Integrating satellite data and discharge modelling for lifetime assessment of reservoirs due to sedimentation

Dr. Fabian von Trentini, Karin Schenk
EOMAP GmbH & Co KG
Schlosshof 4, 82229 Seefeld
Germany | eomap.com

Introduction
Reliable data on sediment fluxes and other hydrologically relevant data are usually rare and expensive to gather. Such data would help to reduce investment risks and operational costs of hydropower systems. Spatially and temporally highly resolved satellite data can nowadays significantly contribute with related measurements that otherwise would not be available. However, the uptake and integration of these comprehensive data into business relevant information for the hydropower industry so far was not an easy task for various reasons.
EOMAP's innovative HYPOS approach is catalyzing innovation with an operational service for appropriate environmental and economic investment planning and monitoring based on Earth Observation (EO) technologies and modelling for the hydropower industry. The developed online accessible decision support tool provides essential assets for hydro power managers, planners, and decision makers in their work. The subscription portal brings together high-quality satellite-based measurements for historic time periods, actual current monitoring, up-to-date modelled hydrological parameters, with nowcasting on various orderable levels of detail and available in-situ data for integrated baseline and environmental impact assessments. The service provides cost-efficient, independent, standardized, and consistent information over a wide range of different water bodies and spatial scales.
The portal features a visualization and analysis environment for various data sets in one place:

- Raster layers of satellite derived water quality parameters like turbidity
- Hydrological modelling data like discharge
- Any in-situ measurements from stations or sampling points (e.g. validation data of sediment concentrations or complementary data on water constituents, biodiversity etc.)
- A smart suite of dashboards and plots enables the user to efficiently retrieve relevant information from the raw data in various ways.

In this paper, an approach to combine different data sets for sediment flow estimation is applied for the Poechos reservoir in Peru and the Lagdo reservoir in Cameroon, which both experience sedimentation. The dynamics of the sedimentation is, however, not fully clear yet, despite several studies and bathymetry campaigns. The HYPOS approach is applied to the two reservoirs to estimate the mean annual sediment flow into the reservoirs and to quantify the interannual dynamics to sediment management strategies.

1. Context
The HYPOS solution is a commercially available service offered by EOMAP. It was mainly developed during the HYPOS project, funded by the European Union. Within the GDA (Global Development Assistance) Water Resources project, funded by the European Space Agency (ESA) in collaboration with the World Bank, it was applied to Poechos and Lagdo reservoirs to assess the added value for the World Bank team.

2. Data and methods
The sediment load for two reservoirs is assessed with a combination of satellite-derived turbidity and discharge from hydrological modelling. The general methodology includes two steps:

- The turbidity from satellite measurements is translated to suspended sediment concentrations (SSC) with different formulas (global/regional).
- Usually, high sediment loads occur during high flood days. The SSC values are therefore related with the discharge data from the same day to obtain a power regression law. With this regression, gaps in the SSC

measurements (via satellite-derived turbidity) can be filled and the much longer time series of discharge can be used to obtain long-term data of sediment loads.

This approach is applied to the Pochos reservoir in Peru and the Lagdo reservoir in Cameroon. The turbidity data is retrieved from both Sentinel-2 and Landsat 8/9 satellites with multispectral sensors in the optical and near infrared bandwidth. This results in almost 400 satellite images for Lagdo and over 500 images for Poechos over the years 2016-2023. These turbidity measurements are transformed into SSC values with a simple 1:1 relationship and regional formulas of higher complexity. The discharge is taken from two different hydrological model setups. For Lagdo, the global model World-wide HYPE of the Swedish Meteorological and Hydrological Institute (SMHI) is applied for the years 1981-2020, while for Poechos a combination of the conceptual rainfall-runoff (ARNO/VIC) model and a river-routing (RAPID) model is available from 1981 to 2022 (Llauca et al. 2023).

