Saisonales Wasserressourcen-Management in Trockenregionen: Praxistransfer regionalisierter globaler Informationen (SaWaM)

im Rahmen der Forschungsinitiative

Globale Ressource Wasser (GROW)

an den Projektträger Karlsruhe und das Bundesministerium für Bildung und Forschung

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Abschlussbericht

Projektleitung: **Prof. Dr. Harald Kunstmann**

Projektkoordination: **Dr. Christof Lorenz**

Karlsruher Institut für Technologie
Institut für Meteorologie und Klimaforschung
Campus Alpin, Kreuzeckbahnstr. 19
82467 Garmisch-Partenkirchen
Tel.: 08821 183 208
Fax: 08821 243
harald.kunstmann@kit.edu
christof.lorenz@kit.edu

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Projektteilnehmer

Einrichtung: **Karlsruher Institut für Technologie (KIT)**
Institut / Abteilung: Institut für Meteorologie und Klimaforschung – Atmosphärische Umweltforschung, Abteilung Regionales Klima und Hydrologie und Abteilung Ökosystem-Atmosphäre Interaktionen
Teilprojekt: Koordination, Hydrometeorologie und Ökosystemfunktionalität
Förderkennzeichen: 02WGR1421A
Aufgabenbereich: Projektkoordination, Evaluierung von globalen hydrometeorologischen Informationen für das Wassermanagement, Regionalisierung von saisonalen Vorhersagen, Ökosystemmodellierung

Einrichtung: **Universität Potsdam**
Institut / Abteilung: Institut für Umweltwissenschaften und Geographie – AG Hydrologie und Klimatologie
Teilprojekt: Regionale Modellierung des Wassermanagements und der hydro-sedimentologischen Prozesse sowie statistisches Downscaling zur saisonalen Vorhersage
Förderkennzeichen: 02WGR1421B
Aufgabenbereich: Hydrologische Modellierung der SaWaM-Einzugsgebiete inkl. Beschreibung von Sedimentprozessen, statistische Regionalisierung von saisonalen Vorhersagen

Einrichtung: **Philipps Universität Marburg**
Institut / Abteilung: Fachbereich Geographie – Physische Geographie – Klimageographie und Umweltmodellierung
Teilprojekt: Satellitengestützte Niederschlagsfernerkundung - Entwicklung eines neuen Verfahrens zur raumzeitlich hochaufgelösten Niederschlagsableitung mittels geostationären Satellitendaten und Global Precipitation Mission Radardaten
Förderkennzeichen: 02WGR1421C
Aufgabenbereich: Ableitung von räumlich und zeitlich hoch aufgelösten Niederschlagsinformationen aus Fernerkundungsdaten

Einrichtung: **Universität Stuttgart**
Institut / Abteilung: Geodätisches Institut
Teilprojekt: Satellitengestützte Zeitreihen von Wasserstand, Abfluss und Gesamtwasserspeicherung in Trockenregionen
Förderkennzeichen: 02WGR1421D
Aufgabenbereich: Ableitung von Abfluss- und Wasserstands- und Speicherinformationen aus Satellitendaten

Einrichtung: **TU Berlin**
Institut / Abteilung: Institut für Ökologie – FG Ökohydrologie und Landschaftsbewertung
Teilprojekt: Saisonale Vorhersage des pflanzenbenötigten Wassers und Identifikation von Erosions-Hotspot-Gebieten zur Minimierung von

Reservoirsedimentation für ein vorausschauendes Stauseemanagement in Trockengebieten
Förderkennzeichen: 02WGR1421E
Aufgabenbereich: Ableitung von Erosions-Prozessen und -Hotspots in den SaWaM-Zielregionen

Einrichtung: **GeoForschungsZentrum (GFZ) Potsdam**
Institut / Abteilung: Sektion 1.4: Fernerkundung und Geoinformatik
Teilprojekt: Erfassung der saisonalen und langfristigen Vegetationsdynamig aus Satellitendaten-Zeitreihen
Förderkennzeichen: 02WGR1421F
Aufgabenbereich: Ableitung von Vegetationsparametern und deren Dynamik aus Fernerkundungsdaten

Einrichtung: **UmweltForschungsZentrum (UFZ) Leipzig**
Institut / Abteilung: Themenbereich Smarte Modelle und Monitoring – Department Hydrosystemmodellierung
Teilprojekt: Wasserhaushaltssimulation und Saisonale Vorhersage unter Nutzung globaler Informationen
Förderkennzeichen: 02WGR1421G
Aufgabenbereich: Hydrologische Modellierung der SaWaM-Einzugsgebiete

Einrichtung: **Tractebel Engineering GmbH (ehem. Lahmeyer International GmbH)**
Teilprojekt: Teilprojekt 8
Förderkennzeichen: 02WGR1421H
Aufgabenbereich: Anwenderdialog und Praxistransfer

Einrichtung: **GAF AG (Gesellschaft für Angewandte Fernerkundung)**
Teilprojekt: Teilprojekt 9
Förderkennzeichen: 02WGR1421I
Aufgabenbereich: Entwicklung eines Online-Systems zur Entscheidungsunterstützung

Internationale Projektpartner

Iran

- Khuzestan Water and Power Authority (KWPA, https://www.kwpa.ir)

Brasilien

- Fundação Cearense de Meteorologia e Recursos Hídricos (FUNCEME, Foundation Cearense for Meteorology and Water Management, http://www.funceme.br)
- Agência Nacional de Águas e Saneamento Básico (ANA, National Water Agency, http://www2.ana.gov.br)
- Governo do Estado do Ceará (Government of Ceará, https://www.ceara.gov.br)

Sudan

- Sudan Meteorological Authority (SMA, https://www.ersad.gov.sd)
- Ministry of Irrigation and Water Resources (http://wre.gov.sd/en/)
- Hydraulics Research Center (HRC, https://hrc-sudan.sd)
- Dams Implementation Unit (DIU, http://diu.gov.sd, Website aktuell nicht erreichbar)

Ecuador

- Universidad Técnica Particular de Loja (UTPL, https://www.utpl.edu.ec)
- Instituto Nacional Meteorologia e Hidrologia (INAMHI, https://www.inamhi.gob.ec)
- Gobierno Provincial de Loja (https://prefecturaloja.gob.ec)

West-Afrika

- WASCAL (https://wascal.org)

1. Kurzfassung

Die Forschergruppe des SaWaM-Projekts wies nach, dass in sechs dürregefährdeten, semi-ariden Regionen in Südamerika, Afrika und Asien die relative Häufigkeit von Dürremonaten zwischen 1981 und 2018 deutlich von 10 % auf 30 % gestiegen ist. Eine Zunahme der Trockenjahre in den iranischen und brasilianischen Untersuchungsgebieten wurde auch durch beobachtete und modellierte Vegetationsvariablen belegt. Diese Entwicklung erfordert ein konsequentes Handeln, um die Auswirkungen des Klimawandels abzumildern. Wenn Wasserknappheit und Dürren rechtzeitig vorhergesagt werden, können die Verantwortlichen Maßnahmen ergreifen, um größere Schäden so weit wie möglich abzuwenden. Dies erfordert die leistungsfähige Vorhersage von extremen Wetterperioden Monate im Voraus.

Im Rahmen von SaWaM wurde ein Modellsystem für regionalisierte verbesserte saisonale Vorhersagen entwickelt, das Informationen über Wasserressourcen und langfristige hydrometeorologische Extremereignisse mit einer Auflösung von 10 km und bis zu sieben Monaten im Voraus liefert. Bias-Korrektur und Regionalisierung machen öffentlich verfügbare globale saisonale Vorhersagen noch präziser und ermöglichen leistungsfähige Vorhersagezeiträume von bis zu sieben Monaten. Für die halbtrockenen Untersuchungsregionen konnte gezeigt werden, dass durch die Zugrundelegung von saisonalen Vorhersagen für wasserwirtschaftliche Entscheidungen potenzielle wirtschaftliche Einsparungen von bis zu 70 % derjenigen bei optimalem frühzeitigem Handeln erzielt werden können. Diese wirtschaftlichen Vorteile können sogar bis zu sieben Monate im Voraus erreicht werden. Die saisonalen Vorhersagen wurden am Anwendungsbeispiel des Upper Atbara Damms (Sudan) erfolgreich getestet. Durch eine korrekte saisonale Vorhersage wird die Überlaufmenge verringert, so dass mehr Wasser für andere Zwecke zur Verfügung steht, z. B. für die Stromerzeugung, die Bewässerung oder die Trinkwasserversorgung. Das System unterstützt somit Entscheidungen über die Bewirtschaftung der Stauseen und das kritische Dürremanagement.

Die SaWaM-Forscher entwickelten eine skalierbare hydrologische Modellierung, die eine nahtlose Simulation über verschiedene Auflösungen hinweg ermöglicht. Eine solche Modellintegrität trägt zur Eindämmung von Unsicherheiten bei und verbessert die Gesamtzuverlässigkeit des übergreifenden Vorhersagesystems. Da die meisten Flusseinzugsgebiete in den Halbtrockengebieten stark bewirtschaftete Stauseen beinhalten, muss die nicht triviale hydrologische Modellierung des realen Stauseebetriebs berücksichtigt werden. Die Einbeziehung von Betriebsregeln aus der Praxis, wie z. B. Regelkurven und Absicherungsregeln, in hydrologische Modelle ermöglicht es den Staudammbetreibern jedoch, Parallelen zwischen dem Vorhersagesystem und ihrer Arbeit zu ziehen, was für einen erfolgreichen Technologietransfer entscheidend ist. Dennoch sind die Betriebsregeln von Stauseen sensible Informationen und in der Regel geheim, insbesondere in grenzüberschreitenden Regionen. In solchen Fällen ist die Parameterisierung der Reservoirregulierung mit dem Reverse-Engineering-Verfahren sehr pragmatisch. Ein solcher Ansatz wurde im SaWaM-Projekt verwendet, welcher die Datenknappheit umgeht, die Erstellung von hydrologischen Vorhersagen für Endverbraucher ermöglicht und zu einem nachhaltigen Vorhersagesystem führt.

Öffentlich zugängliche Informationen von globalen Modellen zusammen mit Satellitendaten können einen wichtigen Beitrag zu einem verbesserten Wassermanagement leisten, insbesondere in grenzüberschreitenden Flusseinzugsgebieten. Wir empfehlen den lokalen Wasserbehörden, Satellitenaltimetriedaten zu nutzen, um virtuelle Pegelstationen über Seen, Stauseen und Flüssen einzurichten. Dies wird die Gewässerüberwachungsdatenbanken bereichern und ist ein unschätzbares Mittel zur Überwachung in Regionen, in denen aus praktischen oder politischen Gründen keine In-situ-Messungen durchgeführt werden können oder kein Zugang dazu besteht. Außerdem kann die Satellitenaltimetrie wertvolle Informationen für die Gefahrenanalyse liefern. Bei solchen Anwendungen ist es jedoch wichtig, alle Einschränkungen zu berücksichtigen. Obwohl Satellitenaltimetriedaten keine Notfallmaßnahmen ermöglichen, können sie für die nachträgliche Gefahrenabwehr und -analyse von großem Wert sein.

Genaue, echtzeitnahe Niederschlagsinformationen mit hoher räumlicher und zeitlicher Auflösung sind entscheidend für ein nachhaltiges Wassermanagement in semi-ariden Regionen. In diesem Zusammenhang liefert das neu entwickelte satellitengestützte Verfahren zur Niederschlagsableitung flächendeckende Niederschlagsinformationen mit hoher räumlicher und zeitlicher Auflösung, die für landwirtschaftliche Fragestellungen, Belange der Wasserwirtschaft und Energieversorgung sowie des Katastrophenschutzes von zentraler Bedeutung sind. Das entwickelte Verfahren kann weltweit für die operationelle Niederschlagsableitung eingesetzt werden. Der modulare Aufbau des Verfahrens erlaubt die flexible Nutzung unterschiedlicher Satellitensysteme und Datenquellen. Damit ist eine Übertragbarkeit auf andere Einsatzgebiete möglich. Ein weltweit anwendbares satellitengestütztes Niederschlagsverfahren ist von großem Interesse. Dies gilt insbesondere in Gebieten der Welt, in denen der Aufbau eines ausreichend dichten Bodenstationsmessnetzes oder gar eines bodengebundenen Radarnetzes aus Kosten- und Logistikgründen nicht realisierbar ist.

Das Wissen über beobachtete und modellierte Vegetationszustände kann zur Interpretation von Simulationen verwendet werden, die die saisonalen Vorhersagen anwenden, um bevorstehende landwirtschaftliche Dürreperioden in den Untersuchungsgebieten zu identifizieren, beispielsweise über den auf mehreren Indikatoren basierenden kombinierten Dürreindikator. Für vergangene meteorologische Dürreperioden (z. B. 2008 im Iran, 2012-2017 in Rio São Francisco) konnte auf der Grundlage von Satellitenzeitreihenanalysen und modellierten Vegetationsvariablen ein Rückgang der Vegetationsbedeckung nachgewiesen werden, insbesondere bei der Grasvegetation. Zudem wurde aber auch ein Rückgang der Anbauflächen aufgrund des Mangels an Wasser für die Bewässerung festgestellt. Es wurden Regionen ermittelt, in denen das Vegetationssignal mit Klimaschwankungen korreliert und die daher anfälliger für den vorhergesagten Klimawandel hin zu trockeneren und wärmeren Bedingungen sind. Außerdem ist in trockenen Jahren der Anteil des eingehenden Niederschlagswassers, der vom Ökosystem genutzt wird - obwohl die Vegetation reduziert ist - höher als in normalen Jahren, so dass die für die anthropogene Nutzung verfügbare Wassermenge geringer ist. Es konnte gezeigt werden, dass ein hoher Prozentsatz der bewässerten Flächen in ariden oder hyperariden Gebieten nicht mehr bewirtschaftet werden kann, weil eine nicht nachhaltige Wassernutzung heutzutage zu Wasserknappheit führt. Die Kombination von Beobachtung, Fernerkundung und Vorhersage ermöglicht somit eine Bewertung der Dürre in Bezug auf alle für die regionale Wasserwirtschaft relevanten Variablen und Aspekte auf verschiedenen zeitlichen und räumlichen Ebenen.

Erosion und hohe Sedimentfrachten in Flüssen in Trockengebieten führen zur Verschlammung von Stauseen und zur Verringerung der Speicherkapazität, was eine Gefahr für die Wassersicherheit der Bevölkerung, der Landwirtschaft und der Industrie darstellt. In Regionen, in denen die Wasserressourcen für die Bewirtschaftung begrenzt sind, ist die Ermittlung der räumlich-zeitlichen Variabilität von Sedimentquellen von entscheidender Bedeutung, um die Verschlammung zu verringern. In diesem Projekt wurde ein raum-zeitlicher Kartierungsansatz zur Identifizierung von Erosions-Hotspots und Leverage-Gebieten entwickelt, der auf einem minimalen Datenbestand mit global verfügbaren Daten mit zeitlich wechselnder Vegetation und Niederschlägen und Konnektivitätsberechnung beruht. Mit diesem Ansatz können so genannte Leverage-Gebiete identifiziert werden, in denen die Bewirtschaftung von Erosionshotspots vier bis sechs Monate im Voraus die größten Auswirkungen auf die Verringerung von Erosion und Sedimenteintrag in flussabwärts gelegene Gewässer und Stauseen haben würde. Das entwickelte Instrument trägt somit zur Verhinderung der Verlandung von Stauseen bei.

Der im Rahmen von SaWaM entwickelte Prototyp eines Online-Entscheidungsunterstützungssystems fasst die meisten entwickelten Instrumente und Methoden zusammen. Er umfasst die Operationalisierung des regionalen saisonalen Vorhersagesystems - das die wichtigsten hydrometeorologischen Variablen wie Niederschlag, Temperatur und kurzwellige Strahlung in monatlichen Aktualisierungen bereitstellt - und bietet schließlich eine direkte Entscheidungshilfe für lokale Behörden und Interessenvertreter. Eine zusätzliche Modellkette, die die Hydrologie und die Vegetationsdynamik umfasst, liefert in Verbindung mit aus der Fernerkundung abgeleiteten wasserbezogenen Daten retrospektive und echtzeitnahe Informationen. Abgeleitete saisonale hydrologische Vorhersagen können hydrologische Bedingungen wie meteorologische und landwirtschaftliche Dürren, Überschwemmungen, Zuflüsse in Stauseen, den Zustand der Vegetation usw. weit im Voraus anzeigen. Die gut aufbereitete Online-Darstellung von Schlüsseldaten hilft bei der rechtzeitigen Verbreitung von Informationen für die Entscheidungsfindung und trägt zum Verständnis der Daten, ihres Inhalts und ihrer Anwendungsgrenzen bei. Das entwickelte Online-Entscheidungsunterstützungssystem ist daher besonders für Endnutzer in semiariden Regionen von Nutzen, in denen Wassermanager mit den doppelten Herausforderungen von Saisonalität und Unsicherheit konfrontiert sind.

Das SaWaM-Projekt hat gezeigt, dass Satelliteninformationen und hochaufgelöste meteorologische Daten in Zukunft von einer unabhängigen Stelle genutzt werden könnten, um die Erreichung der SDG-Indikatoren (z. B. zur Wasserverfügbarkeit, zum Ertrag und zur Effizienz der landwirtschaftlichen Wassernutzung) zu überwachen. Für eine differenzierte Situations- und Risikobewertung sowie für die Validierung von modell- und satellitengestützten Variablen sind jedoch nach wie vor qualitätsgeprüfte lokale Beobachtungsdaten (z. B. Klima- und physiografische Daten) unerlässlich, die in klimasensiblen Regionen mit schwacher Infrastruktur nach wie vor nur spärlich verfügbar sind. Ein Mindestmaß an Monitoring und ein konsistentes Datenmanagement als Grundlage des Wasser- und Sedimentmanagements bleiben langfristige Aufgaben.

Das SaWaM-Projekt hat darüber hinaus gezeigt, dass der persönliche und kontinuierliche Austausch zwischen Wissenschaftlern und lokalen Entscheidungsträgern der Schlüssel für die erfolgreiche Entwicklung neuer Methoden und für eine verbesserte

Entscheidungsunterstützung ist. Es musste das Vertrauen von den beteiligten internationalen Akteuren aufgebaut werden und in Zukunft können neue Projekte auf den Errungenschaften von SaWaM aufbauen.

2. Summary

The researchers of the SaWaM project provided evidence that in six drought-prone, semi-arid regions in South America, Africa and Asia, the relative frequency of drought months increased significantly from 10% to 30% between 1981 and 2018. An increase in dry years in the Iranian and Brazilian study areas was also evidenced by observed and modeled vegetation variables. This calls for consistent action to mitigate the impacts of climate change. If water scarcity and droughts are predicted in a timely manner, the responsible actors can take measures to avert greater damage as much as possible. This requires the skillful prediction of extreme weather periods months in advance.

Within SaWaM, a model system for regionalized improved seasonal forecasts was developed to provide information on water resources and long-term hydrometeorological extreme periods at a resolution of 10 km and up to seven months in advance. Bias correction and regionalization make publicly available global seasonal forecasts more accurate and allow skillful forecast periods of up to seven months. For the semi-arid study regions, it was shown that by basing water management decisions on seasonal forecasts, potential economic savings of up to 70% of those with optimal early action can be achieved. Economic benefits from forecast-based action can even be achieved up to seven months ahead. The seasonal forecast was successfully tested using practical examples of the Upper Atbara Dam (Sudan). Correct seasonal forecasting reduces spillage, making more water available for other purposes, e.g. power generation, irrigation or potable water. This system thereby supports reservoir management decisions and critical drought management.

The SaWaM researchers developed scalable hydrological modeling enabling seamless model output across resolutions. Such model integrity helps in curbing uncertainty and improves the overall reliability of the overarching forecasting system. As most river basins in the semi-arid areas include highly managed reservoirs, the non-trivial hydrological modeling of real world reservoir operation has to be considered. However, inclusion of real world operation language such as rule curves and hedging rules in hydrological models allows dam operators to better draw parallels between the forecasting system and their work, which is crucial for successful technology transfer. Still, operation rules at reservoirs are sensitive information and usually classified, especially in transboundary regions. In such cases, parameterization of reservoir regulation with reverse engineered operation becomes very pragmatic. Such an approach was used in the SaWaM project, which circumvents data congestion, enables the production of reservoir hydrologic forecasts for end users, and leads to a sustainable forecasting system.

Publicly accessible information from satellites and global models can make a major contribution to improved water management, especially in transboundary river basins. We recommend that local water authorities benefit from satellite altimetry data in order to establish virtual gauging stations over lakes, reservoirs, and rivers. This will enrich the water monitoring databases and is an invaluable means of monitoring in regions where, for either practical or political reasons, collecting or having access to in situ measurements is not an option. Moreover, satellite altimetry can provide valuable information for hazard analysis. In such applications, however, it is important to consider all the limitations. Although satellite altimetry data cannot provide emergency response, it can be of high value for post hazard mitigation and analysis.

Accurate, near-real-time precipitation information with high spatio-temporal resolution is critical for sustainable water management in semi-arid regions. In this context, the newly developed satellite-based method for precipitation derivation provides area-wide precipitation information with high spatio-temporal resolution, which is of central importance for agricultural issues, concerns of water management and energy supply as well as disaster control. The developed method can be used worldwide for operational precipitation derivation. The modular design of the procedure allows the flexible use of different satellite systems and data sources. Thus, transferability to other areas is possible. A globally applicable satellite-based precipitation method is of great interest. This is especially true in areas of the world where the establishment of a sufficiently dense ground station measurement network or even a ground-based radar network is not feasible for cost and logistical reasons.

