used are complementary: the passive microwave observations provide near-daily continuity but only relative flow variations, while the SAR-based width measurements (via the AMHG method) provide absolute flow magnitudes but at coarser time intervals. By merging these, we effectively leveraged the strengths of each – frequency and accuracy – to overcome their individual limitations. The conceptual validation scenario in the Rioni case was essentially a proof-of-concept of this merged approach. The success of that scenario suggests that similar strategies could be applied to other rivers where ground data are sparse. For instance, any river reach that has a known AMHG relationship (obtainable from even a few satellite images) and coincident passive microwave coverage (from sensors like AMSR-E/2, GPM, etc.) could, in theory, be "gauged" remotely in a comparable manner.

It is important to recognise the limitations of the approach as well. The AMHG method assumes a consistent scaling between river width and discharge, which may be affected by site-specific factors (riverbed changes, tributary inflows between image locations, etc.). Additionally, the passive microwave signal's reliability can be influenced by local conditions (e.g., river width relative to the sensor footprint, surrounding wetlands or floodplains that might also emit a water signal). In the Rioni application, we mitigated some issues by carefully choosing a straight 10 km reach for width measurement and using a microwave site focusing on the same reach. However, uncertainties in the derived discharge series remain – for example, the exact RMSE of the remote-sensed hydrograph relative to a true value is hard to quantify without an independent ground truth. We addressed this by using overlapping periods of observation (the year where we had both methods available) to ensure internal consistency of the remote estimate.

Notwithstanding these caveats, our study demonstrates a viable path for estimating river discharge in ungauged basins. The ability to extend the Rioni discharge series beyond the field measurement period (using remote data since 2002 in the GFDS archive) is particularly attractive. With ~10+ years of remotely sensed flow data, one could calibrate or validate hydrological models for the basin, achieving a task that was previously infeasible due to lack of ground data. Future work should explore this potential: for example, conducting a full calibration of a SWAT or similar model using the remote-sensing derived discharge time series, and comparing the performance (NSE, RMSE) to that of a conventional calibration. Such an exercise – perhaps including multiple basins – would help quantify how useful these remote discharge estimates are for operational hydrology. Moreover, additional improvements are on the horizon: the newly operational Surface Water and Ocean Topography (SWOT) mission, higher-resolution optical satellites, and cloud-computing platforms for image analysis all promise to enhance the accuracy and applicability of remote river discharge estimation.

In summary, the Rioni case study provides a proof-of-concept that merges two cutting-edge remote sensing approaches to derive river discharge information. The separation of signal sources – microwave for timing and SAR for magnitude – and their subsequent integration via a rating curve is a novel contribution of this work. We have shown that even in the absence of traditional gauge data, one can reasonably reconstruct a river's flow hydrograph. This approach can aid in filling data gaps for hydrological modelling and water resource management in regions where ground measurements are unavailable or withheld. With further validation and refinement, satellite-based discharge monitoring could become a valuable tool for river basin management, environmental protection (e.g. controlling nutrient loads to the Black Sea), and climate change adaptation in data-sparse regions.

CONCLUSIONS

The main result of this communication, demonstrated in Fig. 10 above, illustrates that remote sensing can indeed be considered for estimating river discharge time series, even on a daily time-step basis. In conclusion, certain advantages of the proposed approach are reiterated, together with some potential application areas. Additionally, suggestions for possible next steps and developments are provided:

- One advantage of the proposed method is that access to historical imagery is certainly desirable, but not a necessary condition for the generation of discharge time series in absolute values. Training and calibrating the microwave signal with a rating curve generated from one year of remote sensing data could produce a time series for a period of more than 10 years of microwave measurements (available since 2002). This means that calibrating the hydrological model would be feasible, as a 10-year daily time series is generally sufficient for this.

- The availability of historical 30 m resolution Landsat data and the gradual accumulation of cloud-free Sentinel-1A and Sentinel-1B SAR imagery – with even higher resolution and repetition (~20 m and ~6 days) – could gradually enhance the precision and temporal span of the rating curves.

- Cloud-free instances of 10 m and 20 m resolution Sentinel-2A and -2B optical imagery, with a revisit period of 5 days, can further contribute to the frequency of river width measurements, making it feasible to estimate river flow rates with almost the same frequency as microwave radar data.

- Hydrological time series measurements through remote sensing could be further supported and enhanced with the Surface Water and Topography (SWOT) instrument,[14] as demonstrated recently by Andreadis *et al*. (2025).

- The availability of even higher resolution small optical CubeSat data (such as those promoted by https://Planet.com, with global coverage, multispectral, daily revisit, and 3 m and 0.5 m resolution) may allow calibration of much smaller rivers and streams, going below the current limitations of river width measurements using 20–30 m medium resolution remotely sensed imagery.

- One of the following steps could be to test the usability of microwave comprehensively and AMHG-derived time series discharge *ex situ* data for calibration and validation of hydrological models (such as SWAT in the ArcSWAT extension environment), along with comparative statistical checks on Nash–Sutcliffe values, to assess the applicability of river discharge estimation through remote sensing in data-poor locations.

- Fascinating developments are feasible with cloud-based platforms for processing imagery at the pixel level through Analysis Ready Data (ARD), such as the Data Cube technology introduced by CEOS (https://www.opendatacube.org), and pilot implemented in Georgia with support from UNEP and GRID-Geneva (see Chatenoux and Allenbach, 2017 and http://geodatacube.unepgrid.ch). The 'Water Detection' algorithm provides a highly user-friendly environment for searching through all available Landsat scenes and for the straightforward production of water/no-water masks. The ARD cloud

[14] https://swot.jpl.nasa.gov/hydrology.htm

environment for data processing without image download creates an excellent development platform for remote sensing of river discharges, with full integration of all required data and tools in the same programming environment.

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