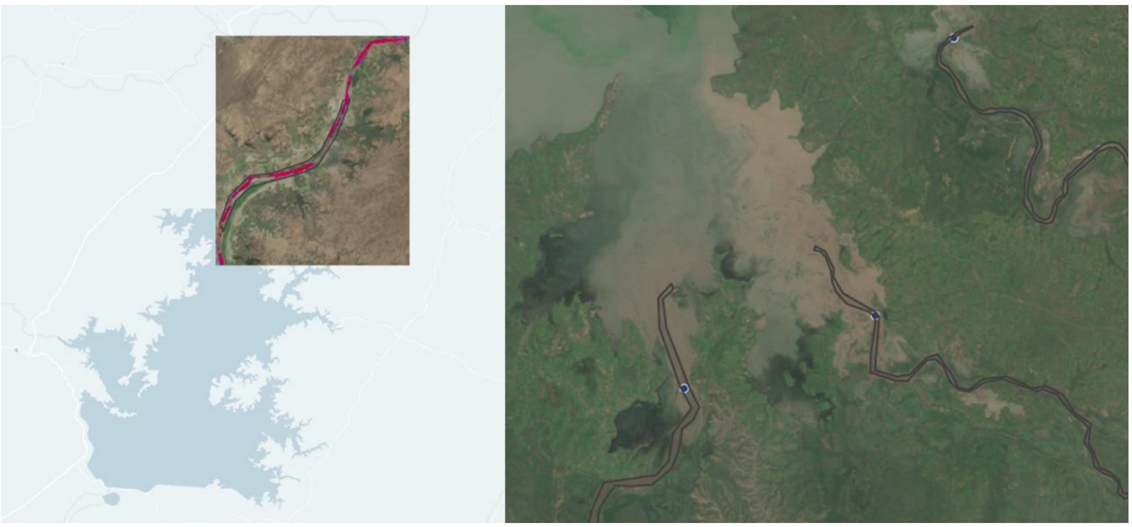

Figure 1: Turbidity retrieval for the Chira river just upstream of the Pochoes reservoir (left) and the three tributaries of the Lagdo reservoir (right). For Poechos, the turbidity product is shown, while for Lagdo the true color image is shown

A second, much simpler method was also applied to see if the results vary much from the complex method described above. The simpler method combines mean monthly discharge volumes and mean monthly turbidity measurements from EO, which are translated into SSC. Multiplying these two monthly values, results in mean sediment fluxes per month. Both variables are average values from all the years available (around 40 years of discharge and 2016-2023 for SSC).

Methods limitations and uncertainties
The turbidity measurements stem from optical remote sensing, which is subject to the influence of cloud cover, which can be prevalent especially during times of higher rainfall. Therefore, potential missing peaks in the data can be attributed to the influence of cloud coverage. This can lead to an underrepresentation of high turbidity levels in the data set.
The transformation from turbidity to SSC is very specific for each catchment in the world. While it often follows a 1:1 relation for low turbidity levels, the relation for higher values can significantly change and become highly non-linear. For the sake of simplicity, we used a 1:1 relation for all turbidity values due to the lack of local calibration data. We expect to enhance the accuracy by applying local regression formulas if available from field measurements or literature research.
The discharge data is the most important input for the sediment flows as it is not only directly used but also determines the SSC via the applied regression formula. For Poechos, we found open accessible data from a national hydrological model of Peru. The validation was generally positive for this model. However, the weakest region of the model is in the North, where Poechos is situated. For Lagdo, we used modelled discharge data from our partner SMHI. Since no measurements are available here, the performance cannot be assessed for this specific catchment.

3. Results and discussion

Poechos

Daily method
A constant discharge time series from the model leads to a daily sediment flow from 1981-2022. A huge variability is the dominant feature of the sediment flow (Figure 2). While in some years the maximum is only around several thousand tons per day, some years' maxima can reach up to 400,000 tons per day. While the most extreme years are 1983 and 1998, an increase in moderate peaks can be observed for the years from around 2008 onwards.