Knowledge from observed and modeled vegetation states can be used to interpret simulations applying the seasonal forecasts to identify upcoming agricultural droughts in the study areas, for instance via the multi-indicator-based Combined Drought Indicator. For past meteorological droughts (e.g., 2008 in Iran, 2012-2017 in Rio São Francisco) a decrease in vegetation cover could be shown based on satellite time series analyses and modelled variables, especially in grassy vegetation but also a decrease in cultivation was found due to the lack of water for irrigation. Regions were identified where the vegetation signal correlates with climatic variations and thus are more susceptible to predicted climate change towards drier and warmer conditions. Also, in dry years, the fraction of incoming precipitation water that is used by the ecosystem - although vegetation is reduced - is higher than in normal years, so that the amount of water available for anthropogenic use is smaller. It could be shown that high percentages of irrigated areas in arid or hyperarid areas are not cultivable anymore because unsustainable water usage resulted in water shortages nowadays. The combination of observation, remote sensing and forecasting allows a drought assessment with respect to all variables and aspects relevant for regional water management on different temporal and spatial scales.

Erosion and high sediment loads in dryland rivers cause reservoir siltation and decrease storage capacity, which pose risk on water security for citizens, agriculture, and industry. In regions where resources for management are limited, identifying spatio-temporal variability of sediment sources is crucial to decrease siltation. In this project a spatio-temporal mapping approach was developed for the identification of erosion hotspots and leverage areas using a minimum data inventory with data globally available with temporal changing vegetation and rainfall and connectivity calculation. The approach can be used to identify so-called leverage areas, where management of erosion hotspots would have the greatest impact in reducing erosion and sediment delivery into downstream water bodies and reservoirs four to six months in advance. The developed tool thus contributes to the prevention of reservoir sedimentation.

The developed online decision support system prototype synthesizes most developed tools and methods within SaWaM. It includes the operationalization of the regional seasonal forecasting system - providing the most relevant hydrometeorological variables of precipitation, temperature and shortwave radiation at monthly updates - and finally offers direct decision support for local authorities and stakeholders. An additional model chain that includes hydrology and vegetation dynamics, combined with remote sensing-derived water-related data, provides retrospective and near-real-time information. Derived seasonal hydrological forecasts can indicate hydrological conditions such as meteorological and agricultural droughts, floods, reservoir inflow, vegetation condition, etc. well in advance. The well-prepared online representation of key data helps in the timely dissemination of information for decision making and aids in understanding the data and its content and limitations. This developed online decision support system is thus especially beneficial to end users in the semi-arid regions where water managers face the dual challenges of seasonality and uncertainty.

The SaWaM project showed that in the future, satellite information and high-resolution meteorological data could be used by an independent body to monitor the achievement of the SDG indicators (e.g., on water availability, yield and agricultural water use efficiency). Nevertheless, for differentiated situations and risk assessment, as well as for validating model- and satellite-derived variables, quality-checked local observational data (such as climate and physiographic data) are still essential; these remain sparsely available in climate-sensitive regions with weak infrastructure. Minimum monitoring and consistent data management as the foundation of water and sediment management remain long-term tasks.

The SaWaM project moreover demonstrated that personal and continuous exchange between scientists and local decision-makers is key for the successful development of new methods and for improved decision support. Trust had to be built up and in the future new projects can build on the achievements of SaWaM.

3. Introduction

Population growth and climate change increasingly threaten the water supply of large parts of the world's population. In 2005, the water supply of about 80% of the world's population was potentially insecure (Vörösmarty et al., 2010). The substantial increase in water consumption is caused in particular by intensive land use, irrigation, and industry. On top of this, erosion of overexploited land areas and the associated increased sediment deposition in reservoirs significantly reduce the reliability of water and energy supplies. Especially regions that are already characterized by limited water resources, i.e. the arid and semi-arid regions, are mainly affected by this development. These regions require sound techniques to monitor, plan and manage their available water resources. In semi-arid regions, unlike in arid regions, much can be achieved with sustainable and science-based water resource management. Particularly, it is the knowledge about the coming months that is crucial for the management and control of water reservoirs, e.g. for power generation or for irrigation in agriculture. Thus, while weather forecasts are used for flood warnings and climate projections for long-term climate adaptation measures, seasonal forecasts for the coming weeks to months enable immediate mitigation measures against climate change. Seasonal forecasts combined with timely monitoring information can thus be a powerful tool for sustainable water resource management.

For this, it is of utmost importance to understand the local climate system including the dynamics and interactions of different water-related variables. However, due to the significant decrease in the number of hydrometeorological in situ stations (Lorenz and Kunstmann, 2012) and high uncertainties in estimates for the current and future water supply (Pilgrim et al., 1988), this is getting increasingly difficult. Scientists and decision makers may therefore rely their planning more and more on global hydrometeorological data sets, remote-sensing products or global model systems. It is the goal of SaWaM to investigate the performance of such global information and in particular global seasonal forecasts, for which we develop methods and tools for regionalization, processing and ultimately the transfer to practice for regional water management in semi-arid regions. The project is carried out in an integrative approach of climate, hydrology, ecosystem research, as well as remote sensing and in close cooperation with German economic partners.

We focus on semi-arid regions in Brazil (the Rio São Francisco basin), Iran (the Karun basin), Sudan (the Blue Nile and Atbara basins), Ecuador (the Catamayo-Chira basin), and West-Africa (the Niger and Volta basins). We further aim at the direct transfer to practice through a close cooperation with local stakeholders and decision makers. In the end, this cooperation shall demonstrate the potential of seasonal forecasts, model based information and remote-sensing products for climate proofing and for regional water management even beyond the project duration in our study regions.

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4. State of the art in science and technology

4.1. Global and regional hydrometeorology: model systems, regionalization, and remote sensing-based methods

Seasonal forecasts, their dynamical & statistical downscaling and statistical error correction

Seasonal forecasts are becoming increasingly important in decision support of a wide range of socio-economic applications, especially with respect to climate change adaptation strategies (Troccoli, 2010). The basis for seasonal forecasts is the existence of interactions between the atmosphere and slowly changing land surface variables, such as sea surface temperature or soil moisture. Just after the seasonally dominant climate signal, the globally acting El Nino Southern Oscillation (ENSO) phenomenon contributes most to the predictability of hydrometeorological variables on seasonal time scales (e.g., Troccoli, 2010). In addition, other signals such as the North Atlantic Oscillation (NAO), the Pacific-North American (PNA), and the Indian Ocean Dipole (IOD) also play a role for different regions worldwide. A distinction is made in seasonal climate forecasting between dynamical and statistical approaches. Dynamical seasonal forecasts have only been established for a few years due to the high computational cost. Currently, 13 Global Producing Centres (GPCs) of Long-Range Forecasts as accredited by the World Meteorological Organization (WMO) provide data for (global) seasonal climate forecasts. Examples include the European Centre for Medium- Range Forecasts (ECMWF), Météo France, UK Met Office, National Centers for Environmental Prediction (NCEP), and the US National Oceanic and Atmospheric Administration (NOAA). These global seasonal forecasts are often spatially too coarsely resolved and error-prone (compared to in situ hydrometeorological observations) for local scale applications. For this reason, further error correction and/or downscaling procedures are needed. For downscaling, we generally distinguish between *dynamical* and *empirical-statistical* approaches. In our own preliminary work, we dynamically downscaled the Climate Forecast System version 2 (NCEP-CFSv2) data for forecasting August precipitation for West Africa (Siegmund et al., 2015). It was shown that by using dynamical downscaling as well as simple bias correction methods, the variance of the CFSv2 ensemble could be significantly reduced. While the dynamical methods using a Regional Climate Model (RCM) are computationally highly expensive, empirical-statistical techniques often have a lower computational demand and are relatively simple to implement in operational systems. However, the latter usually require reliable reference data, which are often not available, particularly in data-sparse regions. In the recent years, there have been significant developments in the empirical-statistical correction approaches in the recent years. One of the most widely used methods is the so-called *bias correction and spatial disaggregation* (BCSD, Wood et al., 2002) which was developed for downscaling climate model outputs to a higher spatial resolution. Since its introduction, there have been numerous adjustments and changes to the classic BCSD approach. Other improved bias correction methods for precipitation from RCM simulations, based on the concept of copula functions, have been developed and tested for Germany (Laux et al., 2011; Mao et al, 2015). As another technique, the so-called *expanded downscaling* (XDS) was developed specifically for estimating local extremes in climate change scenarios and has been validated and applied for quite a few climate regions (Bürger et al., 2011, 2012, 2013). It is also increasingly used for weather forecasting and for short-term forecasts (flash floods, Bürger et al., 2009) to longer-term seasonal forecasts of, e.g., the monsoon. The main strength of the XDS is to obtain not only univariate distributions (including the extremes), but the complete multivariate covariance structure. The different downscaling and correction techniques for global information were addressed in the SaWaM project.

Real-time satellite-based monitoring of precipitation

Deriving precipitation information using passive microwave (PMW) sensors on polar-orbiting satellites works comparatively well over oceans where the background radiometric signal is low and constant (e.g., Kummerow et al. 2001; Ferraro et al. 2005). Validation studies found relatively high inaccuracies over land and during near real time application (Ebert et al. 2007; Kidd et al. 2012). Another aspect is the low spatio-temporal resolution of the PMW data. IR sensors on geostationary (GEO) satellite systems are characterized by a less direct link to precipitation. However, they provide a higher spatio-temporal resolution, which is of great importance for near real time applications. Combined PWW-IR methods attempt to exploit the advantages of both systems for more accurate precipitation dissipation at high spatio-temporal resolution. (e.g., Tapiador et al. 2004; Huffman et al. 2007). However, inaccuracies in the retrieved precipitation information, especially during near real-time, were also found for the combined PMW-IR methods (Turk et al. 2008; Kidd et al. 2012). To improve the accuracy of the PMW-IR techniques, satellite-based active microwave (AMW) systems are particularly suitable. The measurements of the Dual Frequency Precipitation Radar (DPR) of the Global Precipitation Measurement (GPM) Mission (Smith et al. 2007) serve as a reference for calibrating and improving the precipitation products of the PMW sensors of the GPM constellation. The Integrated Multi-SatEllite Retrieval for GPM (IMERG, Huffman et al. 2018) combines the rainfall information from the satellites of the GPM constellation to produce a merged global precipitation product with the highest possible accuracy. However, the problem of the poor spatial resolution of the PMW sensors remains also for this multisensor product. Therefore, IR data from GEO satellites are added to improve the spatio-temporal resolution. However, the integration of GEO-IR data in IMERG is limited to only one IR channel at 10.7 µm, which leads to uncertainties regarding IR based precipitation measurements in the merged IMERG product. In this context, the IMERG development team recommends the use of multispectral GEO data together with modern machine learning techniques to improve these deficiencies (Huffman et al. 2018).

Information on water storage changes via gravity field analysis and satellite altimetry

Almost in parallel to the decline of in situ gauging stations over the past few decades, satellite-based and model-based global data products have been increasingly used to derive hydrometeorological quantities, especially in areas with weak infrastructure. Example overviews of remote sensing-based methods for determining runoff in unobserved catchments are given by Alsdorf et al. (2007) and Sneeuw et al. (2014). Especially in arid and semi-arid areas, climate change makes it increasingly important to provide reliable estimates for key water balance variables, the water surface height being one of them. Satellite altimetry has proven effective in monitoring inland water surfaces, and subsequently, in understanding the hydrological cycle. Since the launch of TOPEX/Poseidon and Envisat missions, monitoring lakes, reservoirs, and rivers has been a research focus (Birkett, 1995; Crétaux et al., 2011). Deriving water level time series from altimetric measurements is by definition a straightforward procedure (Berry et al., 2005; Fu and Cazenave, 2000). As far as inland applications are concerned, however, multiple factors may degrade the reliability of the results. This is mainly rooted in the disproportionality between the cross-over width and radar footprint size, leading to heterogeneous radar reflections, off-nadir measurements, and less characterized waveforms. Imprecise geophysical corrections even further degrade the accuracy and precision of the derived water heights (Crétaux et al., 2009; Maillard et al., 2015; Normandin et al., 2018; Santos da Silva et al., 2010; Schwatke et al., 2015). In order to tackle the problems of inland altimetry many studies have been performed in the direction of retracking (Arabsahebi et al., 2018; Boergens et al., 2016; Davis, 1993; Idris and Deng, 2012; Laxon, 1994; Passaro et al., 2014; Villadsen et al., 2015; Wingham et al., 1986), off-nadir and hooking effect correction (Maillard et al., 2015; Santos da Silva et al., 2010), outlier rejection (Schwatke et al., 2015), etc. The state of the art inland altimetry has also benefited from the recent technological advances. With the launch of CryoSat-2 in 2010, for instance, the delay/Doppler concept was implemented for the first time, reducing the along-track resolution of the altimeter from a few tens of kilometers to about 300 m (Raney, 1998). Same concept has been used ever since by the Copernicus missions Sentinel-3A, Sentinel-3B, and the recently launched Sentinel-6 Michael Freilich. Another technological improvement was the introduction of Open Loop Tracking Command (OLTC) which is especially beneficial to inland applications. The OLTC is an on-board feature used to set the altimeter waveforms reception window. This is done via a priori surface elevation tables and helps in keeping track of inland water bodies (Le Gac et al., 2019). Currently the missions Jason-3, Sentinel-3A, Sentinel-3B, and Sentinel-6 are equipped with OLTC tables. The altimetry community is about to experience yet another major step forward with the launch of the Surface Water and Ocean topography (SWOT) mission in 2022. SWOT is designed based on the so-called wide swath altimetry concept, namely, the use of radar interferometry at near-nadir incidence to achieve global coverage in acquiring centimeter-level accurate water elevation (Biancamaria et al., 2016; Rodriguez et al., 2018).

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4.2. Global and regional ecosystem modeling: state detection and functionality

Dynamic ecosystem modeling

While the global impacts of rising temperatures and CO_2 concentrations have been subject of numerous studies, there is limited knowledge about the projected changes in precipitation amount and distribution (IPCC, 2014). The patterns of precipitation changes do not show large-scale uniform trends but rather are highly variable spatially and their effects depend largely on the existing vegetation and its sensitivity. Their analysis thus requires fine resolution studies. Process-oriented models such as dynamic vegetation models provide tools to investigate the effect of rainfall amount and distribution on the vegetation type and its sensitivity and the provision of ecosystem services (especially carbon storage, crop yields, provisioning of water, Bayer et al. 2015, Gerten et al. 2007, Krause et al. 2016). This is especially important in drylands, where water resources are scarce. In SaWaM, the global vegetation model LPJ-GUESS (standard spatial resolution 0.5° ~50 km) was run in the study regions on a finer resolution using regional input data (higher resolution land-use data, SaWaM downscaled climate data).

Ecosystem monitoring from satellite remote sensing

In addition to process-oriented models, the globally available Earth observation satellites with their high spatio-temporal resolution are also an important source of data for the regional assessment of the seasonal and long-term dynamics of vegetation cover as a function of the water balance (and runoff/sediment transport). Linking satellite information with models is still a challenge (e.g. bridging different spatial/temporal scales), on the other hand with the potential for adding significant value. In recent years, the possibilities of satellite time series analysis have expanded to several decades (Belward et al. 2008, Kennedy et al. 2014), enabled by the opening of the LANDSATsatellite data archive in 2008 (30m spatial resolution, Wulder et al. 2012). With the open data policy of the large space agencies and the increasing availability of long satellite time series of medium spatial resolution (LANDSAT since 1972, MODIS since 2001) as well as the launch of the Sentinel-2 mission of ESA in 2015 with a comparatively high spatial resolution (10m/20m), the development of satellite time series analyses has increased strongly. Thus, software for the harmonisation and analysis of satellite time series, such as FORCE, eo-learn, and BFAST, has been developed in recent years, as well as cloud-based platforms that allow access to and analysis of large amounts of data (e.g., GoogleEarthEngine).

Significance of erosion hotspots

Siltation of reservoirs, also frequently called sediment entrapment or infilling of reservoirs, is a significant problem in semi-arid regions where water is scarce and land degradation frequently results in high sediment loads in rivers entering reservoirs (Cooper et al. 2018, Rhamani et al. 2018, Zarfl & Lucia, 2018). The sediment inflow in reservoirs reduces water storage volume, thereby endangering the water available for citizens, irrigated agriculture, and hydropower energy generation (Abbdelrezzak & Findikakis, 2018). When water is the dominant mechanism of soil loss across a catchment, soil-water conservation measures in sediment source areas can drastically decrease catchment sediment yields (Liu et al. 2018, Shi et al. 2019). Modeling and monitoring studies showed that timely and spatially adjusted management can significantly decrease downstream sediment delivery (Nunes et al. 2013, Mullan et al. 2016). However, sediment sources are unknown in many semi-arid catchments, and no data are available to adjust management accordingly. Moreover, limited financial resources to apply soil-water conservation measures and institutional barriers pose further challenges for water and land managers (UN Water, 2018). In such situations, identifying and managing areas contributing to high sediment yields, also called sediment hotspots, are crucial to decrease sediment inputs to reservoirs.

Application of sediment hot spot mapping and delivery of reliable outputs is limited by data availability and understanding of the processes driving sediment delivery in respective catchments. The misidentification of sediment sources and pathways increases the risk of reservoir infilling with serious consequences on water shortages in semi-arid regions already unprivileged in many aspects (e.g., economically and environmentally). Retaining reservoir volumes is of primary importance for sustaining drinking water, irrigation water availability, and hydropower generation, and is a primary concern of water managers.

There is an urgent need to improve current mapping approaches for the so-called leverage areas, which are sediment hotspots where management would have the greatest impact on reducing erosion and sediment delivery into downstream bodies (e.g., dam, catchment and outlet). For this purpose, mapping approaches are required which explicitly take into account the severe data sparseness of semi-arid catchments such as Iran and Sudan.

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4.3. Regional hydrosystem modeling and water management

Scalable Seasonal Hydrological Forecasting with Representative Reservoir Operation

The main problem of current global drought and flood monitoring systems is their low spatial resolution of their products (about 0.5°) and the lack of validation of the simulated hydrological variables (e.g., soil moisture or runoff). Existing systems (e.g., EFAS in Europe) are not seamless, nor scalable. Hydrological models (HM) lie at the center of any seasonal hydrological forecasting system (SHFS). We identified two major drawbacks in the state of the art HMs.

First, the contemporary hydrological modeling efforts have overlooked the consistency of simulations across resolutions i.e. lack scalability. Scalability is an important feature of model reliability as model parameters can then be transferred across scales to obtain virtually the same output. In SaWaM, we are interested in reliable simulations of hydrology with reservoirs. Existing HMs either classify reservoirs into classes and process them differently (CamaFlood in Shin et al. 2020, LHFD in Shin et al. 2019, PCR-GLOB in Sutanudjaja et al. 2018, Wada et al. 2014 and Van Beek et al. 2011, VIC-ResOpt in Dang et al. 2020, VIC in Haddeland et al. 2006b and Haddeland et al. 2006a, DHVSM in Zhao et al. 2016, SPHY in Terink et al. 2015, LPJmL in Biemans et al. 2011, LISFLOOD in Zajac et al. 2017 and Burek et al. 2013) or they treat all reservoirs equally but accommodate only one reservoir on a major stream per grid (CWatM in Burek et al. 2020, H08 in Hanasaki et al. 2018, Hanasaki et al. 2010, Hanasaki et al. 2008 and Hanasaki et al. 2006, WaterGAP in MullerSchmied et al. 2020 and Doll et al. 2003, WBMplus in Wisser et al. 2010). Both of these approaches impede scalability as in the former scheme the reservoir class changes with model resolution and in the latter scheme the one reservoir per grid approach leads to reservoirs appearing and disappearing across scales.

Second, the existing HMs have indirect representations of reservoir regulation. Due to this, it is hard to draw parallels between the techniques used in HMs and the reservoir operation reality which is the conjunctive use of rule curves, demand estimates and hedging rules. Out of the three, only demand estimation has been comprehensively studied in operational HMs.

Regional modeling of water management and hydro-sedimentological processes

The water availability in semi-arid regions is largely dependent on regional forms of water use and water management. Hydro-sedimentological models describe the relevant hydrological and sediment processes, e.g., surface runoff in the often variable rainfall seasons, hydrological connectivity, as well as the mechanisms and effects of water management impacts, e.g., irrigation water demand, water retention and sediment flows in reservoirs (e.g., Loucks et al. 2005, Morris & Fan 1997, Palmieri et al. 2001).

The complexity of these models has increased steadily in recent years and decades (e.g. Arnold et al. 1989, Kirkby 1997, Mauser et al. 2015), but there is a gap between highly generalized models suitable for larger scales (e.g., Krysanova et al. 2000, Rohwer et al. 2006) and detailed small-scale models (e.g., at slope scales) with high data requirements emerged (e.g. Blöschl & Sivapalan 1995, Güntner & Bronstert 2004, Schmidt 1991, Sidorchuk 1998).

With the WASA-SED model (Müller et al. 2010), which is geared toward semi-arid conditions, a hydro-sedimentological model system was developed, using a multiscale approach (areas between a few hectares and several 100 000 km²) on a regional scale. Crucial aspects of the practical water management and their impacts (e.g., coverage of irrigation demands, expected sediment flows into reservoir bodies as a function of existing vegetation condition, etc.) have not yet been realized, however. These are to be implemented in SaWaM using the example of developing regions in order to enable integrated regional modeling of hydrosystems and sediment fluxes, under changing boundary conditions and requirements, including different options of water management.

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4.4. Water management practice, user dialogue and development of the online prototype

Reservoir management in the context of large-scale water management projects

The management of a reservoir upstream of a dam has the objective to efficiently use stored water volume, for example, to increase the annual electricity production at hydropower plants or to reserve water for irrigation or drinking water. At Tractebel Engineering, dams are designed primarily for power generation or as multipurpose projects for various purposes (e.g. power generation, irrigation, drinking water, flood control). Based on historical data, mostly discharge time series of the last decades are used to perform reservoir management. Thus, over many years, variations in inflow are considered with a daily to monthly time step. Optimized reservoir management through seasonal prediction of relevant parameters, such as inflow, precipitation, temperature, or sediment input to the reservoir, is often not considered due to the lack of appropriate practical methods and tools. Consideration of seasonal forecasting would lead to improved estimation of water supply. The flow diagram in Figure 1 shows an example of the difference between planning a hydropower plant with and without seasonal forecasting as it is shown in practice at Tractebel.

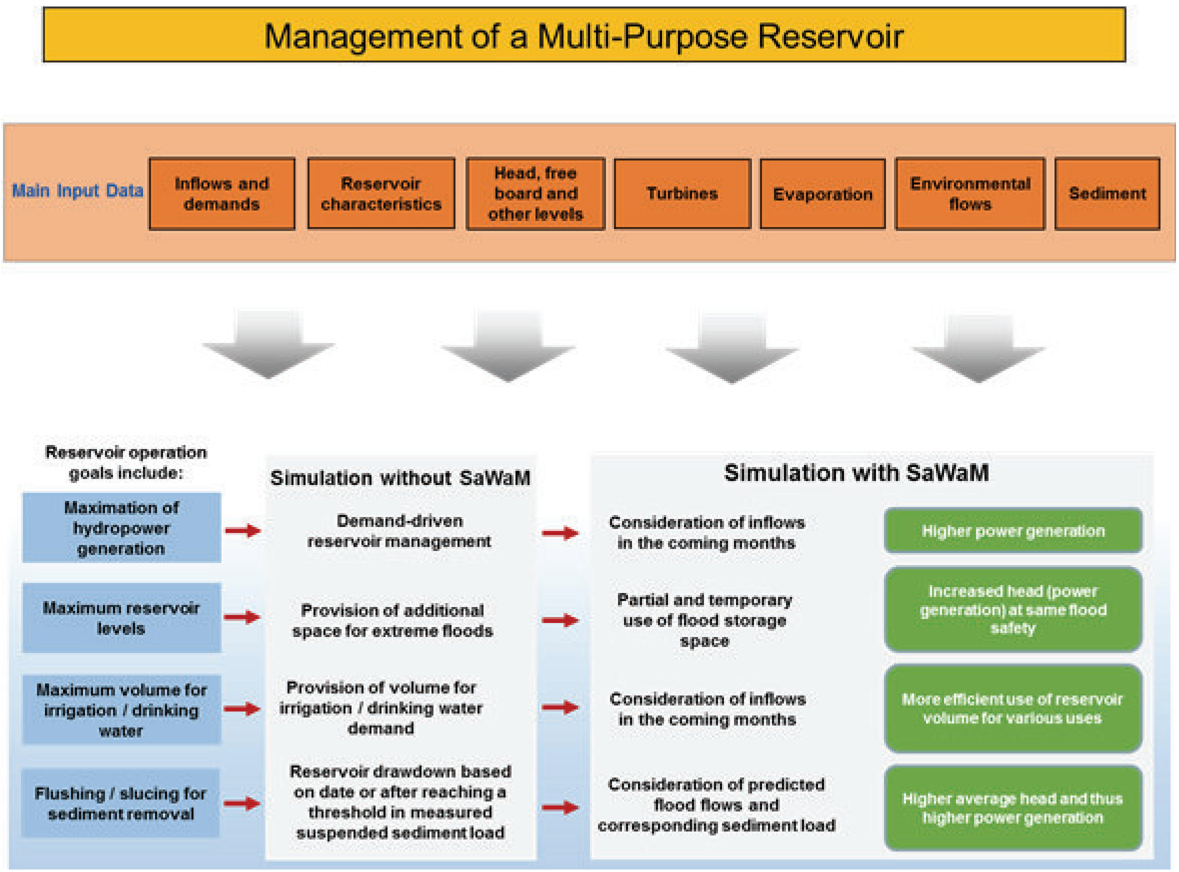

Figure 1: Information requirements and typical process of reservoir management (practical experience Tractebel)

Tractebel has not yet incorporated seasonal water supply forecasting into reservoir management and would like to raise interest for this optimization of reservoir management with dam operators.

SW-Development of Online Prototype for Decision Support

Dam and reservoir management are depending on numerous environmental parameters defined by the environmental situation in the basin they are situated in. To better understand and work in this environment practitioners and decision makers can gain significant insights into these systems using spatio-temporal information. Historical information on basins and upstream situations of dams together with the recent situation and forecasts are presented in the Online Prototype developed for SaWaM. It is based on State-of-the-art technologies for web based spatio-temporal representation of geo-information, using OGC based standards and interface protocols.

The following requirements collection, development and test steps needed to be performed:

- Development of a basic concept for visualisation and data retrieval
- Development and testing of integration of multidimensional data from hydro-climatological and hydrological models into the online application
- Feedback on water management practices from partners and users in the target areas during project meetings and workshops
- Collection of additional available information layers
- Selection of main information layers during midterm meeting
- Easy access to complex information presenting absolute and categorised model results
- Definition and selection of information layers
- Division in Forecast and Hindcast (history)
- Presentation of forecasts and accuracy information with accuracy information
- Development of the Online Prototype for decision support (DSS)

The system is self-explanatory providing the content in different layers together with scientific background information and explanations.

4.5. Description of the study regions

SaWaM focuses on target regions that are already characterized by water scarcity, namely semi-arid regions. Here, the considerable increase in water consumption is caused in particular by intensified land use, irrigation, but also by industry. Erosion of overused land surfaces and consequent increased sediment deposition in reservoirs can significantly limit the long-term reliability of water and energy supplies. Sustainable and science-based water resource management can potentially increase this reliability considerably, especially if improved planning information is derived in regions that are typically data- and infrastructure-poor. This was exactly the goal of SaWaM. We selected a total of five regions for the development and transfer into practice of our SaWaM methods.

1. Sudan/Ethiopia - Tekeze-Atbara and Blue Nile basins
2. Iran - Karun basin
3. Brazil - extended catchment area of the São Francisco River
4. Ecuador/Peru - Catamayo-Chira basin
5. West Africa - Niger and Volta basins.

In all five areas, long-standing cooperations and thus excellent conditions for an effective project integration already existed through the project partners (Fig. 1). In Sudan we even participated directly with an ongoing project of our economic partner Tractebel Engineering GmbH.

Figure 1: Overview of the SaWaM target regions and integrated project partners.

Sudan/Ethiopia - Tekeze-Atbara and Blue Nile basins

The Tekeze-Atbara and the Blue Nile rivers are the main tributaries of the River Nile with an area of 205,000 km^2 and 308,000 km^2, respectively. The Blue Nile river alone already contributes by 57 % to the River Nile runoff. More than 70 % of the annual precipitation in case of the Blue Nile and more than 80 % in case of Tekeze-Atbara fall within the rainy season from June to September. The annual rainfall for the Blue Nile and Tekeze-Atbara sum up to 1336 mm and 727 mm, respectively (Lorenz et al., 2021). The basins are thus characterized by a semi-arid climate with an extended dry period and one rainy season. The headwaters are located in mountainous areas of the Ethiopian Highlands with relatively high seasonal precipitation amounts, while the downstream conditions are mainly arid. The basins are heavily managed including many reservoirs which are used for maintaining water security and also electrical power supply throughout the year.

The multipurpose Upper Atbara Dam Complex is currently the largest infrastructure project in Sudan and has been a major pillar for the country's development since its completion in 2017. The primary objective of the project is to store and provide water for the 300,000 ha Upper Atbara Irrigation Project and for the 150,000 ha of the existing New Halfa Irrigation Area, and to use this water to generate 320 MW of environmentally friendly electrical power. Furthermore, the Gadaref region is supplied with 75 million liters of clean drinking water per day from the reservoir. The need for food production and the need for electrical power for industrial consumers and households for the rapidly growing population are two of the most important challenges in Sudan. The project is located about 400 km east of the capital Khartoum and near the Ethiopian border, about 20 km upstream of the confluence of the Upper Atbara and Setit rivers, and includes Rumela Dam on the Upper Atbara and Burdana Dam on the Setit. The Rumela Dam reaches a height of 55 meters and the Burdana Dam on Setit a height of 50 meters. The two dams are connected by a 13 km long earthfill dam crossing both rivers. The double dam project has a total reservoir with a storage capacity of about 2.7 billion cubic meters of water at a maximum water level of 521.0 meters above sea level. The project includes a hydropower plant at Rumela Dam with a total installed capacity of 320 MW and an outlet structure to manage inflows for irrigation and water supply. Reservoir management requires very comprehensive consideration, as various, sometimes competing, issues need to be taken into account, such as lowering the reservoir water level in time before the annual flood to minimize sediment deposition in the reservoir while providing sufficient water for irrigation.

Just off the Sudanese-Ethiopian border, the Grand Ethiopian Renaissance Dam (GERD) has been under construction since 2011 with a reservoir capacity of 74 billion m^3, which is about 1.5 times the mean annual flow of the Blue Nile. The GERD will thus be the largest dam ever constructed in the Blue Nile basin and the largest hydroelectric power generation in Africa. The filling of the reservoir started in 2020 and will continue for 6 to 7 years reaching the full supply level of 640 m a.m.s.l. The installed capacity of the dam is 5150 MW and is expected to generate about 16 TWh of energy annually. There is consensus that the GERD will completely change the flow regime of the Blue Nile with reduced Blue Nile floods and increased base flow (Mordos et al., 2020; Wheeler et al., 2020). Agreements are still missing on the transboundary management of dam operations on the GERD and the downstream dams such as the High Aswan Dam in Egypt. In particular, multi-year droughts require a careful coordination of the management of water resources in this transboundary basin. This underscores the urgent need for longer-term forecasts to mitigate the impacts of extreme climatic events, to improve regional disaster preparedness, and to better plan the distribution of water resources for the coming season, particularly in transboundary river basins.

Iran - Karun basin

The Karun river basin is one of the largest river basins in Iran. The greater Karun river basin is formed by the Dez and Karun River basins, which originate in the Zagros Mountains. The total catchment area is 67,000 km^2, of which 67 % is in the mountains and 33 % in the foothills and lowlands. The Karun flows into the Persian Gulf. More than 70 % of the annual precipitation falls within the rainy season from December to March. Here, the annual precipitation varies from 153 mm in the southern lowland areas to 2000 mm in the mountains. Especially high contrasts between the dry and wet season of the Karun basin are also observed in terms of temperature, with a range of more than 40°C (Lorenz et al., 2021). Climatically, the region is characterized arid to semi-arid. There is also a very strong climatic and elevation gradient from the head- to the tailwater within only a few hundred kilometers. The long-term mean annual runoff for the basin up to the Gotvand gauge is reported to be 410 m^3/s. In the downstream catchment, the Dez River is the only significant tributary, contributing 230 m^3/s to the total runoff.

In its middle and lower reaches is the Iranian province of Khuzestan, which depends almost entirely on this river for water and electricity. Khuzestan is one of Iran's most industrially developed zones, with nearly 90% of Iran's oil production and about 25% of Iran's heavy industry. 4.5 million people live in the region. The center of the province is the city of Ahvaz, which lies on the banks of the Karun River and has a population of about 1.1 million.

Currently, with the Dez, Karun 4-, Karun 3-, Karun 1- (Shahid Abaspour Dam), Godarlandar as well as Gotvand dams, a total of six hydropower plants with a total of 16.8 billion liters of dam capacity, 9,470 WM total capacity and 20,614 GWh total annual electricity production have been implemented in the study area. In this respect, the Karun is the most important Iranian river basin for hydropower generation. At the same time, increasing sedimentation in reservoirs is a serious problem for all dams. It is currently considered the most important challenge to securing long-term hydropower generation. It is assumed that about 1,134,702 ha of agricultural land in the study area is suitable for irrigation activities. Already, 25 modern irrigation networks irrigate about 325,560 ha of land, 24 other networks with poorer modernization standards irrigate an additional 15,750 ha of land, and three other networks of older type irrigate a total of 40,000 ha of land. This also makes the Karun region the most important center for agriculture and food production in Iran. Increasingly heavy use of the Karun River's water resources has led to a sharp decline in the area of wetlands in the lower reaches of the river, about 50-100 km from its mouth in the Persian Gulf (Horolazim and Shadegan wetlands), with significant ecological problems, but also consequences for the population, such as increasing salinization of water resources.

Brazil - extended catchment area of the São Francisco River

The study area of the São Francisco river basin is one of the most important river basins in Brazil, with 741,000 km^2. Much of the area belongs to the country's famous "dry polygon". The annual precipitation is 858 mm and 60 % of it falls in the rainy season between December and March (Lorenz et al, 2021). Much of the São Francisco basin extends into a semi-arid area where approximately 15 million inhabitants rely heavily on its water resources. As a result, the use of river water is under great demand pressure, both because of limited, natural water availability, and because of an increased demand for water (due to a wide variety of reasons) within the last few years.

The river is heavily managed by dams, river diversions, and water withdrawals. The area of the basin is characterized by intensive agriculture and mining activity, the latter mainly in the upper reaches. 75 % of the river water is generated in the upper reaches of the state of Minas Gerais. This area is relatively heavily populated and mining has long been an important economic factor. Thus, Minas Gerais is characterized by extensive environmental impacts, a loss of biodiversity and severe soil erosion. In particular, high sediment mobility affects the approximately 50 hydropower plants in the river basin, which in some cases has considerable consequences for local water and electricity supplies. For example, the Cachoeira Dourada reservoir has already lost 40% of its reservoir volume over the last 50 years. Sediment deposition ("siltation") is a serious problem in almost all reservoirs, especially in the lower reaches of the São Francisco River, where climatic conditions are semi-arid and dams are key to regional water and power supply. In a large-scale national initiative, Brazil's Ministério da Integração Nacional (MI 2015) initiated the Basin Interlinking Project, which aims to improve water supply for 12 million people in urban and rural areas of the states of Ceará, Rio Grande do Norte, Paraíba, and Pernambuco by transferring water from the São Francisco to the river systems there. These areas, located north of the basin, will be connected by a 402-km-long northern spillway and a 220-km-long eastern spillway. In this way, the São Francisco river basin expands into a larger hydrological system, the "Extended" São Francisco river basin. The São Francisco basin is therefore highly complex because different water users compete, upstream and downstream consumptive uses strongly affect each other, and interrelated reservoirs or newly constructed river transfers tend to affect adjacent basins that are even more water-scarce than the São Francisco basin.

Ecuador/Peru - Catamayo-Chira basin

The Catamayo-Chira Basin covers an area of about 18,000 km^2 in the area of the border between Ecuador and Peru. The main course of the Catamayo Chira River is 315 km long and high climatic and topographic gradients are present within these few hundreds of kilometers. The altitude level in the area ranges from about 100 m a.s.l. at Poechos Dam to 3788 m a.s.l. at Fierro Urcu Peak in Ecuador. The terrain, rainfall distribution, and land cover within the basin are highly variable, as is its biodiversity, which includes eleven holdridge life zones. The predominant land cover of the basin is mountain rainforest (41 %), followed by grassland (29 %), tumbesian dry forest (14 %), and cropland (10 %). Large areas of the basin are protected areas, including the two UNESCO "Podocarpus - El Condor" and (bi-national) Bosque Seco Biosphere Reserves. The headwaters are mostly located in Ecuador and are covered by mountain rainforests and Andean paramo.

The rainy season is mainly between January and April, contributing 65 % to the annual rainfall that is the highest among the study regions with 1666 mm (Lorenz et al., 2021). The average annual discharge of the Chira River (at Sullana) is 480 m^3/s with daily values ranging from 25 m^3/s (October) to 3000 m^3/s (March).

The Poechos Dam (capacity: 885 x 106 m^3, water surface 55 km^2) was commissioned in 1976 for power generation (15.4 MW capacity, 60 GWh annual production), flood control for downstream towns such as Sullana (230,000 inhabitants), and irrigation of about 350 km2 of agricultural land in the Piura Basin. The average annual inflow to the Poechos Dam is 3.2 × 109 m^3. Rapid land-use changes, especially ongoing deforestation in the upper reaches, and climate change have now led to major water management problems. For example, the usable volume of the reservoir has decreased by 53 % since construction. One reason for this is the high sediment input caused mainly by increasing deforestation in the Ecuadorian headwaters and high precipitation intensities during El Niño events. During La Niña events, on the other hand, water scarcity prevails. Sustainable water management is hampered in particular by the poor hydrometeorological data situation in the area.

West Africa - Niger and Volta basins

The Volta Basin in West Africa covers an area of approximately 414,000 km^2, with Ghana sharing the largest share of 40 % and Burkina Faso 42 % of the total area. Other countries participating in the total area of the Volta Basin are Benin, Togo, Niger, Mali and Ivory Coast. The Volta Basin is composed of several sub-basins, of which those of the Black and White Volta are the largest. Both rivers flow into the Volta Reservoir, which covers about 8500 km^2 and is impounded by the Akosombo Dam located in southeastern Ghana. The climate of the Volta Basin can be characterized as semi-arid in the north to sub-humid in the south. The mean annual precipitation totals range from about 400 mm in the north to 2000 mm in the southeast. About 80 % of the precipitation falls between July and September, which makes the rain-fed agriculture that prevails there strongly dependent on precipitation. In the semi-arid regions in the north, the (intra-)seasonal rainfall variability is greatest. There, above all, a more precise forecast of the start of the rainy season and the associated sowing date is of decisive importance for agricultural production success. A population growth of about 3 % combined with strong exploitation of natural resources threatens food security in the region. In addition, the Volta Reservoir is predominantly used for power generation, but poor management regularly results in power outages.

The Niger River basin surrounding the Volta has a size of 2.261 million km^2 and supplies about 110 million people with water. It covers a total of 10 countries, of which Niger, Mali and Nigeria account for about 75 % by area. Rainfall variability in the basin varies widely nationally, with the greatest range found in Mali, where annual rainfall totals vary from 1500 mm in the south to 50 mm in the north. Similar to the Volta Basin, frequently recurring periods of low water, but also extreme floods, lead to crop failures and increasingly threaten the livelihoods of the local population. The data basis of hydrometeorological and geological data is insufficient and does not provide a sufficient basis for sustainable and integrated water resource management.

5. Results

5.1. Regionalized operational hydrometeorological seasonal forecasting for improved climate proofing: system development, economic benefit, performance gain

Tanja Portele[1], Christof Lorenz[1], Patrick Laux[1], Maurus Borne[1], Berhon Dibrani[2], Harald Kunstmann[1]

[1]Karlsruhe Institute of Technology (KIT/IMK-IFU), [2]Tractebel Engineering GmbH

Increasing demands for water in a wide range of fields will enhance the amount of people suffering from water scarcity in the near future. Particularly semi-arid regions are lacking reliable knowledge about the available freshwater resources and the occurrence of extreme events for the next season. In semi-arid regions, the interannual variability of seasonal rainfall and climate change is further expected to stress water availability and to increase the recurrence and intensity of extreme events such as droughts or floods. Local decision makers therefore need reliable long-term hydrometeorological forecasts to support the seasonal management of water resources, reservoir operations and agriculture.

Increasing frequencies of climate extreme events in semi-arid regions

The semi-arid study regions are highly exposed to climate change. With respect to the occurrence of warm extreme events and droughts between 1981 and 2018, a significant trend of increasing relative frequencies was identified across the study regions of Extended São Francisco, Niger, Volta, Atbara, Blue Nile and Karun (Fig. 1). On average, the relative frequency of warm extreme events with temperatures above the 80 percent quantile significantly increased from 10 % to 60 %. For long-term droughts, with a standardized precipitation and evapotranspiration index over six months (SPEI6) smaller than -1, the relative frequency likewise increased from below 10 % to around 30 % within the last decades. Climate change thus increases the frequencies of extreme events causing human suffering and major economic damage. This calls for sound action against climate change and long-term measures for the planning and managing of water resources months ahead.

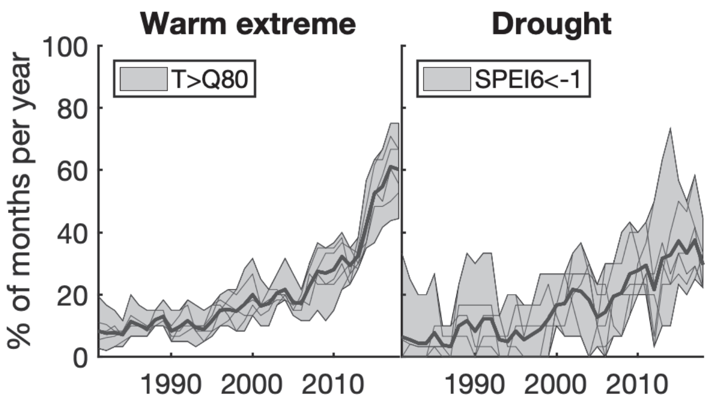

Figure 1: Relative frequency of climate variables from 1981–2018. The relative frequency of ERA5 mean temperature (*T*, left), and drought index (SPEI, right) exceeding the respective quantile event thresholds (> Q80,< −1) are shown for the basin-averages of Karun, Extended São Francisco, Tekeze-Atbara, Blue Nile, Niger and Volta. The thick solid lines denote the mean relative frequency over the 6 basins, and the shaded areas encompass the thin solid lines for the 5-year moving averages of relative frequencies of the individual basins. (Figure adapted from Portele et al., 2021).