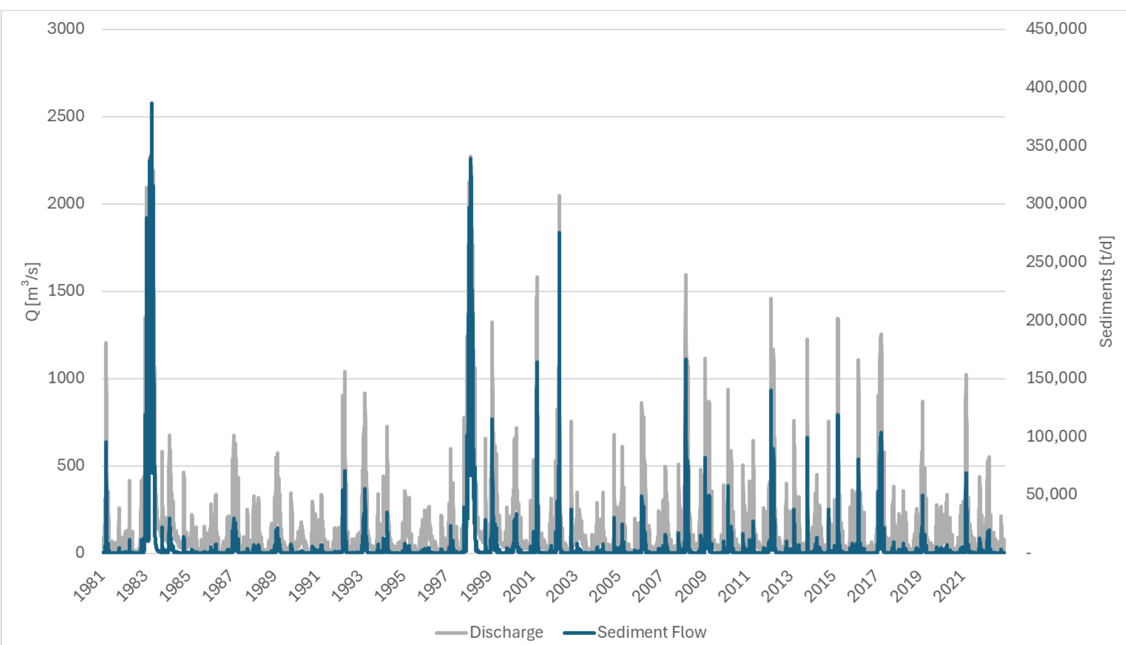

Figure 2: Daily modelled discharge and the resulting sediment flow

The annual values also show a large variability while most of the years contribute between 100,000 t/a to 4,000,000 t/a. The extremely elevated sediment flows for 1983 and 1998 can be explained by the very extreme El Nino situations in those years and also appear as extreme years in scientific publications[1]. Half of the total accumulated sediment flow of the 42 years is solely contributed by those two years (Figure 3). This total sum is around 92 Mio tons for the daily method. This is well below data from other surveys, where already more than 470 Mio m³ (assumption of 1 t = 1 m³) have accumulated and reduced the capacity by about 50 %[2].

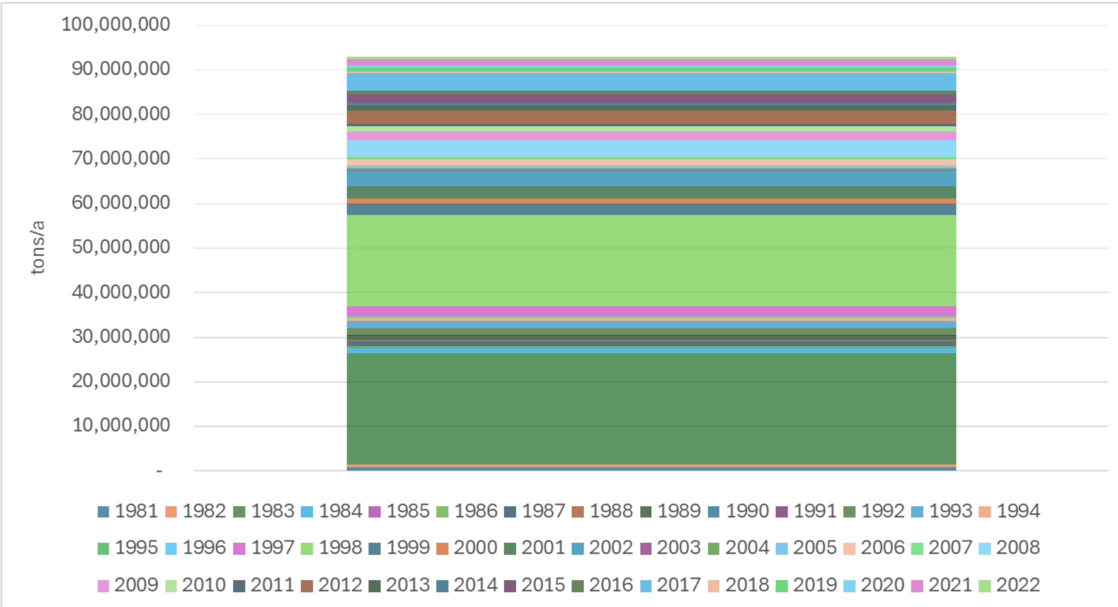

Figure 3: Stacked annual sediment flow sums [t/a]