Global seasonal forecasts offer economic benefit for hydrological decision-making

By predicting rainfall amounts and temperatures more accurately for weeks and months ahead, local decision makers can, for example, manage and plan water reservoirs more proactively. In particular, by providing early warning of drought or warm extreme events, seasonal forecasts provide the opportunity to take timely action to minimize damage and losses, and more effectively mitigate the impacts of climate change. However, decision makers still hesitate to use seasonal forecasts. They claim a lack of confidence and credibility due to their probabilistic nature and consequent uncertainties.

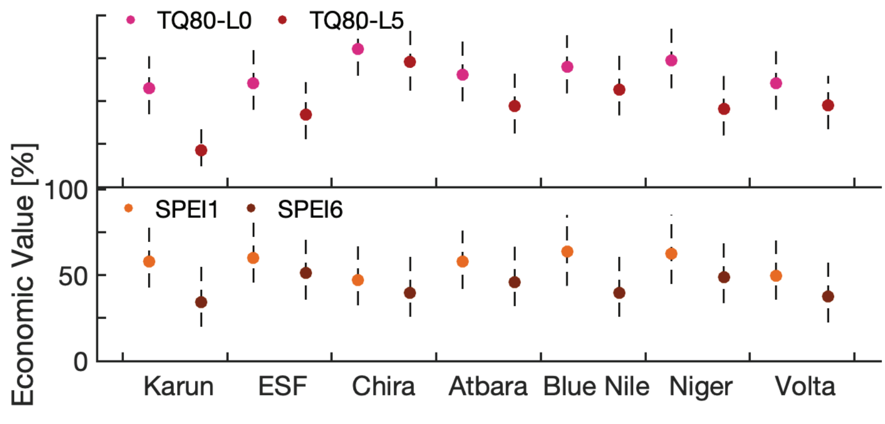

Figure 2: Maximum potential economic value (PEV_{max}) for forecast-based action. PEV_{max} of SEAS5 with reference ERA5 is shown for the seven river basins for rainy seasons of the hindcast period 1981-2016. Colored dots represent the fully evaluated PEV_{max} for the events of T > Q80 for leadmonths 0 (L0) and 5 (L5), and for the events SPEI < −1 and SPI < −1 for aggregation scales over one (SPI1/SPEI1) and 6 months (SPI6/ SPEI6). The uncertainty of the estimation of PEV_{max} is assessed with the confidence range between the 10% and 90% quantiles of bootstrap resampling (dashed line). (Figure adapted from Portele et al., 2021).

To implement and promote the use of seasonal forecasts, - as a first step - the actual economic benefits must be demonstrated when decisions and actions are based on forecasts. Within SaWaM, we therefore addressed the crucial question of whether beneficial proactive drought-and extreme event preparedness as well as risk mitigation in water management could be provided by the use of global seasonal forecasts (Portele et al., 2021). Here, the potential economic value (PEV) assessment is a direct way to recommend actions based on forecast probabilities without having detailed operational information and interaction with a decision maker. It evaluates decisions based on relative economic savings. User costs and losses associated with the decisions are also considered.

For the assessment of *PEV*, we used basin-averages of the latest global seasonal forecast product SEAS5 by the European Centre for Medium-Range Weather Forecasts (ECMWF) at a resolution of 35 km and defined extreme events with relative thresholds to circumvent possible biases in absolute values. We showed that seasonal drought forecasts save up to 70 percent of the costs that would have been possible if optimal action had been taken at an early stage (Fig. 2). For warm extreme events, potential economic savings even above 70 % are possible. These savings not exist for short lead time, i.e. short forecast horizons of one month (lead month 0), but also for high lead times and long forecast aggregation times: For very warm months and droughts, savings of at least 20 % are achieved even for forecast horizons of six months ahead. For the large Upper Atbara Dam in Sudan, we were able to exemplify the exact savings potential for a drought year in cooperation with our industry partner Tractebel Engineering GmbH. It amounts to 16 million US dollars.

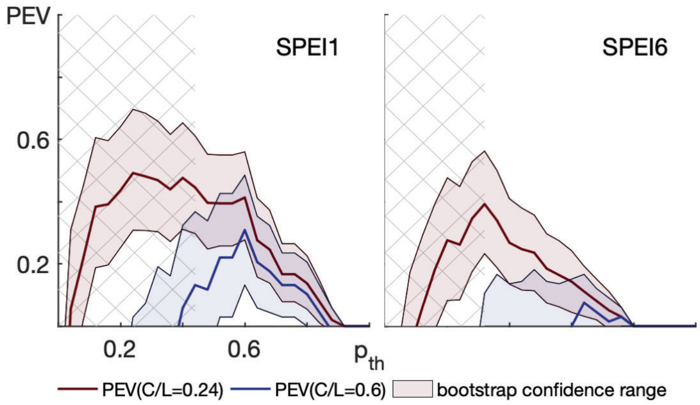

Figure 3: Potential economic value (*PEV*) as a function of probability threshold p_{th} for the Tekeze-Atbara basin. *PEV* of SEAS5 with reference ERA5 is depicted for drought events (over 1 month: SPEI1, over 6 months: SPEI6) during rainy seasons of the hindcast period 1981-2016 for users' cost-loss ratios of 0.24 (red) and 0.6 (blue). The uncertainty of the estimation of PEV_{max} is assessed with the confidence range between the 10 % and 90 % quantiles of bootstrap resampling (shaded area). The cross-hatched area further represents where the hit rate H > 0.5 to base the choice of p_{th} on the event maximization criterion. (Figure adapted from Portele et al., 2021).

Our approach further enables the direct decision-support according to maximum achievable economic benefit for a given user's cost-loss situation and the given forecast probability of the extreme event (Fig. 3). For water management policies, forecast probability thresholds for early action plans can thus be suggested based on criteria for minimizing the expenses (expense minimization) and maximizing the number of hit events (event maximization, including a certain degree of risk aversion of the decision maker). For the example of the Tekeze-Atbara basin, a user with a cost-loss ratio of 0.6 (blue in Fig. 3) would thus mostly benefit from forecasts of short-term droughts (SPEI1) with forecast probabilities around 0.6. However, to minimize his risk and to include the event maximization criteria (cross-hatched in Fig. 3), the decision-maker would be advised to use probability thresholds between 0.4 and 0.43. In general, users with lower cost-loss ratios can benefit more than users with high cost-loss ratios and also show larger ranges of beneficial probability thresholds, especially for long forecast horizons (six months drought index SPEI6).

Longer-term, sustainable planning several months in advance of the next rainy season is becoming increasingly important. With increasing demands on water management as drought and warm weather extremes have become more frequent in recent decades, switching to beneficial early actions based on seasonal forecasts saves costs and supports climate mitigation (Portele et al, 2021). Therefore, we emphasize the benefit and necessity of incorporating seasonal forecasts into hydrological decision making.

Performance gain of regionalized and bias-corrected seasonal forecasts

Since climate information from globally available seasonal forecast models is often too coarse for final local application in decision making below the basin scale or for spatially distributed climate impact models, and furthermore often suffers from biases when absolute values are required, the regionalization and correction of global forecasts is essential as a second step for sustainable regional water resource management. Within the SaWaM project, we therefore developed a regional hydrometeorological seasonal forecasting system applying a regionalization and bias-correction approach to global seasonal forecasts to be able to provide high-resolution (0.1°), pixel-based information on absolute rainfall amounts, temperatures and incoming solar radiation (Lorenz et al., 2021).

In data-scarce regions, the definition of the suitable reference data set for bias-correction is already challenging. In some regions, like in Iran or Sudan, the uncertainty of different reference data sets with respect to precipitation is large. In other regions, like Northeast Brazil, a higher level of agreement is evident. Regarding the necessity of a comprehensive reference data set also for impact modelling, a reference is required including the different hydrometeorological variables of precipitation, temperature and incoming radiation. Therefore, we used the high resolution (0.1°) land surface replay of the ECMWF reanalysis system ERA5 (i.e., ERA5-Land) as a comprehensive reference data set, providing the required consistent hydrometeorological information. With ERA5-Land, both a bias-correction and spatial disaggregation (BCSD) to 0.1° of the global seasonal forecasts was performed.

The latest global seasonal forecasting system SEAS5 of ECMWF was used in the SaWaM project issued each month with a forecast horizon of 215 days. In the BCSD-approach, we corrected the daily data of the SEAS5 forecasts with the ERA5-Land reference through empirical quantile mapping of the cumulative distribution functions including a moving 15-day-window aligned around the current forecast day. In the bias-correction, both the correction of values above or below the reference range of quantiles, and the correction of wet- and dry day frequencies were accounted for. Spatial disaggregation was performed through bilinear interpolation. The BCSD-based seasonal forecasts, produced in SaWaM, are freely available via the World Data Center for Climate (WDCC) from the German Climate Computing Center (DKRZ).

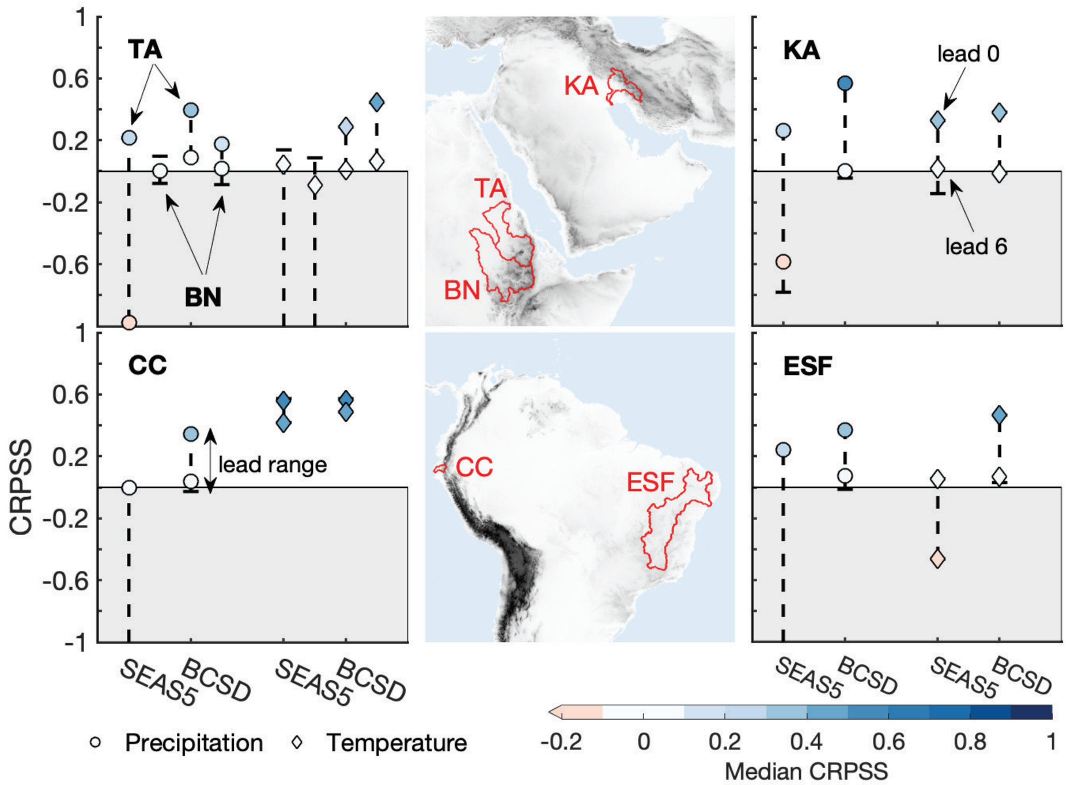

Figure 4: Overall performance evaluated by the Continuous Ranked Probability Skill Score (CRPSS) for precipitation and temperature forecasts of one month during the basins' rainy season of SEAS5 raw forecasts and bias-corrected and spatially disaggregated (BSCD) SEAS5. CRPSS is shown for lead 0 to lead 6 forecasts for July for the basins of Tekeze-Atbara/ Blue Nile (TABN), and for February for the Karun (KA), Catamayo-Chira (CC) and Extended São Francisco (ESF) basins. A CRPSS > 0 defines an on median (1981-2016) better seasonal forecast than a simple climatological forecast.

A fully operationalized regionalization and bias-correction system produces seasonal forecasts after each release of the global seasonal forecasts SEAS5 for the regional hydrometeorology at 0.1° horizontal resolution and with forecast horizons up to seven months ahead. The BSCD approach produces skillful seasonal forecasts over the SaWaM target regions (Fig. 4). With respect to a simple climatological forecast, raw SEAS5 forecasts show limited forecast skill evaluated with the continuous ranked probability skill score (CRPSS), in particular at higher forecast lead times. SEAS5-BCSD forecasts, on the contrary, provide good overall performance (CRPSS) even up to seven months ahead for precipitation and temperature forecasts in the study regions. The BCSD approach further allows for spatial correction of the hydrometeorological fields, providing high agreement with the reference data ERA5-Land (Fig. 5).

SEAS5-BCSD currently is the first publicly available daily high-resolution seasonal forecast product that covers multiple regions and variables for such a long period. It hence provides a unique test-bed as driving data for hydrological, ecosystem or climate impact models. Being further visualized in the SaWaM online tool (https://sawam.gaf.de/), our forecasts provide a crucial contribution for disaster preparedness and, finally, climate proofing of regional water management in climatically sensitive semi-arid regions.

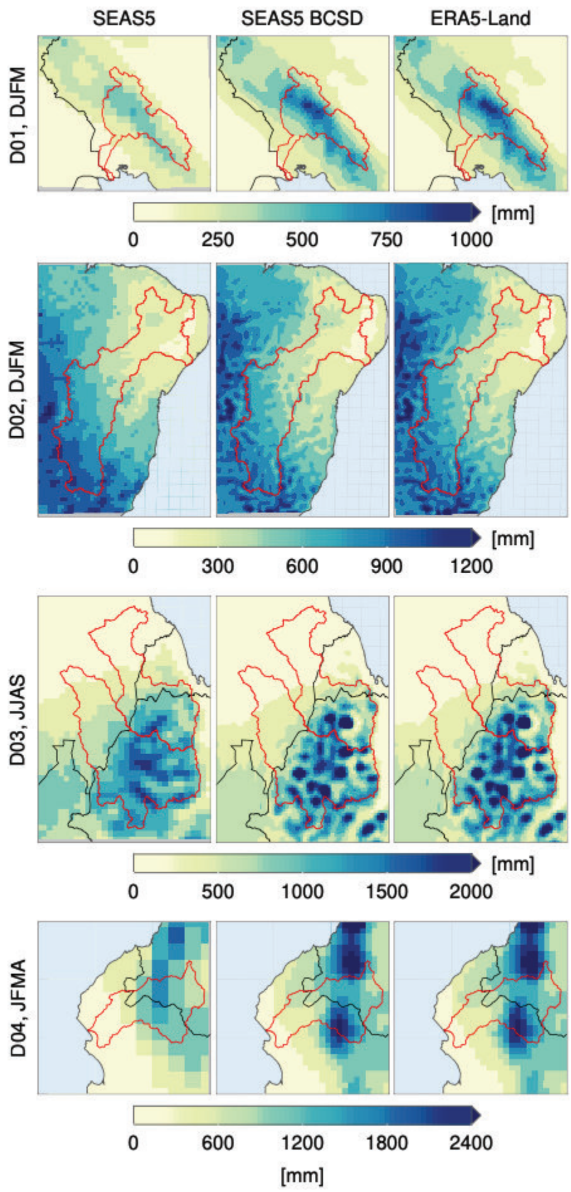

Figure 5: Total precipitation during the four main months of the rainy season for the (from top to bottom) Karun, Extended São Francisco, Tekeze-Atbara/Blue Nile, and Catamayo-Chira domains for SEAS5 (lead 0), SEAS5- BCSD (lead 0) and ERA5-Land averaged over the period 1981 to 2016. (Figure from Lorenz et al., 2021).

Development of seasonal sub-basin-scale runoff predictions

In addition to precipitation and temperature, information on runoff is also needed for sustainable water resource management. Employing the SEAS5-BCSD forecasts and the global freely available datasets of reanalysis precipitation (ERA5-Land), we applied an Ensemble Kalman Filter (EnKF) framework to predict basin-scale runoff. This approach is derived from a previous study (Lorenz et al., 2015), where EnKF-based basin-scale runoff estimations were proven to provide promising results on monthly time scales. For the Kalman Filter-based study, the Rio São Francisco River Basin (SFRB) in Brazil is investigated. Being disposed to have increasing water-related problems in the future (Cunha et al., 2018), the SFRB requires sustainable mitigation strategies and therefore provides a suitable testbed for the EnKF-based seasonal hydrological forecasting system.

The study is based on 12 sub-basins of the SFRB and monthly time series over a total period of 30 years between 1981 and 2011. The 12 sub-basins were delineated given the spatial distribution of the precipitation products and associated with runoff gauges situated at the sub-basins outlet. The daily discharge data of the 12 chosen gauges are collected from the ANA (Brazilian National Water Agency) database and are monthly averaged. Reference precipitation is taken from the ERA5-Land climate reanalysis dataset. Monthly seasonal forecasts for precipitation are obtained from ECMWFs latest seasonal forecasting system SEAS5, which are bias-corrected and spatially disaggregated towards ERA5-Land (SEAS5-BCSD, Lorenz et al., 2020). In the Ensemble Kalman Filter (EnKF), runoff is estimated using least squares predictions, exploiting the spatio-temporal auto- and cross-covariance structures between runoff and precipitation. For the forecast initialization, the observation vector includes the historical precipitation (ERA5-Land) and runoff (ANA) vectors. The corresponding error covariance is equal to zero since we consider perfect observations. During the forecast, the predicted state is updated at each time step using the SEAS5-BCSD precipitation forecasts at the corresponding forecast lead time and including all SEAS5-BCSD ensemble members. Indeed, the whole ensemble is assimilated in order to benefit from all the information contained in the forecasts. Finally, the observation error covariance is estimated from the squared ensemble spread of the SEAS5-BCSD precipitation ensemble forecasts for the given region and forecast horizon.

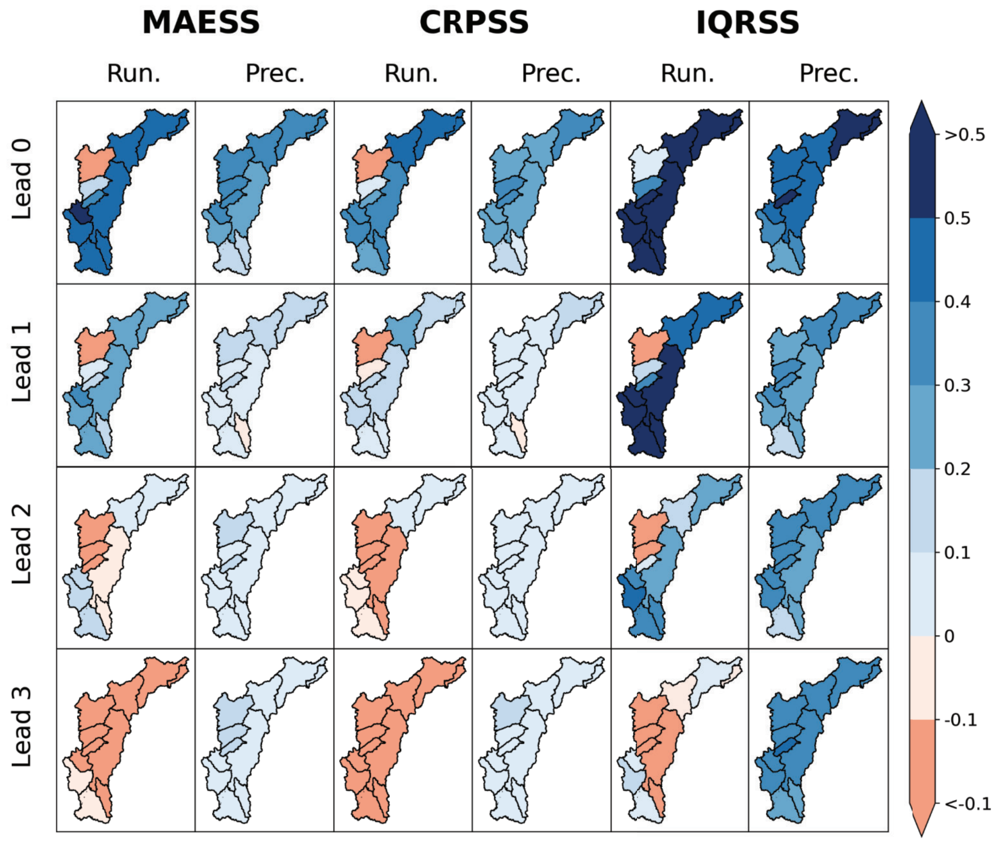

Figure 6: Skill scores of runoff reforecasts (Run.) and SEAS5 BCSD precipitation predictions (Prec.) averaged during the main rainy season for the first four lead times over the 11 SFRB sub-catchments. Since scores aren't linear for negative values, all scores below the threshold of -0.1 aren't shown in this figure.