Monthly Method

Mean monthly discharge volumes [m³/month] were aggregated from the daily discharge data of the model. This was multiplied with the mean monthly SSC from EO data from 2016-2023 [mg/l]. The result shows that the mean annual sediment flow is around 822,000 t/year.

Table 1: Monthly method for Chira River (Poechos)

Month	Monthly Discharge Poechos [m³/mon]	Monthly Mean SSC Poechos [mg/m³]	Sedflux Poechos [t/mon]
Jan	464,517,856	106,548	49,493
Feb	733,844,567	169,640	124,489
Mar	1,120,245,689	326,277	365,511
Apr	835,749,426	236,858	197,954
May	396,710,203	71,191	28,242
Jun	198,002,912	23,250	4,604
Jul	103,695,763	35,401	3,671
Aug	77,391,491	15,116	1,170
Sep	62,938,245	16,139	1,016
Oct	304,810,167	34,906	10,640
Nov	270,128,273	48,836	13,192
Dec	248,092,686	90,498	22,452
Sum [t/a]			**822,433**

[1] https://hess.copernicus.org/articles/27/3191/2023/#section13
[2] http://eusebioingolb.weebly.com/uploads/2/5/2/4/2524387/sedim_poechos_junes.pdf

Lagdo

Daily method

The daily modelled discharge and the turbidity measurements from 2016-2023 lead to daily sediment flows for the three major tributaries Benue, Mayo Rey and Mayo Godi. The time series show much less interannual variability than in Poechos.

Annual aggregation for this data shows that Benue and Mayo Rey show very similar sums for 1981-2020 of around 6.8 Mio tons, while Mayo Godi shows 3 Mio tons for this period. The fraction of total inflow of the three tributaries shows similar means for Benue and Mayo Rey, but a much larger variability in Benue river. Mayo Godi usually contributes less than 20 % of the total inflow and shows similar variability as Mayo Rey.