The performance of the framework was assessed for 11 sub-basins of the Rio São Francisco basin by comparing predicted against observed runoff. The performance was also assessed for the SEAS5-BSCD predictions to evaluate its role and added value in the performance of the runoff predictions. The sharpness, accuracy and overall performance were analysed using the different ensemble skill scores, namely the Inter-Quantile Range Skill Score (IQRSS), the Mean Absolute Error Skill Score (MAESS) and the Continuous Ranked Probability Skill Score (CRPSS). The forecasts were validated against a reference climatological ensemble.

Figure 6 shows the seasonally averaged skill scores, respectively, of the EnKF runoff reforecasts and corresponding SEAS5-BCSD precipitation predictions during the main rainy season (November - March) for the first four lead months in all regions. The skill of the predictions is shown in colors from blue (better skill than the reference forecast) to orange (worse skill than the reference forecast). Overall, the EnKF runoff predictions have a good performance over most months. As expected, the skill decreases with lead time. The positive skill in the runoff predictions for all skill scores demonstrates the ability of the assimilation framework to capture the concurrent precipitation-runoff relationship on sub-basin scale and to provide skillful estimates of runoff for 1-2 months ahead. Furthermore, the noisy and systematically underestimated forecasts of regions 5, 6 and 7 of the western state of Bahia illustrate how severely runoff predictions are affected when the statistical correlation between rainfall and runoff is disturbed by anthropogenic activities. This approach, driven by global freely available information for regional runoff predictions has a great potential for regional decision-support and seasonal water resources management. This includes the development of institutional systems and national policies for drought preparedness plans, early warning procedures or sustainable reservoir management with a computationally cheap and easily transferable approach.

Towards dynamical downscaling of seasonal forecasts

Besides statistical bias correction and spatial disaggregation, the skill of dynamically downscaled seasonal forecasts was targeted in our project. Due to the very high computational demands of dynamical downscaling, this task could not be achieved for all SaWaM project regions. We decided to focus on South America (SA) and Northern Sub-Saharan Africa (NSSA) applying the Weather Research and Forecasting Model (WRF).

It is well known that the model performance depends largely on the choice of the physical parameterization schemes, but optimal configurations may vary e.g. from region to region. Besides land-surface processes, the most crucial processes to be parameterized in ESMs include radiation (RA), cumulus convection (CU), cloud microphysics (MP), and planetary boundary layer (PBL), partly with complex interactions. Before conducting long-term climate simulations, it is therefore a necessary prerequisite to identify a suitable combination of physics parameterization schemes for these processes. We did so by conducting an ensemble of WRF simulations applying different physics schemes for a run time of several years, with slightly different setups for both study regions in SA and NSSA, respectively.

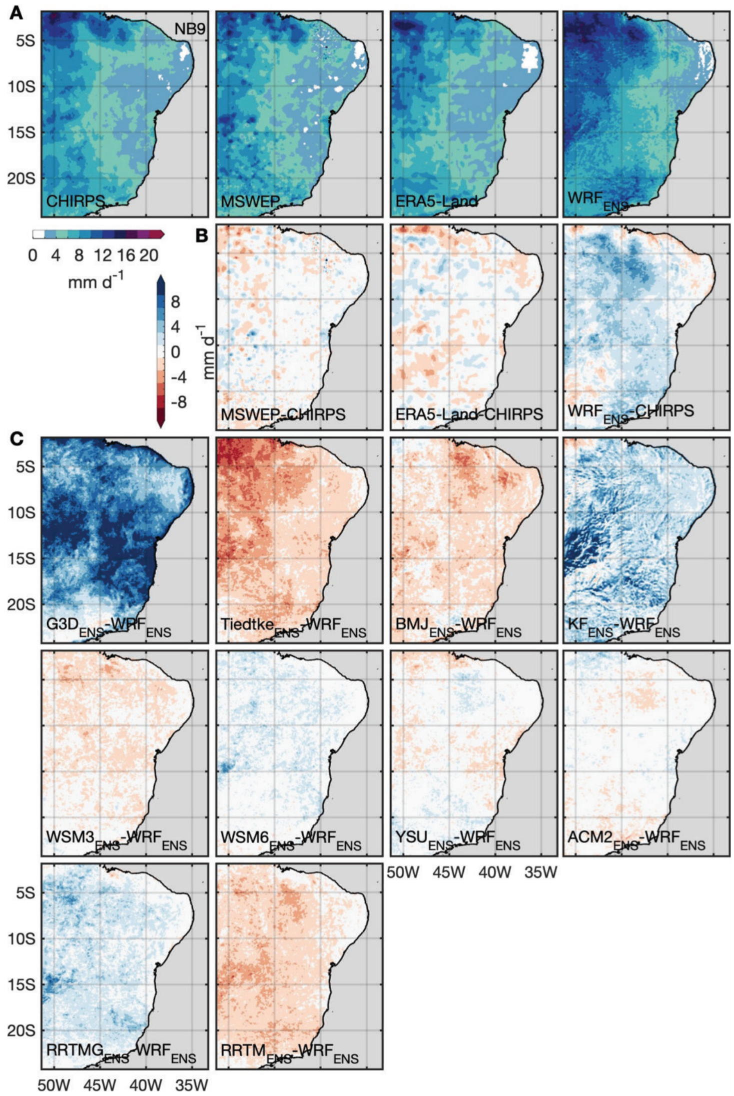

Figure 7: (A) Observed and simulated mean precipitation in January, February and March 2007 of CHIRPS, MSWEP, ERA5-Land and WRF ensemble median (WRF_{ENS}) over the Northeast Brazil 9-km-domain (NB9). (B) Bias of MSWEP, ERA5-Land and WRF_{ENS} against CHIRPS. (C) Deviation of the parameterization sub-ensemble median from WRF_{ENS} (Figure from Portele etal., 2021b).

In our analysis for SA, we used ensemble-based evaluation methods revealing the tendencies of individual parameterization schemes on e.g. precipitation amounts. One sub-ensemble consisted of all runs applying one fixed parameterization scheme. For the example of the Northeast Brazil 9-km-WRF-domain, Fig. 7 illustrates the divergence within the WRF ensemble for different applied parameterization schemes. The deviation of the median of these sub-ensembles from the total WRF_{ENS} (Fig. 7C) is larger than the uncertainty in the observations (Fig. 7B). The variation of the deviations from WRF_{ENS} is largest within the CU (G3D, Tiedtke, BMJ, KF) and RA (RRTMG, RRTM) sub-ensembles. The MP (WSM3, WSM6) and PBL (YSU, ACM2) sub-ensemble medians rather represent WRF_{ENS}. This shows the large uncertainty introduced by the CU and RA schemes (Portele et al., 2021b).

Similar conclusions about the impacts of the different parameterization schemes are drawn from the study of Laux et al. (2021). We applied traditional (Taylor diagrams, probability densities) and more innovative performance metrics (eSAL, empirical Copula functions) for their validation against different P and T observation data. We found that the selection of the

CU parameterization scheme has resulted in the highest impact with respect to the representation of P, followed by the RA parametrization scheme. The G3D CU scheme, in general, led to partly high model overestimation (wet biases) of P and stronger model underestimation (cold biases) of T compared to the Tiedtke scheme in NSSA. Both, the PBL as well as the MP scheme showed much less impact on the WRF model results. Yet another crucial unanswered question is whether or not the findings from the reanalysis-based WRF evaluation can be directly transferred to (sub)seasonal forecasts.

Towards new circulation type bias-correction techniques for seasonal forecasts

In order to improve (seasonal) climate predictions, and thus preparedness in Northeast Brazil (NEB), a circulation pattern (CP) classification algorithm has been developed. The approach is based on the Simulated ANnealing and Diversified RAndomization clustering (SANDRA) algorithm. In a first step, suitable predictor variables and cluster domain setting are evaluated using ERA-Interim reanalyses. It is found that near surface variables such as geopotential at 1,000 hPa ($GP_{1,000}$) or mean sea level pressure (MSLP) should be combined with horizontal wind speed at the upper 700 hPa level ($UWND_{700}$). A 11-cluster solution is favoured due to the trade-offs between interpretability of the cluster centroids and the explained variances of the predictors. Second, occurrence and transition probabilities of this 11-cluster solution of $GP_{1,000}$ and $UWND_{700}$ are analysed, and typical CPs, which are linked to dry and wet conditions in the region, are identified. The suitability of the new classification to be potentially applied for statistical downscaling or CP-conditional bias correction approach is analysed. The CP-conditional cumulative density functions (CDFs) exhibit discriminative power to separate between wet and dry conditions (Fig. 8), indicating a good performance of the CP approach.

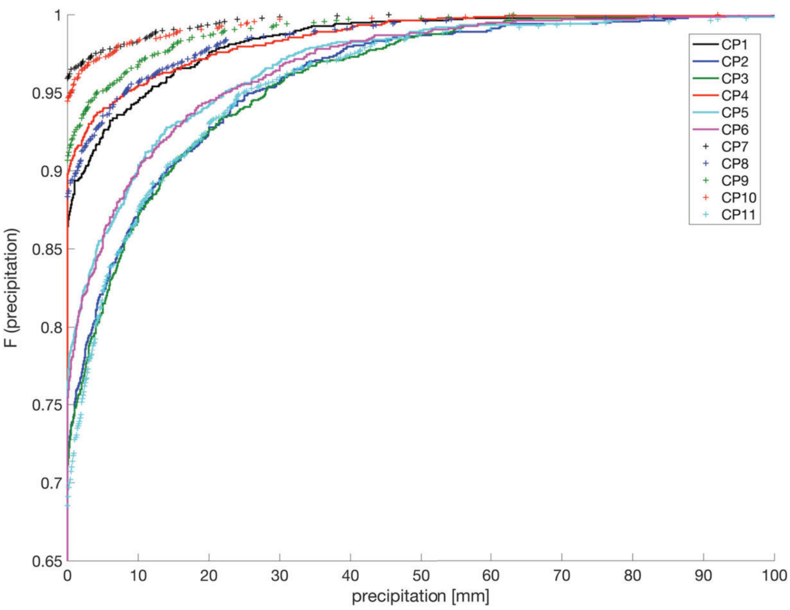

Figure 8: Empirical cumulative distribution function of the selected 11-cluster-solution for one arbitrarily selected precipitation gauge in the region (Figure from Laux et al., 2020).

The findings of this study open various avenues for applications in water resources management in NEB, such as a tool for statistical downscaling of GCMs based on CPs, or a CP-conditional bias correction algorithm of RCM output, also obtained from seasonal forecasts. Therefore, one may capitalize on the fact that a typical “wet” CP has a different precipitation distribution in time and space compared to a “dry” CP, which has been demonstrated in Laux et al. (2020). This may finally lead to more efficient and robust model corrections when compared to those using the full distribution for correction. A correction based on separate months does usually implicitly account for this, however, this may not be a suitable solution when the same transfer functions are applied in future climate impact studies since the timing of seasons might shift. As such, a CP-conditional bias correction approach can be seen as one potential solution to partly overcome the caveats due to the stationary assumptions, which exist for other bias correction approaches.

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5.2. Probabilistic evaluation of downscaled seasonal predictions

Gerd Bürger[1], Christof Lorenz[2], Tanja Portele[2]

[1]*Uni Potsdam,* [2]*KIT/IMK-IFU*

We evaluated atmospheric seasonal predictions (ECMWF/SEAS5) as downscaled by two methods, the quantile-mapping based approach BCSD and the regression variant XDS. The probabilistic evaluation is conducted for the two semiarid regions of the Karun river basin (KB) in Iran and the São Francisco basin (SFB) in Brazil. Upper, medium, and lower tercile are probabilistically predicted, and corresponding skill is estimated for lead times from 1 day to 6 months. To be able to compare different lead times, a seamless filter is applied (Bürger 2020). The potential for water management applications in semiarid regions is discussed.

The downscaling schemes were applied following Wood et al. (2002) for BCSD and Bürger et al. (2009) for XDS. The corresponding output was fed into the seamless filter. Remaining biases from the SEAS5 ensemble were removed by applying ensemble calibration by way of logistic regression.

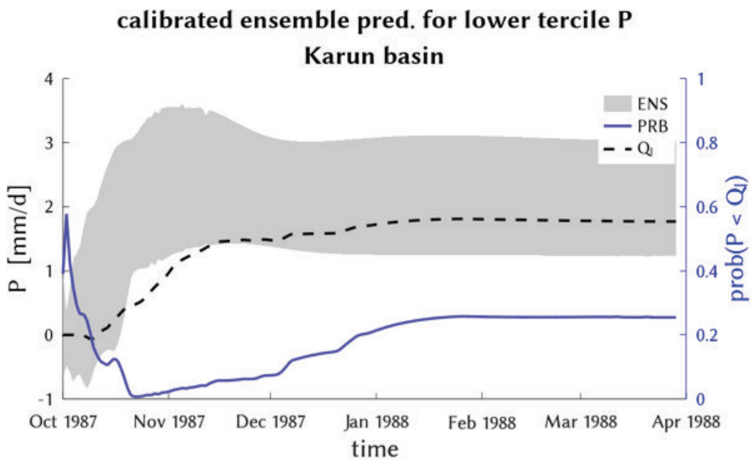

Figure 1: Probabilistic SEAS5/XDS forecast issued October 1987. The observed lower tercile (black dashed) is compared to the calibrated ensemble (90% confidence band as gray strip), resulting in a corresponding probabilistic prediction (blue).

Figure 1 shows as a typical result the lower tercile forecast issued October 1987. After about a month, observed and forecast precipitation (P) do not change much anymore due to the stronger filtering with lead time. Please note that ensemble calibration may occasionally produce P<0. While for the very first days very low precipitation is predicted with a corresponding larger lower tercile probability, probability drops after about a month as the predicted ensemble is persistently larger than the observed long-term lower tercile.

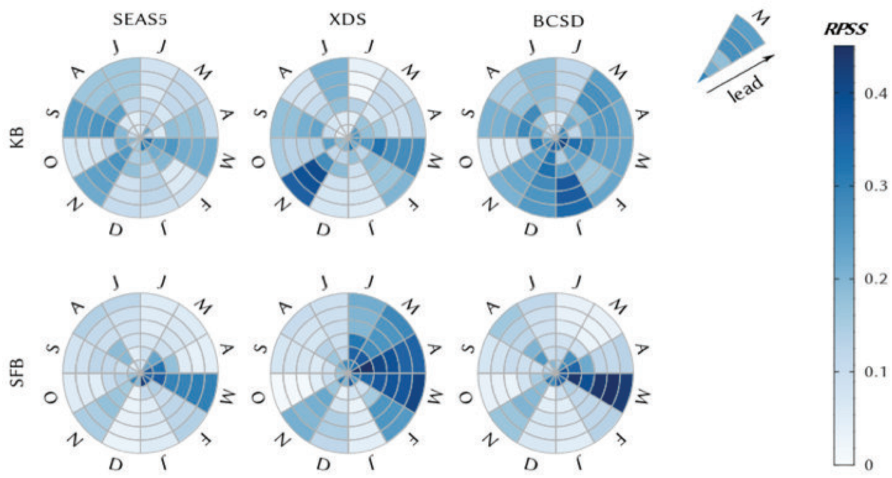

Figure 2: RPSS for predicting P terciles. For each disk, a sector represents the forecasts issued at the month depicted at the outer circle, each cylinder represents the lead time in months, starting at the center. Skill is reported as monthly average. The first column depicts no downscaling, followed by the two downscaling schemes; rows correspond to basins.

With results being quite diverse across predictands, regions, lead times, and methods, the application of downscaling generally improves prediction skill. This is confirmed in Figure 2, which summarizes our findings in a fairly consistent manner: For predicting (upper, medium, and lower) terciles, the RPSS shows that the KB is better predicted by SEAS5/BCSD and the SFB by SEAS5/XDS.

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5.3. Seasonal Hydrological Forecasting System for SaWaM

Shrestha, P.K.[1], Samaniego, L.[1], Lorenz, C.[2], Rakovec O.[1]

[1]UFZ, [2]KIT/IMK-IFU

The dual challenge of water managers in semi-arid regions

Semi-arid regions are characterized by low annual precipitation. Most of the annual precipitation occurs within a short period of time in a year exhibing a very skewed distribution. Apart from such strong annual seasonality, the hydrology in semi-arid regions is also characterized by uncertainty with inter-annual variability. An apt example of this is the region of Khuzestan in Iran where the hydrological conditions flipped in two consecutive years. The region saw one of its driest years on record in 2017/18 and record-breaking flooding in 2018/19. With such levels of seasonality and uncertainty, the water management community in these regions will greatly benefit from reliable hydrological forecasts provided a few months in advance. This undoubtedly alleviates the issue of water resource planning of farmers (soil moisture), river managers (streamflow) and reservoir operators (inflow, level, evaporation loss) in the semi-arid. Numerical modeling of these regions, however, is not trivial due to existing anthropogenic features (e.g. dams) that are adaptation measures for semi-arid conditions.

Scalability leads to greater reliability of hydrological forecasts

Numerical modeling of seasonal and uncertain hydrology of semi-arid is a challenge. The best candidates available for this challenge are distributed hydrological models which are state-of-the-art tools in hydrological modeling that enable model-based-action at local scale. However, numerical modeling incurs additional uncertainty in simulations due to model uncertainties. Although a perfect modeling approach doesn’t exist, a major issue of distributed models is scalability wherein model output varies greatly with resolution of simulation. Scalability is an important feature of model reliability as model parameters can then be transferred across scales to obtain virtually the same output. We employ the mesoscale hydrological model, mHM, which overcomes this issue with Multiscale Parameter Regionalization, MPR (Samaniego et al. 2010) and Sub-grid Catchment Contribution, SCC (Shrestha et al. 2020) techniques, producing seamless scalable state variables, fluxes and, overall, a quasi-scale independent basin hydrology.

Within SaWaM, we developed a novel SCC reservoir routing scheme (Shrestha et al. 2020) and made comparisons with the conventional D8 routing scheme (O’Callaghan and Mark, 1984). As shown in Figure 1, the performance metrics (KGE, NSE) of mHM are much more stable for SCC compared to D8 across model resolutions. This new found scalability of reservoir fluxes-states and downstream model simulations enhances the reliability of the hydrological forecasting efforts in SaWaM as shown in Figure 2. This figure shows SCC to constrain the spread of ensemble maximum, median and minimum across the resolutions. This improvement of forecast precision has been observed over basins of catchment size varying by four orders of magnitude.

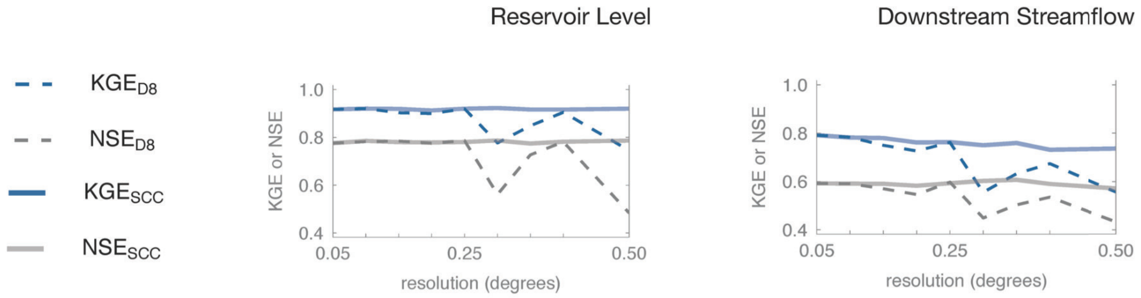

Figure 1: Scalability test for the D8 and SCC schemes, for reservoir level and downstream streamflow for Trés Marias reservoir, Brazil.

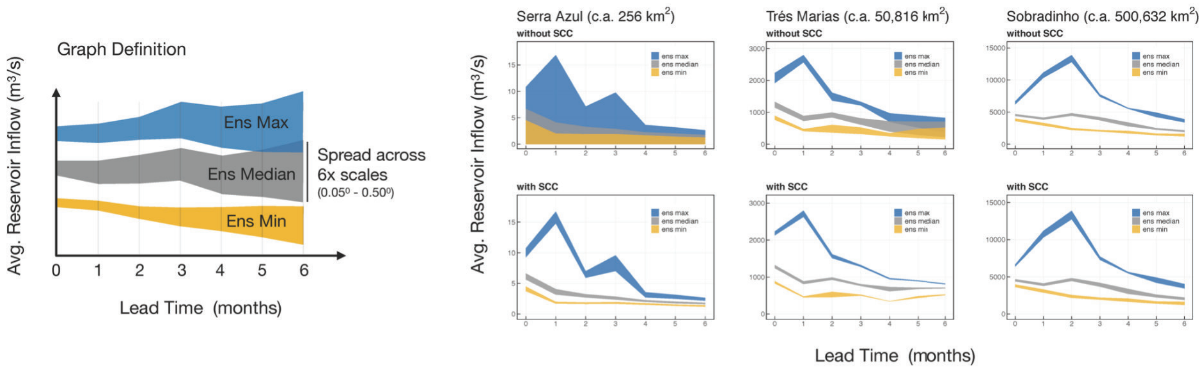

Figure 2: Scalability of mHM across six resolutions ranging from 0.05 to 0.50^0. mHM is able to produce sharper forecasts across model resolutions with the novel Subgrid Catchment Contribution (SCC) reservoir routing scheme. Top - without SCC (D8), Bottom - with SCC. Acronym: c.a. - catchment area.

Hydrological modeling that represents real world reservoir operation

A forecasting system that is understandable is a prerequisite for effective praxis-transfer to the end users. This remains true for end users from the reservoir regulation community as well. Although hydrological models (HMs) are superior in geographical coverage to water management models, they have been implementing rather simplified representation of reservoirs. We advocate inclusion of real world reservoir regulation features in HMs for better understanding of model simulations by reservoir operators. mHM partitions reservoirs into zones (Figure 3A) and simulates rule curves and demand hedging (Figure 3B) - the real world operating language at dams. This enables dam operators to study ensemble forecasts of reservoir simulations and abstract operation adaptation clues, especially at regional scales. For demonstration, we calibrated mHM with a new reservoir regulation parameterization at the project regions using the dynamically dimensioned search (DDS) algorithm (Tolson et al. 2007). We use a bivariate objective function with equal weights on reservoir volume and downstream streamflow for satisfaction of Pareto optimum (Solander et al. 2016). The objective function employs Kling–Gupta efficiency, KGE (Gupta et al. 2009) for reservoir volume and Nash-Sutcliffe efficiency, NSE (Nash and Sutcliffe, 1970) for downstream streamflow. The model performance of mHM at the Trés Marias reservoir is shown as an example in Figure 4.

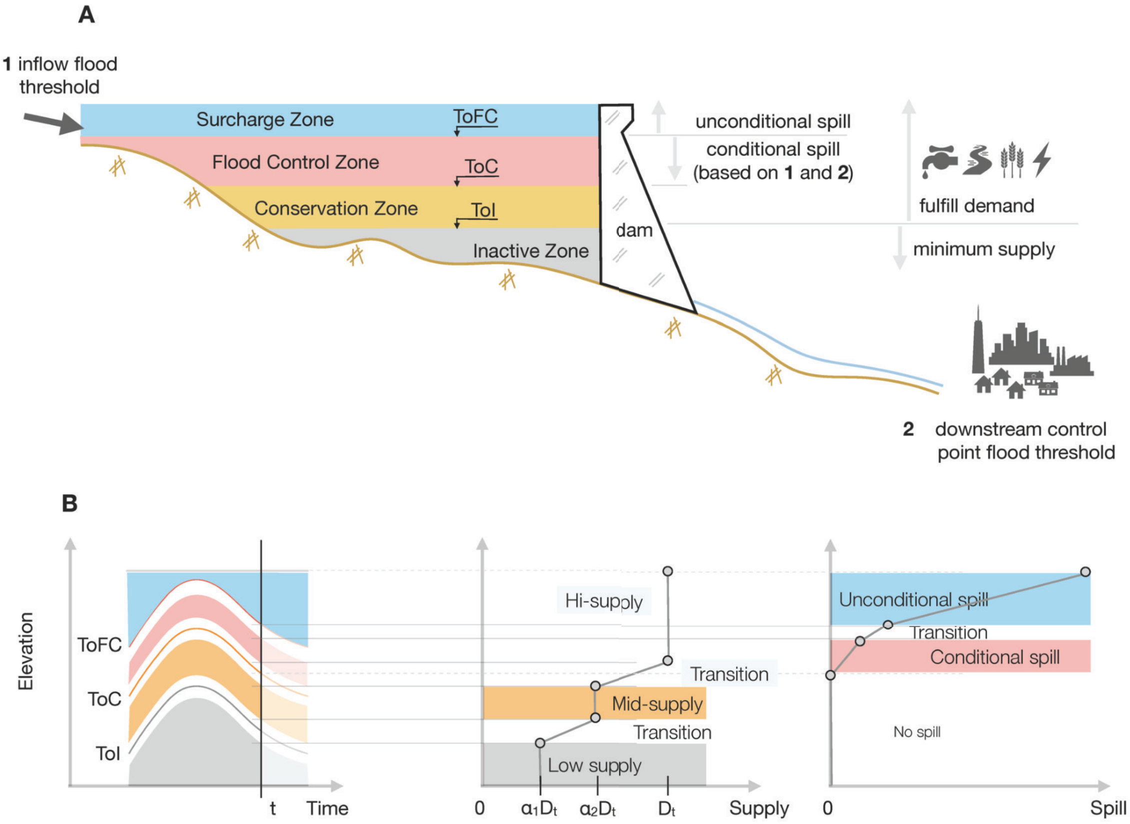

Figure 3: A - Storage zoning implemented in mHM. B - Schematics of rule curves and hedging rule for demand and spill release. Acronyms: ToI - top of inactive zone, ToC - top of conservation zone, ToFC - top of flood control zone.

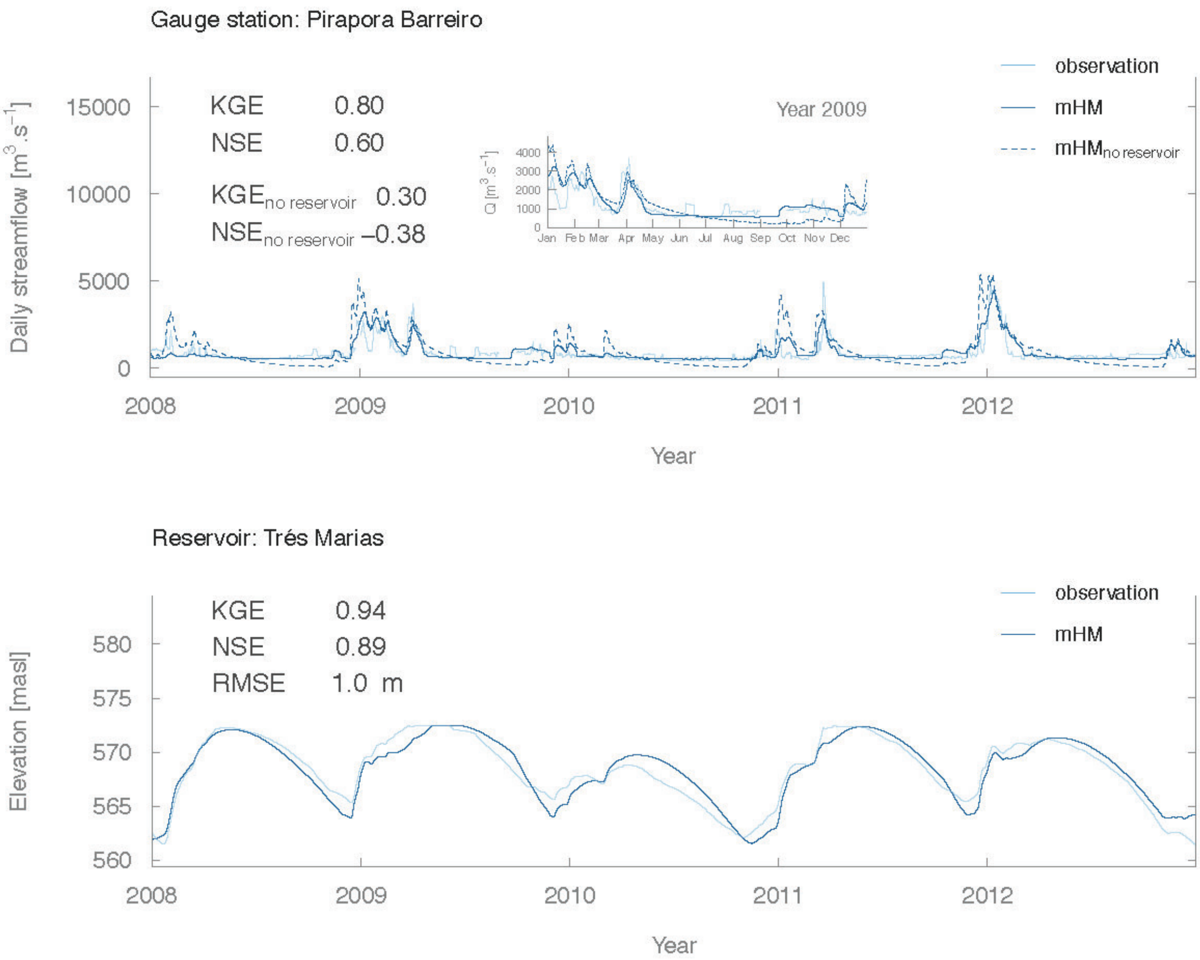

Figure 4: Calibration results (daily). Above - streamflow comparison at a gauging station (Pirapora Barreiro) downstream of the Trés Marias reservoir. The Figure also shows the comparison of hydrograph fit with and without mLM. Below - water level comparison at the Trés Marias reservoir.

A progressive forecasting system for tracking hydrological extremes

During the visits to the study regions, the project team realized the necessity of a decision support system (DSS) based on numerical forecasting. The in-place DSS in the regions were either totally absent or the water managers were using conventional approaches that incur high uncertainty. The DSS developed in this project is based on the state-of-the-art seasonal hydrological forecasting system (SHFS) which is a timely upgrade to the existing systems. Moreover, data sharing could be a significant hurdle in developing regions and transboundary regions as in the case of this project. For instance, the operation rules at reservoirs are usually company kept secret and/ or highly classified information. SHFS bypasses these sensitive data wherein the hydrological model (mHM) produces reservoir forecasts based on reverse engineered operation rules. Besides, mHM exploits available global data sets for system setup and model forcing. With minimum reliance on local data sets, SHFS bypasses the data deadlock and produces forecasts usable to parties on both sides of the border. This progressive nature of SHFS makes it a leading yet sustainable forecasting system, opening avenues for further cooperation among the transboundary member states.

The SaWaM DSS addresses the fate of moisture and provides soil moisture based indicators. These indicators help farmers to foresee soil moisture conditions six months in advance. Farmers will exploit DSS to better plan their cropping tasks and make better decisions. The numerical modeling of soil moisture in SHFS significantly improves a farmer's chance to achieve the desired result. This should curb risks related to yield. As a demonstration, we carried out hindcasting experiments wherein seasonal forecasting for months March, July and August were conducted for the Sudan to describe the evolution of the drought of August 2015 (Figure 5). The DSS is able to detect the beginning of the drought as early as March, with a six month lead time (L). Then, the system successfully tracks this event until July (L2). Finally, the forecast in August shows that the skill of the system for tracking the event is quite high considering that the extent of the event resembles the reference run with observed data. This shows the capability of the DSS to provide essential information of future droughts.

Also flooding is of concern in semi-arid areas, especially in populated areas. With DSS streamflow forecasts, the city water regulators would have preparation time in order of months. This benefits them greatly in planning prevention measures. Similarly, dry conditions affect water navigation managers and populations dependent on direct stream water. They too will greatly benefit from streamflow indicators of the DSS. Figure 6 shows the seasonal forecast for the Sudanese Flood of June 2019 for the months of January until June. With a six months lead time (L6), the DSS shows potential for above normal-flow conditions in June, which corresponds to the start of the rainy season. The best estimate of the flooding area, however, can be expected at shorter lead times due to the improvement of the meteorological forecasts.

Figure 5: DSS tracking a drought event of August 2015 in Tekezé-Atbara and Blue Nile basins of Sudan.

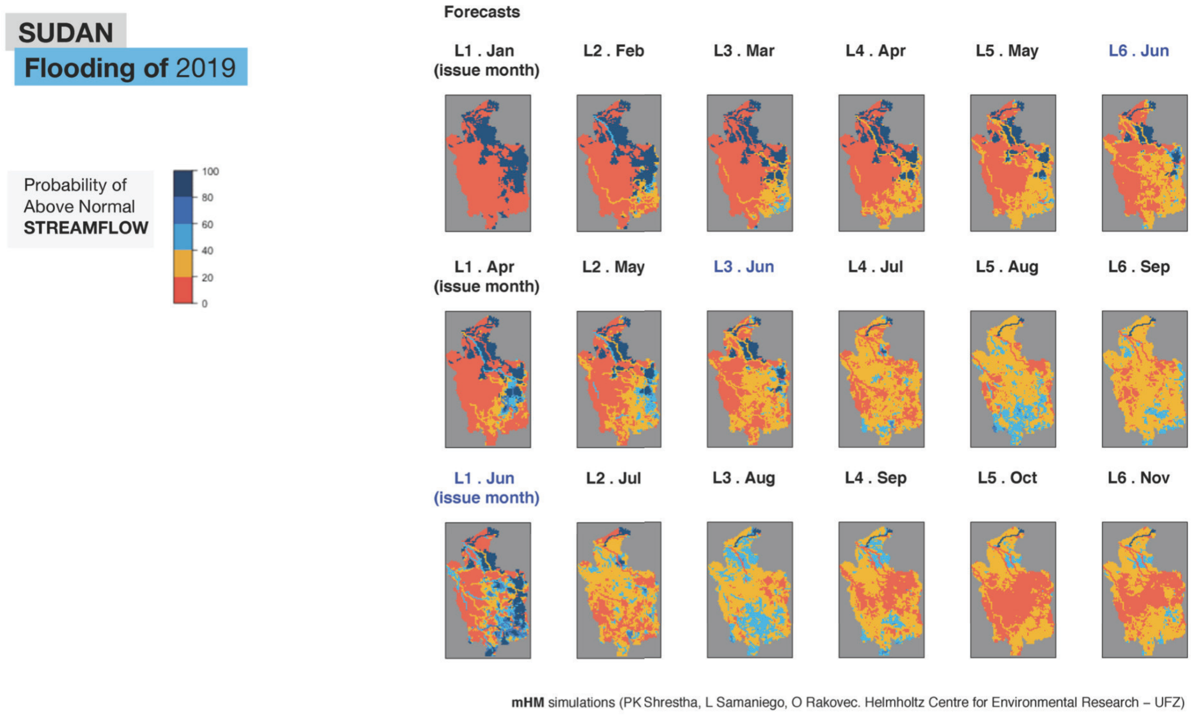

Figure 6: DSS tracking a flood event of June 2019 in Tekezé-Atbara and Blue Nile basins of Sudan.

In conclusion, the decision support system (DSS) is able to give reliable early indication of hydrological conditions in the project region, in some cases as early as six months ahead of time. This information is of great value for water managers dealing with uncertain hydro-climatological conditions in semi-arid regions. The skill of the forecasts improves as the point of time approaches present conditions. This reiterates the fact that meteorological forcings are the drivers of hydrological models and their skill is of utmost importance in seasonal hydrological forecasting.

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5.4. Hydro-sedimentological modelling of the river catchments Karun-Dez, Iran, and Rio São Francisco, Brazil

Anne Müller[1], Axel Bronstert[1], Paul Voit[1], Josephin Diether[1], Morteza Zargar[2], Maryam Mousavi[2], Francisco das Chagas Vasconcelos Júnior[3]

[1]University of Potsdam, [2]Avaye Ab Shabnam Consulting Engineering Company, Ahvaz, Iran, [3]Fundação Cearense de Meteorologia e Recursos Hídricos FUNCEME, Brazil

Besides water scarcity, soil erosion and sediment deposition in reservoirs are among the biggest challenges for water security in semi-arid environments, which are characterized by intense water use and management. Hydrological and sedimentological variables are modelled with the Water Availability In semi-arid Regions Including Sediment (WASA-SED) model, which was adopted to enable hydro-sedimentological modelling for the upper mesoscale, including reservoirs and irrigation.

Within SaWaM, the WASA-SED model system was adapted for catchment sizes of the upper mesoscale and improved to enable hydro-sedimentological modelling considering reservoirs and irrigation practice (Müller et al. 2010, WASA-SED Model 2020). Necessary input data for model set up and parametrization (e.g. DEM, land-cover, soil, waterbodies) originate predominantly from globally available open-source data. Observed runoff and sediment data for model validation and calibration were provided by local SaWaM-project partners. Pre-processing of climate data for model input includes, e. g., the aggregation of rainfall P from different sources to areal means for gridded P products compared to interpolation to sub-catchment from observed P station data.

Hydro-sedimentological modelling was carried out for the catchments of Karun-Dez, Iran (ca. 60 200 km²), and Rio São Francisco, Brazil (ca. 743 000 km²) (e. g. Smetanová et al. 2020). Analyses of runoff and sediment dynamics show that different precipitation (P) products may vary significantly. Observed P station data in the target areas pose challenges for modelling, too, due to a lack of spatial and temporal coverage or additional uncertainty introduced by the chosen interpolation method and parameters.

Novel sediment model results are possible for the target regions, given reliable rainfall information. For hydro-sediment modelling, ERA5-Land climate data proved as the most adequate model driver, due to a high spatial resolution (0.1°), availability of all required model input climate variables, and reasonable results for runoff (validation with observed runoff data).

The novel irrigation module for WASA-SED was implemented and tested for the Rio São Francisco catchment, allowing to represent water abstractions for irrigation purposes from different sources (groundwater, river, reservoirs, external sources), inter- and intra-basin transfers and seasonality of irrigation practices. The newly developed irrigation module allows further adaptation of WASA-SED to dryland environments, an extended range of fine-tuning possibilities and scenario studies with a minimum of additional data required (Voit 2021).

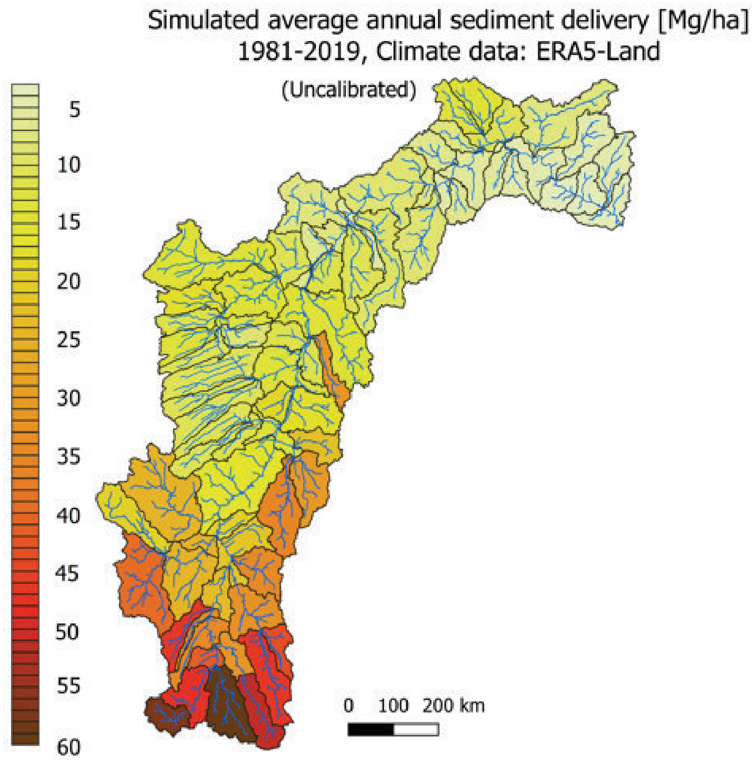

Figure 1: Modelled average annual Sediment delivery, São Francisco Basin, Brazil

We stress the importance of good quality regional climate and physiographic data for any model setup, calibration, and validation. Using ensembles of different data sources may enhance robust results. Documentation of extensive data (pre-)processing and open-source publication of data and software are of high importance for result reproducibility (e. g. Müller et al. 2019, WASA-SED Model 2020).

Both catchments of Karun-Dez, Iran, and Rio São Francisco Basin, Brazil, are characterized by intense water management and a high number of hydraulic structures. Reservoir sedimentation poses a high, yet underrated risk for water security, e. g. endangering water supply and hydroelectric water power generation. Field measurements (such as reservoir bed level changes) and modelling can provide valuable information for quantifying reservoir sedimentation and reservoir life time. In order to decrease sedimentation rates, a sustainable and long-term catchment management is required (Müller et al. 2021).

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5.5. Identification of erosion hotspot and leverage areas

Eva Paton[1], Anna Smetanova[1]

[1]TU Berlin

Land degradation and water availability in semi- arid regions are interdependent challenges for management that are influenced by climatic and anthropogenic changes. Erosion and high sediment loads in rivers result in reservoir siltation and reduce storage capacity, which pose risk on water security for citizens, agriculture, and industry. In regions where resources for management are limited, identifying spatial-temporal variability of sediment sources is crucial to decrease siltation. Despite widespread availability of rigorous methods, approaches simplifying spatial and temporal variability of erosion are often inappropriately applied to very data sparse semi-arid regions.

This study aimed to illustrate why and how data availability constrains the identification of key leverage areas for sediment management. We define “leverage areas” as sediment hotspots where management would have the greatest impact on reducing erosion and sediment delivery into downstream bodies (e.g., dam, catchment and outlet). Mapping approaches for erosion hotspot mapping are investigated, and two examples of data-sparse mesoscale catchments (in Iran and Sudan) illustrated how mapping of sediment of hotspots in data sparse semi-arid catchments can be enhanced using freely available global datasets. Lastly, we discuss which methodological approaches can be applied for mapping spatial and temporal variability and for validating results, and which challenges are common for research and management in data sparse areas.

In this work, we developed a spatio-temporal mapping approach for the identification of erosion hotspots and leverage areas in all case study regions using a minimum data inventory with data globally available with temporal changing vegetation and rainfall and connectivity calculation (Figure 1). Mapping sediment management hotspots requires conceptualizing of: (i) processes causing erosion (sediment production), transport (sediment delivery), and accumulation (deposition or sedimentation); and (ii) identifying and describing of functional relationships between processes and dominant factors in a specific geographic area. Multiple geomorphic processes are leading to reservoir siltation, e.g., runoff or subsurface-flow induced water erosion, wind erosion, or mass processes, such as landslides.