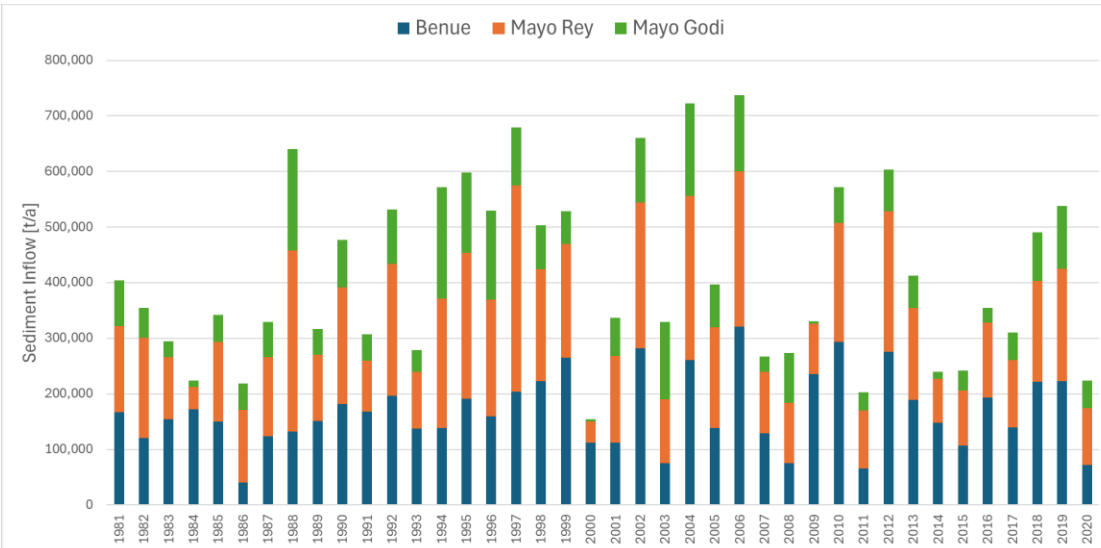

Figure 4: Annual sediment flows for Lagdo, separated by the three tributaries

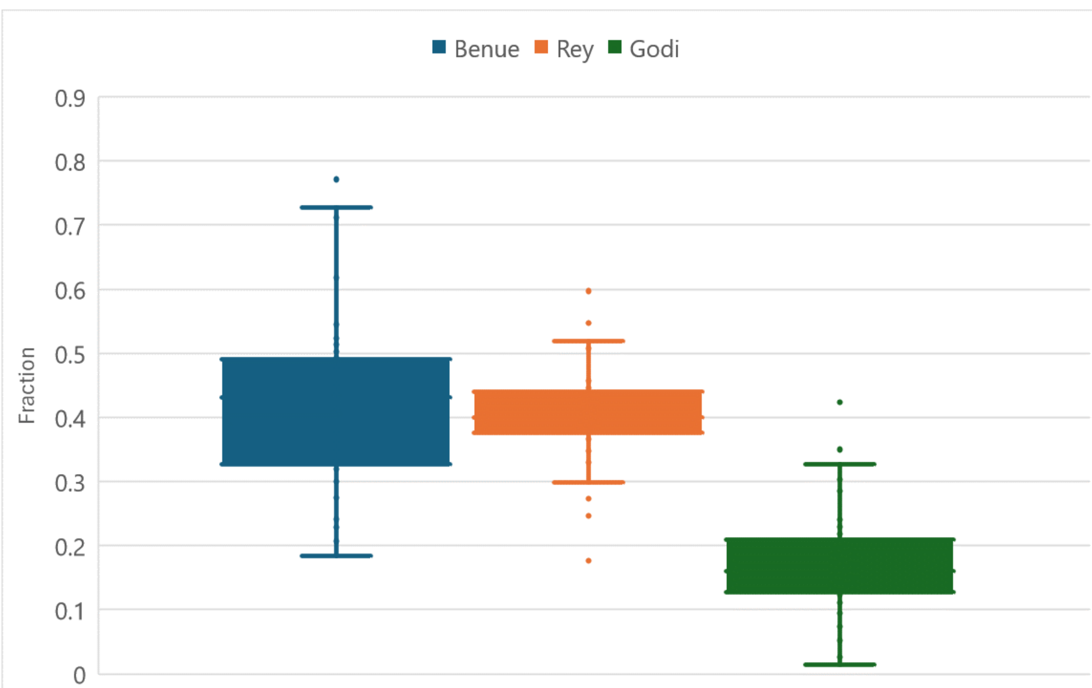

Figure 5: Boxplots of the annual sediment flow fractions of the three tributaries

Monthly method
The monthly method first of all shows that the discharge is basically zero during the dry period from Nov/Dec to Apr/May and that almost all discharge appears in the months from July to October. A similar seasonality, but less distinct can be seen for the monthly SSC in the three rivers.
If all three rivers are summed up, a total of 590,679 tons per year are flowing into the reservoir in a mean year.

Table 2: Monthly method for Benue river (Lagdo)

Month	Monthly Discharge Benue [m³/mon]	Monthly Mean SSC Benue [mg/m³]	Sedflux Benue [t/mon]
Jan	-	29,146	-
Feb	-	28,234	-
Mar	-	19,092	-
Apr	70,843	51,614	4
May	5,488,288	97,863	537
Jun	15,892,517	198,437	3,154
Jul	85,300,916	206,044	17,576
Aug	350,581,574	164,893	57,808
Sep	606,992,514	174,710	106,048
Oct	439,212,926	87,240	38,317
Nov	52,118,231	42,029	2,190
Dec	498,953	26,816	13
Sum [t/a]			**225,647**

4. Limitations and discussion
Two methods were applied to estimate the sediment inflow into the Poechos and Lagdo reservoir.
1) A complex method based on daily discharge data and the relation between discharge and SSC
2) A simple method based on mean monthly values of discharge and SSC
Both methods underestimate the sediment loads, compared to bathymetry measurements, which serve as the reference. The underestimation can generally be explained by three factors:

a) If the modelled discharge is underestimating the actual discharge
b) the 1:1 relation from turbidity to SSC results in relatively low SSC values that go into the derivation of the Q-SSC regression formula; also the EO derivation of turbidity can be adapted to high turbidity levels (this has been successfully tested in the Rhone)
c) The methodology can generally only depict the finer sediments in the upper part of the water column. Sediments in lower parts of the river and especially bedload cannot be detected properly. For example in Lagdo, one study found that the material is mainly coarse sand.

However, we see that the difference between bathymetric results and the two applied methods are in a similar range. For Poechos, the 473 Mio tons (or m³) are about 5 times as the 92 Mio tons from the daily method. The monthly method reveals a much larger factor of 16, but this does not include SSC measurements for the extreme El Nino years 1983 and 1998. This method generally has more problems with the high interannual variability of Poechos inflows, when averaging over all years. However, when assuming that about half of the sediments were contributed during these two extreme years and the method rather resembles an average year, doubling the amount of the monthly method results in a factor of 8 instead of 16. Another study[3] found a relation between monthly discharge and monthly sediment concentration:

Sediment flow [t] = $6.5765 \cdot Q^{2.1891}$

where Q is the mean discharge of a month in m³/s. With this formula, the factor increases to 10.9.
For Lagdo, the initial storage capacity was 7.7 billion m³ when it was build. A bathymetric survey from 2005 revealed that 1.8 billion m³ have already been lost to sedimentation, which results in an average loss of 75 Mio m³

[3] https://repositorio.ana.gob.pe/handle/20.500.12543/743

per year. While the daily method shows around 10.7 Mio m³, the monthly method results in about 14.2 Mio m³ for the same period respectively. This leads to scale-up factors of 7 (daily) and 5 (monthly). When the local formula from Poechos (Morocho) is applied for Lagdo, the factor is 7.8.

Table 1: Scale-up factors for both methods to match with bathymetry measurements

	Poechos	Lagdo
Monthly	16 (8)	5
Monthly (Morocho)	10.9	7.8
Daily	5.1	7

There is a wide range of scale-up factors, but it seems there is a general possibility to use such an empirical scale-up factor to estimate the sedimentation in those two reservoirs with a value range between 5 and 8. It must be mentioned here that the daily method was very well validated against discharge and SSC measurements in the river Devoll in Albania, when the TUR-SSC relation was locally calibrated. The daily method (EO and hyd. model) only showed a 5 % deviation from the results from the sediment flow derived from those measurements. However, also here bathymetric surveys showed a factor of around 10 that was between the river-based estimations and the sedimentation in the reservoir.

5. Conclusions

It becomes apparent that there is great potential in estimating sediment flows with a combination of EO data and modeled discharge. This is especially true for data scarce catchments, where no in-situ measurements are available. However, the total lack of in-situ measurements increases the uncertainty for the discharge amounts and dynamics as well as for the translation of measured turbidity into sediment concentrations. Here, some local knowledge can bring significant improvements to the approach, even stations were only in operation for short time periods. For example, a SSC measurement station provides data from 2015-2016 only, this can be used to establish a locally calibrated turbidity-concentration relation, which can then be applied to much longer turbidity time series from EO to derive more robust annual estimations due to reduced interannual variability effects.

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The Authors

Fabian von Trentini is a project and innovation manager at EOMAP, leading amongst others the GDA AID Water Resources and InCubed EOSmart dissemination and technical activities. This includes the coordination between the partners, as well as internal development planning and assessment. Furthermore, Fabian is the head of innovation management in the water quality branch of EOMAP. He holds a master in physical geography and conducted research on climate change impacts and hydrological modelling during his 6 years as research fellow at LMU Munich.

Karin Schenk studied Geography with focus on remote sensing and GIS at the university of Tübingen and is leading the water quality section at EOMAP. She has more than 10 years of professional experience in the fields of earth observation services and applied solutions. She developed successful commercial water monitoring services for various environmental agencies and industry clients, and leaded or participated at EU funded projects such as FRESHMON, GLaSS, INFORM or SPACE-O to innovate satellite-based services.