Mapping erosional hotspots for management is spatially and temporarily scale dependent. A single map of erosional hotspots is simply a snapshot of the state (current or future) of a coupled natural-human system and represents a combination of potential and actual properties. Conceptualizing sediment hotspot mapping for management requires clarified aims, which help define dominant processes (e.g., hillslope erosion or sediment delivery to reservoir); spatial scales, which help to define the area of interest and appropriate resolution (e.g., particular hillslope or catchment above reservoir); and temporal scales, which help to define period of interest and appropriate resolution (e.g., long-term mean, seasonal, and actual state after an event).

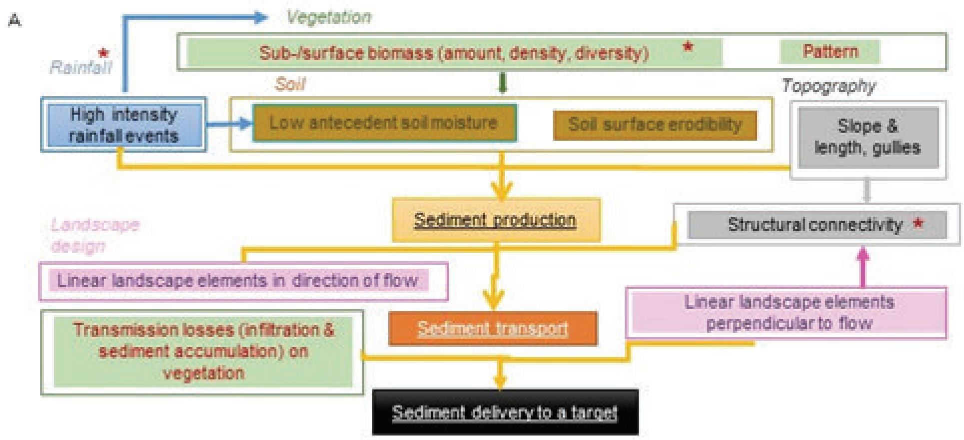

Figure 1: Mesoscale mapping of sediment source hotspots

Figure 1 conceptualizes the sub-processes leading to sediment delivery in semi-arid landscapes, and their controlling factors comprising: (i) rainfall properties; (ii) soil properties; in interaction with (iii) vegetation properties; (iv) topography; and (v) landscape design (the patterns of artificial or natural linear landscape elements and land uses). Hereby, sediment production and transport through landscape rather than runoff generation and propagation through landscape are in the focus, without considering the sediment production and transport in streams.

Different data inventories influence differences in spatial and temporal accuracy of representations of physical reality of erosion and sediment transfer, and a range of methods can be applied if high quality datasets are available. However, to demonstrate the effect of different inventories (including data-sparse boundary conditions) for mapping of erosion hotspots, basic GIS mapping methods were chosen with a workflow and are visualized in Figure 2. The hotspots and emerging hotspots were calculated using the Getis-Ord Gi* statistics (Ord & Getis, 1995) in ArcGis 10.4. This geostatistical approach allowed distinguishing areas where features with high (hotspots) or low (cold-spots) values were surrounded with other features with high (low) values. Each feature was compared to its neighborhood, and each neighborhood sum with the sum of all datasets. The emerging hotspots were analyzed in the spatio-temporal domain. The analysis allowed distinguishing whether hotspots are stable, emerging, or diminishing in relation to a given point of time.

Topography data (USGS EROS, 2018) were pre-processed as required for connectivity index calculation (Crema et al. 2018). We calculated the connectivity index to targets - dams and rivers (vectorized from Q Gis and Arc Info Base Maps). The setting for spatial conceptualization of the relationship was fixed-threshold distance, which means that effects of neighboring features diminish with distance. The Euclidean distance (connecting two points with a straight line) was chosen as a distance calculation method. We applied false discovery rate correction (ArcGis 10.4), which reduced the critical values of statistical significance (p) due to spatial dependence. Hotspots identified by 95% confidence provided the final output (settings: GiBin > 2, GiZScore > 0, and GiPvalue < 0.1).

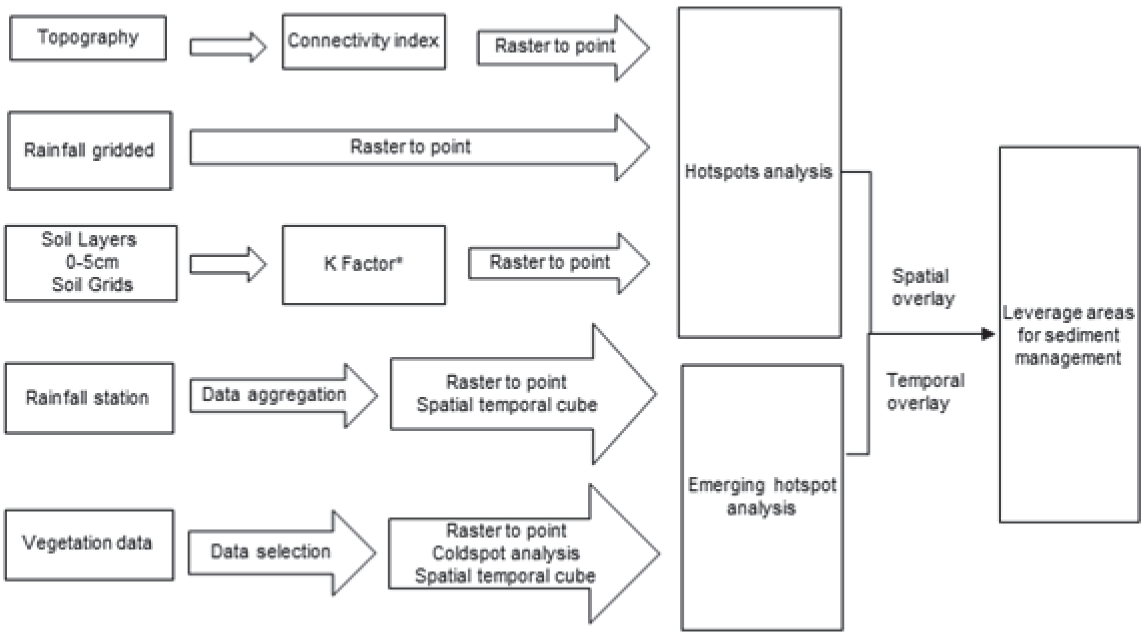

Figure 2: Workflow of the mapping method for the identification of erosion hotspots and leverage areas

Soil Grid (Hengl et al. 2017) layers (1 km) - silt, clay, and loam - were used to calculate texture (Massei 1995). Texture, together with GIS layers (dominant soil type, organic matter, and coarse sediments), was used to calculate K factors using previously published methodology (Panagos et al. 2014). An African soil map (Hengl et al. 2017) was used for soil types in Upper Atbara. The hotspot analysis and selection followed the above-mentioned settings.

Rainfall station data from Karun (2000–2016; 29 stations; 15 hydrological years) were aggregated to monthly rainfall depths, and a shape file containing station location and the corresponding number of data points was used to build up spatial-temporal cube (settings: time step: 30 days; distance interval: 20 km; and summary fields: max, mean, sum, and med). These were included in an emerging hot-spot analysis (Crema et al. 2018, with a neighbourhood distance of 60 km; neighborhood time step of 1 and statistically significant hotspots selected using GiZScore > 0, GiPvalue < 0.1, and GiBin > 2).

Vegetation data (Jenkerson et al. 2010) were selected to visually represent maximum spatial distribution of low NDVI values (at the end of the season, or in December or May) from time-series 2000–2016. Afterwards, we filtered out negative values (no ecological meaning), and focused on point values from which hotspots were calculated. Statistically significant cold-spots (setting: GiPValue < 0.1, GiZScore < 0,and GiBin > −2) were selected, turned into points, and spatial-temporal cubes (time step: 1 year; and distance interval: 1000 m) were built for emerging hotspot analysis (Cantreul et al. 2018). Statistically significant hotspots (GiZScore < 0, GiPValue < 0.1, and GiBin > 2) were selected for remaining hotspot analyses (connectivity index, gridded rainfall data, and K factor). In emerging hotspot analysis, the “last step” was to define the targeted temporal overlay (e.g., end of December). The leverage areas represented the spatial-temporal overlay of hotspots or emerging hotspots of four controlling variables. Only statistically significant hotspots and emerging hotspots of the four controlling factors (with >90% probability of occurrence) were overlaid. For the spatial intersect, a buffer of three times the minimal layer spatial resolution (3 × 1 km) was allowed.

In combination with a seasonal forecast, leverage areas could now be identified with the new mapping approach, where management of erosion hotspots would have the greatest impact in reducing erosion and sediment delivery into downstream water bodies, four to six months in advance. Early adaptation of the land-use in a fraction of the catchment area (Figure 3 depicted for Karun (Iran) and Upper Atbara (Sudan)) will result in a significant reduction of erosion load and downstream reservoir siltation.

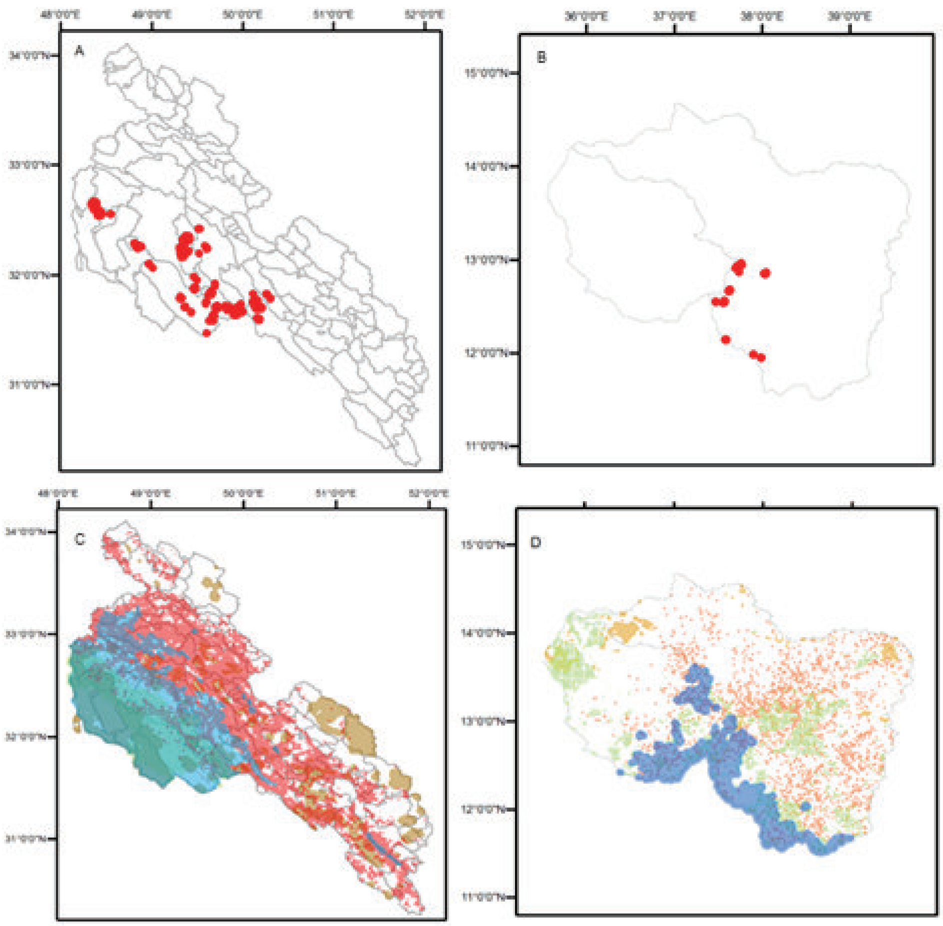

Figure 3: Leverage areas for two types of sediment management interventions First type (**A**,**B**): Hotspots map for planning ad-hoc sediment management (**A**) at the beginning of December in Karun and (**B**) in May in Upper Atbara. Global gridded monthly rainfall depth [55] was used. (C): Hotspots maps overlaid with spatial-temporal dimensions (Karun, Iran, 2000–2016). Hotspots (HS) or emerging hotspots (EHS) of rainfall (blue), connectivity (red), soil erodibility (**D**) Hot spots (HS) or emerging hotspots (EHS; 2000–2016) maps of rainfall (blue HS, rainfall dataset [56]), connectivity (red HS), soil erodibility (brown HS), and vegetation (green EHS) in Upper Atbara at the beginning of rainy season (May).

For validation of the hotspot mapping method, spatial distribution of erosion hotspots was compared to observed and modelled sediment yield in Karun. Sediment data from sediment monitoring stations (39) in Karun consisted of continuous measurement with frequency of mostly one day in a month between October 1999 and September 2012. They were considered to represent monthly sediment volume, and, if more measurements were available in a month, cumulative value was considered. We calculated area-specific sediment yield (Mg km^{-2} $month^{-1}$) for each measuring station. Consequently, long-term mean from annual mean values and long-term sediment yield in December were related to the spatial distribution of hotspots. Modeled values of daily sub-catchment sediment yield were obtained by using

WASA-SED, (see also section 4.4 of this report), a process-based, spatially semi-distributed, and time-continuous hydrological and erosion model, specially developed for semi-arid landscapes (Figure 4 and description therein).

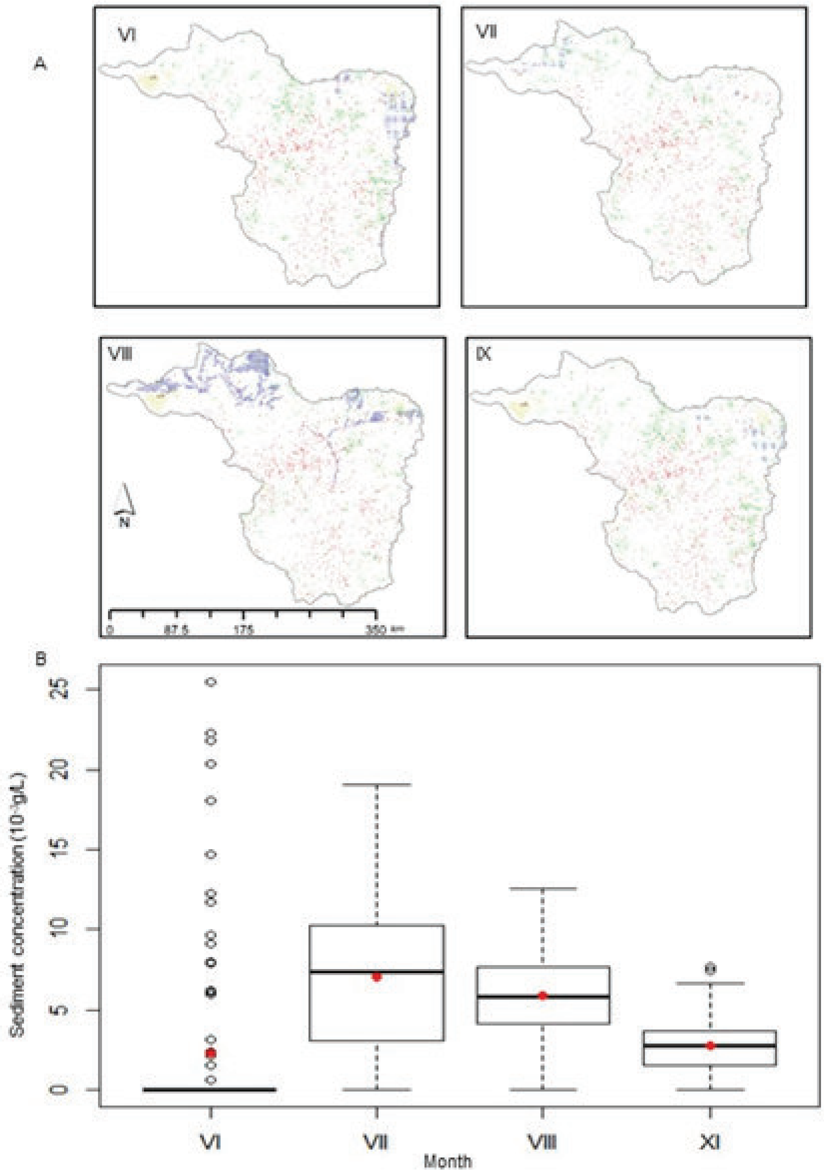

Figure 4: Comparison of hotspot mapping outputs with short-term measured sediment data in Setit catchment (Upper Atbara, Sudan): VI, June; VII, July; VIII, August; and IX, September. (**A**) Hotspots of soil erodibility (brown), connectivity (red), and monthly rainfall depth in respective month (blue) are plotted. Green indicates vegetation hotspots at the beginning of the month, which were occurring each year between 2014 and 2016. (**B**) Boxplot of sediment concentration (10−3 g/L) measured at catchment outlet in the respective month (2014–2016). First quartiles, medians, and third quartiles are plotted, while whiskers represent 1.5 × interquartile range. Inter-annual means are plotted as red dots.

The combined use of the mesoscale erosion hotspot tool and the seasonal forecast illustrate how, where and why land-use managers have to work in concert with water management authorities to avoid upstream erosion and minimize siltation. More detailed information on the functioning and application of the mapping methods can be found in the publication by Smetanova et al. (2020).

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5.6. Vegetation and water dynamics from satellite remote sensing

Robert Behling[1], Sigrid Roessner[1], Saskia Foerster[1]

[1]*German Research Centre for Geosciences GFZ Potsdam*

Basin-wide land surface information with respect to vegetation cover, land use and flooding are crucial for an effective water resources management. The ever increasing amount of globally available optical and radar satellite data allows the observation of long-term trends and seasonal variability of the land surface cover by means of big-data time series analysis approaches. The observed trends and dynamics are controlled by the hydro-meteorological regime and human interference. Therefore, the aim of this subproject was to observe land surface dynamics by satellite time series analysis in relation to observed hydro-meteorological dynamics as well as land and water resources management.

Time series of optical satellite data are utilized to analyze vegetation and water dynamics in different spatial and temporal scales. The MODIS sensor has acquired daily imagery of 250m pixel size since February 2000. The Copernicus Sentinel-2 mission has allowed analysis of higher spatial detail since 2015, with imagery of a pixel size of 10m to 20m taken approx. every 5 days. Both datasets are globally and freely available.
Vegetation indices (VI) such as NDVI and EVI are used to derive quantitative and qualitative parameters of intra- and inter-annual vegetation dynamics. Quantitative parameters are the long-term trend (Fig. 1), annual variations, days of vegetation coverage, number of crop cycles and phenological parameters (e.g. start/peak/length of season). Qualitative parameters can be derived by using land cover specific VI-trajectories and ground truth data to derive e.g. land cover maps and irrigation masks. A water index (NDWI) based on Sentinel-2 is further used to derive detailed knowledge about the extent and duration of inundation areas in case of extreme flood events.

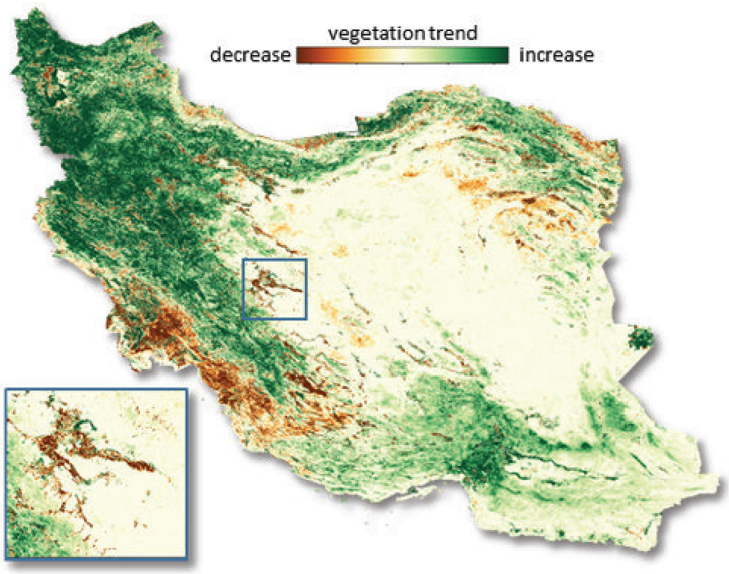

Figure 1: Vegetation trend for Iran (2001-2019) using MODIS NDVI. The enlarged section shows a large irrigated agricultural area around Isfahan with negative vegetation development due to water scarcity.

For the SaWaM target regions Karun (Iran), Rio São Francisco (Brazil), Tekeze-Atbara and Blue-Nile (Sudan/Ethiopia), Catamayo-Chira (Ecuador) monthly VI parameters and their annual variations from the long-term average were derived. In general, the vegetation signal clearly follows the overall water availability and dry and wet years show a clearly decreased and increased vegetation signal, respectively. In case of meteorological droughts (e.g. 2008 in Iran, 2012-2017 in Rio São Francisco) the vegetation was clearly affected showing a general lower VI signal, especially in grassy vegetation but also in a decreased cultivation due to the lack of water for irrigation. Moreover, in most regions an increase in (irrigated) agricultural areas is observed in the MODIS time span (2000-2019).
Using Sentinel-2 the vegetation and water dynamics were analyzed at higher spatial detail for the Karun catchment, Iran. Using VI-trajectories and ground truth data a catchment wide land cover map at 10m spatial resolution was produced as well as specific parameters such as an irrigation mask or days of vegetation coverage were derived (Fig. 2). Moreover, the Sentinel-2 images allowed a detailed mapping of surface water cover during the extreme flood event in 2019 (Fig. 2) that caused widespread inundation of bare soils and agricultural fields that lasted for several months (Behling et al. 2019, 2000).

For the entire Iran, the MODIS-based vegetation dynamics were analyzed in regard to the climatic variations (e.g. precipitation, temperature derived by ERA5-Land). The expertise of the partners of the SaWaM consortium allowed a profound analysis of vegetation dynamics (MODIS: NDVI) against meteorological parameters (ERA5-Land: precipitation, temperature, aridity index) and the catchment-wide total water storage (GRACE) in a cross-project study by GFZ-Potsdam, KIT-RKH and University of Stuttgart (Behling et al. 2021, in preparation). It could be shown for the area of Iran that the annual vegetation expansion and vitality significantly follows the annual meteorological water availability (precipitation, aridity) (Fig. 3). Compared to the strongly decreasing total water storage, the vegetation development is negatively correlated, which suggests the increase of irrigated agriculture with unsustainable water use.

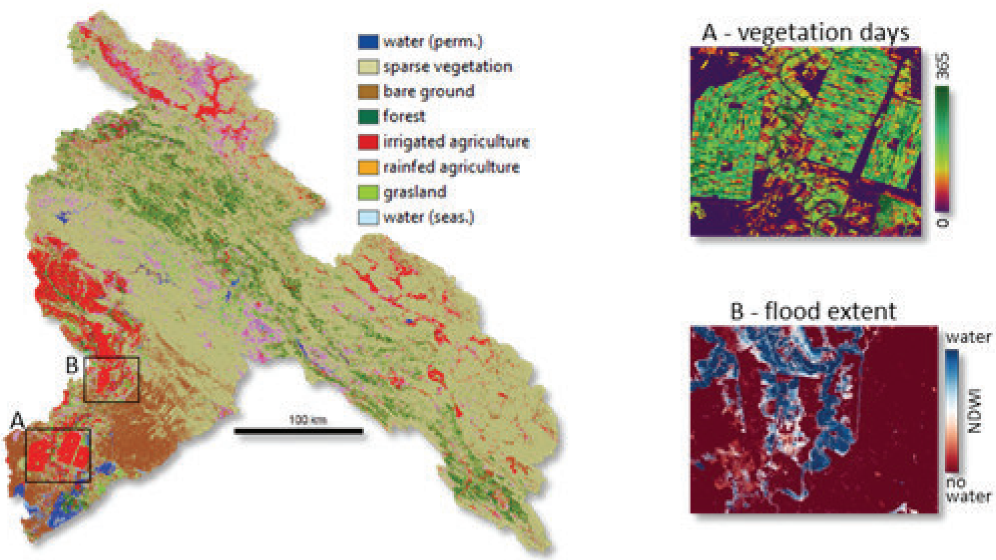

Figure 2: Sentinel-2 based parameter derivation in Karun, Iran: Land cover (left), days with vegetation cover (A, inset), flood extent during 2019 flood (B, inset)

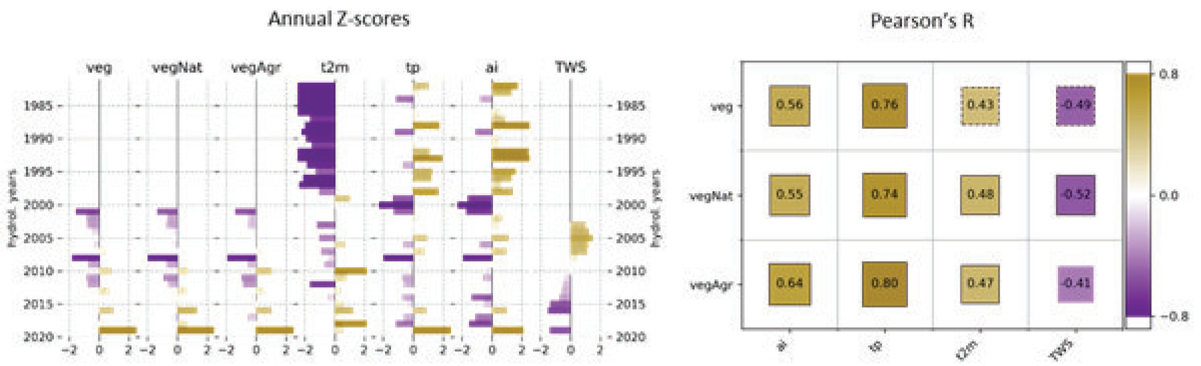

Figure 3: - Iran-wide integrative annual variation of vegetation and hydrometeorological parameters. Left: Annual variation from the reference period (defined by GRACE-TWS availability) in Z values. Right: Correlation of annual variations of different vegetation parameters (veg - total Iran, vegNat - natural vegetation, vegAgr - agricultural vegetation) and hydro-meteorological parameters.

Using recently available global land cover maps (Copernicus land cover products), vegetation dynamics and climate dynamics, the sustainability of agricultural water consumptions was evaluated. It could be shown that high percentages of strongly irrigated areas in arid or hyperarid regions are not cultivable anymore because unsustainable water usage resulted in water shortages nowadays (e.g. Isfahan, Shiraz) (Fig. 1, inset).

In conclusion, optical remote sensing time series data can serve as a valuable contribution to evaluate water management, e.g. in case of floods, irrigation, and preservation of natural ecosystems. Even though the project aims at making use of globally available data from satellite observations and modelling, for detailed and quantitative derivation of land surface characteristics from satellite data, in-situ information is still indispensable, which is, however, often inconsistent and hard to obtain.

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5.7. Ecosystem responses to changing rainfall patterns

Anita D. Bayer[1], Christine Mihalyfi-Dean[1], Almut Arneth[1], Christof Lorenz[1]

[1]*Karlsruhe Institute of Technology (KIT/IMK-IFU)*

In semi-arid regions, small scale approaches are needed to investigate the interplay between rainfall and the type and sensitivity of the existing vegetation. This task is critical considering the limited resources and the dependency of the population to the services that are provided by the ecosystems, such as crop yields, irrigation water or water for hydropower generation. The state-of-the-art dynamic vegetation model LPJ-GUESS was used in SaWaM to investigate the interplay of seasonal weather, vegetation pattern and the ecosystem water balance in form of long-term and seasonal trends. We compared modeled vegetation variables with those from satellite remote sensing. The development regions in Iran and Brazil were the focus for this analysis.

The LPJ-GUESS model is a process-based dynamic vegetation model (DGVM, Smith et al., 2014, Lindeskog et al., 2015), which simulates large-scale dynamics in vegetation distribution and biogeochemical cycles under coupled C-N dynamics. Model input data are climate variables, atmospheric CO_2, soil texture, nitrogen deposition and fertilization, and land-use information. The ecosystem state is represented by variables related to the productivity of the vegetation and various nutrient cycles (water, C, N).

The model with a standard resolution of 0.5° (~50 km) was refined to run on a 0.1° x 0.1° (~10 km) grid using adequately processed regional input data on land use and crop management and spatially-disaggregated climate data from WP1. Long-term and seasonal trends of modelled net primary productivity (NPP) and the fraction of absorbed photosynthetically-active radiation (fPAR) were compared to the trends of variables from satellite remote sensing (normalized differentiated vegetation index, NDVI). In addition, ecosystem water cycle variables were considered (e.g., soil water content, water used by the ecosystem, excess water, irrigation water). Rainfall patterns from reanalyses were considered for the historic period and of downscaled seasonal predictions (from WP1) for the near future period.

Results show reduced plant growth in both regions in Brazil and Iran (time series analysis 1981-2018), mainly as a result of severe droughts over the last years. Not only natural vegetation is affected but also crops, which results in large yield losses during driest years. The NDVI derived from remote sensing data followed the spatial and temporal rainfall patterns better than the calculated NPP and fPAR variables. This could be due to an insufficient implementation of the drought resistance of plants in the vegetation model used. However, it must be taken into account that the accuracy of the NDVI is also subject to fluctuations due to many influencing factors, e.g., the atmosphere. For robust statements it is therefore advisable to use modeled and observed variables.

For the working area Rio Sao Francisco in Brazil, positive deviations from the long-term mean in water-related variables were found up to the year 2011 (with the exception of individual years in between with negative deviations). Maximum values for precipitation were 30% above the long-term average, 60% in runoff water and about 20% in soil water and ecosystem water use. After that, the time series showed negative deviations until 2018.

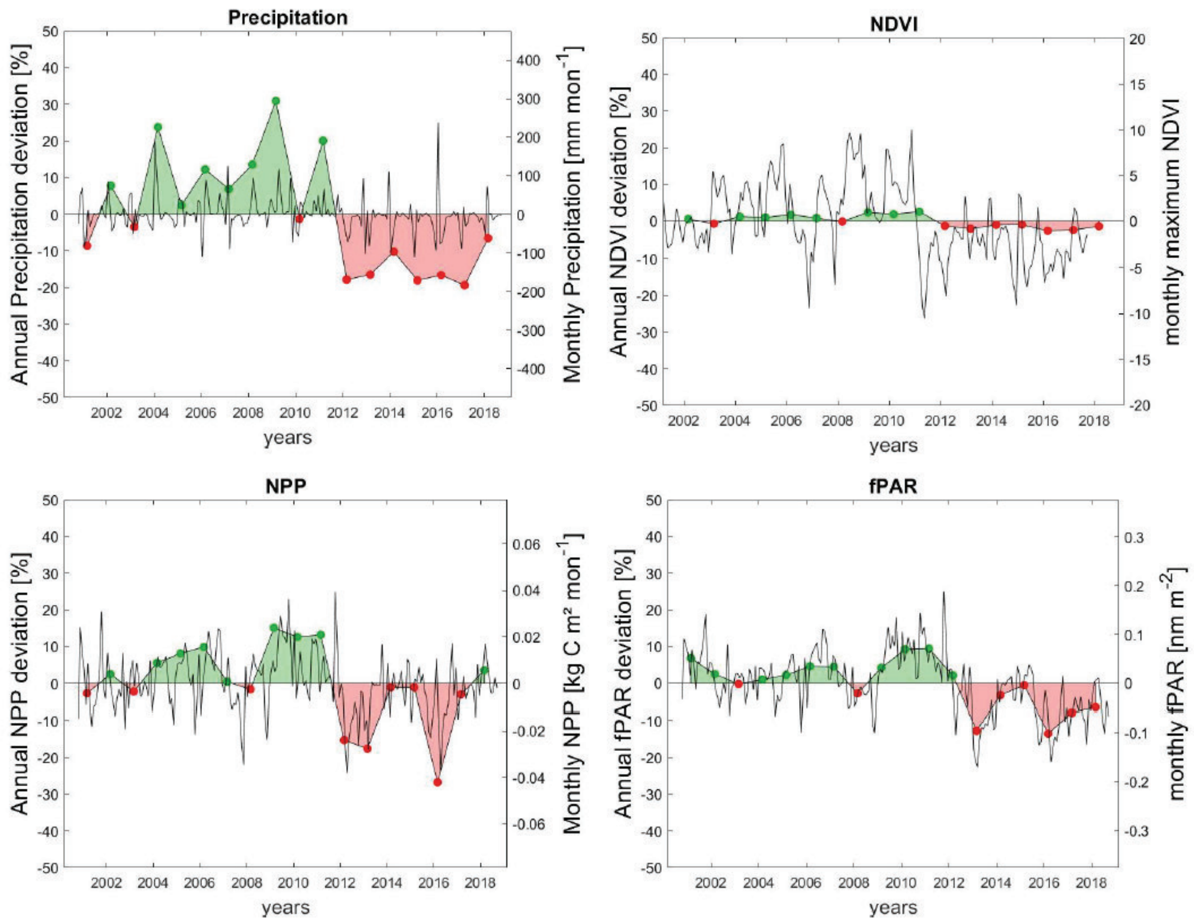

Figure 1: Annual deviation of precipitation, remotely sensed NDVI and modelled NPP and fPARfor the example of the Rio São Francisco basin in Brazil. Black lines are absolute deviations of monthly means above or below the average, corresponding to the right y-axis. The green areas show positive, red areas show negative relative annual deviations, i.e. by how many percent higher or lower the annual values are compared to the average, referred to the left y-axis. Timeline is from 2000-2018 for each hydrological year (Oct-Sept).

The hydrological variables confirmed the long-term trend towards drier years, with less rainfall and reduced runoff. During drought periods, simulated ecosystem water consumption was less affected than precipitation such that the fraction of water consumed by the ecosystem increases. This exacerbates the scarcity of water potentially used by humans. However, these results should not be interpreted as removal of vegetation being positive for human water availability. Ecosystems and evapotranspiration are crucial parts of the water cycle and for cloud formation, and removal of vegetation leads to negative feedback, enhancing droughts.

Based on LPJ-GUESS simulation results and precipitation inputs (WP1), we derived the Combined Drought Indicator (CDI, Sepulcre-Canto et al., 2012) for both study areas (see Figure 3 for an example). CDI is used for detecting and monitoring areas that either are affected or have the potential to be affected by agricultural drought and classifies them into four warning levels. It does that by combining three biophysical variables: the standardized precipitation index (SPI-3), the soil moisture anomaly and fPAR anomaly. The three variables untangle the cause-effect relationship for agricultural drought, whereby a shortage of precipitation leads to a soil moisture deficit, which in turn results in a reduction of vegetation productivity. Timelines of CDI data are included in the SaWaM DSS prototype together with ecosystem variables NPP and ecosystem water usage.

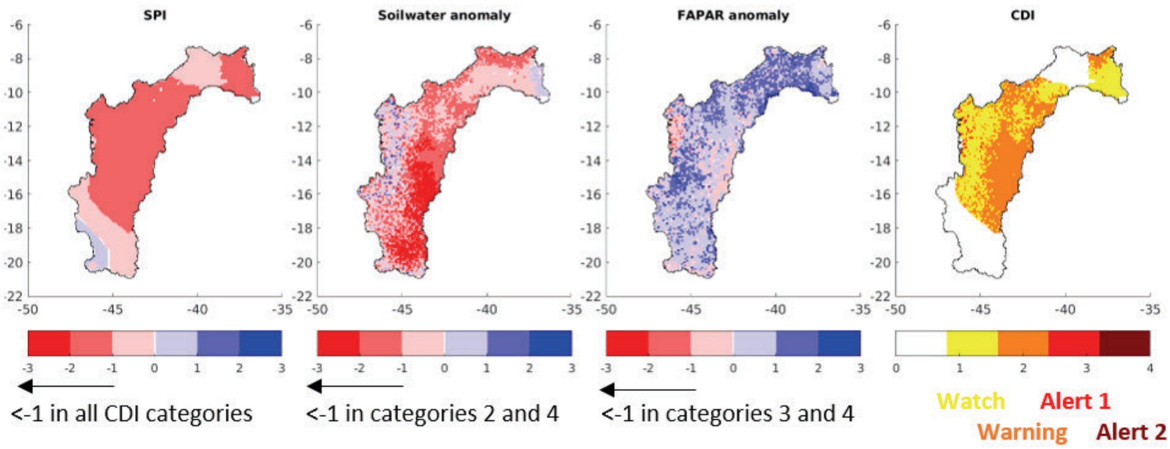

Figure 3: Example of anomalies in biophysical variables and classified Combined Drought Indicator for Sao Francisco basin, Brazil for August 2017.

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5.8. High resolution precipitation in near-real time from satellites

Nazli Turini[1], Boris Thies[1], Jörg Bendix[1]

[1] *Philipps-University Marburg*

In semi-arid areas, limited water availability from precipitation poses a problem for agriculture, drinking water supply and hydropower generation. In this context, area-wide, information on precipitation distribution with a high spatio-temporal resolution is important for water resource management. In most semi-arid regions, however, the precipitation measurement network is not dense enough to provide such information. This is also true for the semi-arid regions in the SaWaM project. Here, satellite-based precipitation products are often the only source of area-wide precipitation data.

NASA's IMERG product combines precipitation information from different satellites into a global precipitation product with the highest possible accuracy. However, the integration of IR data is limited to only one IR channel at 10.7 µm, leading to uncertainties in IR-based precipitation derivation. In this context, the IMERG development team recommends the use of multispectral GEO data along with advanced machine learning techniques to improve the accuracy of the derived precipitation information (Huffman et al. 2018). Here, multispectral sensors from the new GEO systems such as Meteosat and GOES offer the potential to improve the IR-based precipitation information of the IMERG product (e.g., Kühnlein et al., 2014; Meyer et al., 2017; Min et al., 2019). At the regional scale, these GEO systems can provide precipitation information at a higher spatio-temporal resolution. This allows capturing small-scale and short-living precipitation events more accurately. Recently, machine learning techniques have been increasingly used to combine precipitation information from different sources with multispectral GEO data and to account for the complex, non-linear relationships between satellite data and precipitation information (e.g., Kühnlein et al., 2014; Meyer et al., 2017; Min et al., 2019). Therefore, the goal of the subproject remote sensing of precipitation was to combine the advantages of the second generation GEO systems and the new GPM IMERG rainfall product using machine learning algorithms to provide regional precipitation information with high spatio-temporal resolution for the regions of the SaWaM project.

Figure 1 gives an overview of the developed rainfall retrieval technique. The algorithm uses multispectral IR data from the GEO systems Meteosat Second Generation and GOES-16 to derive the precipitation information. The MW based precipitation information from IMERG-V06 was used as a reference to train Random Forest (RF) models. The retrieval technique includes two steps: (i) precipitation area classification and (ii) precipitation rate assignment. In each step, separate feature selection and hyperparameter tuning are performed. The derived precipitation information is validated with independent precipitation information that was not considered in the training of the RF models. To analyze the potential improvement over algorithms using only one IR channel, the validation results were compared to those of the IR only precipitation dataset of the IMERG product.

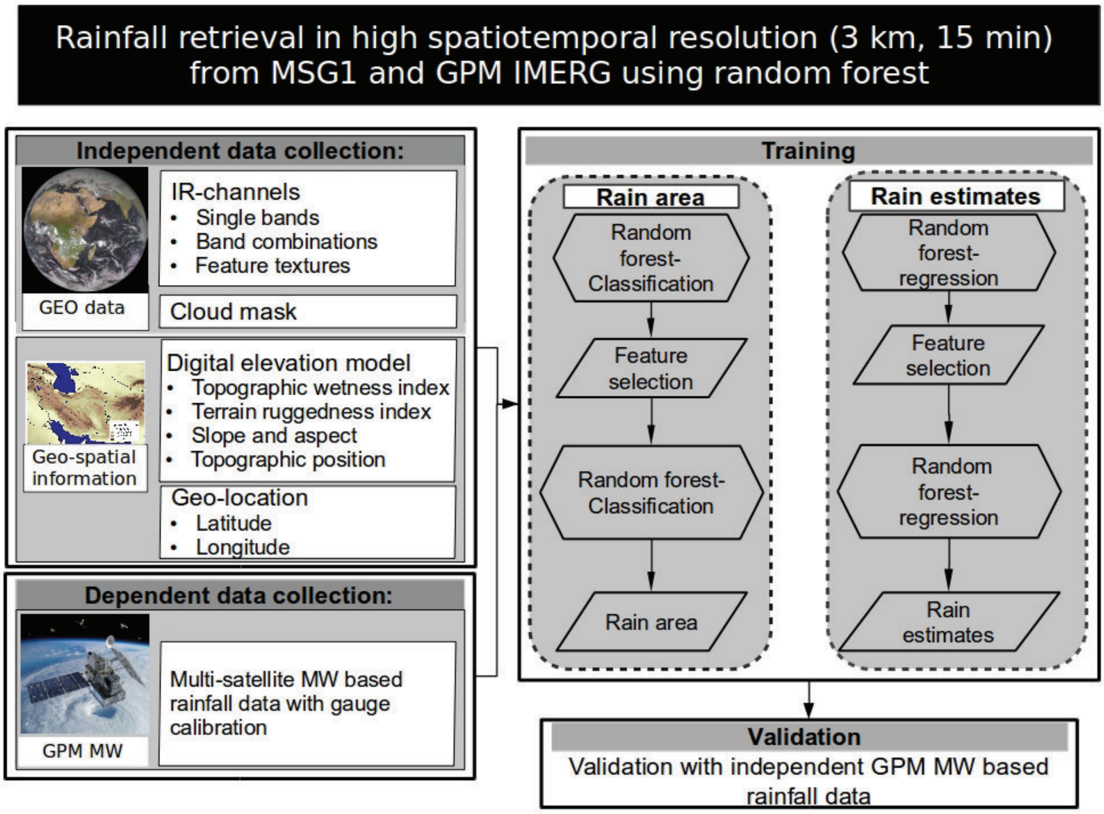

Figure 1: Schematic view of the rainfall retrieval workflow.

To assemble the most robust dataset for model training and validation, the following criteria were considered: (i) The time lag between the GEO data and the MW based IMERG data had to be less than 7 minutes. (ii) The IMERG quality index had to be greater than or equal to 0.9. (iii) The threshold of 0.2 mm/h was used to distinguish between raining and non-raining pixels (Hou et al. 2014). (iv) Only cloudy pixels were considered. A cloud mask was used for this purpose. The resulting dataset was randomly split into a training dataset (70%) and a validation dataset (30%). To determine and use the most important predictors, a backward feature selection was performed considering the feature importance and the out-of-bag score on monthly aggregation. Similarly, tuning of hyperparameters was performed on a monthly basis. Criteria here were the out-of-bag score and the computation time.
To account for the imbalance between the more frequent non-raining pixels versus the less frequent raining pixels as well as between the more frequent pixels with low rainfall intensities versus the less frequent pixels with high rainfall intensities during model training, an undersampling procedure was used to remove the pixels with the higher frequencies in favor of the less frequent pixels. Further details on data preparation, model development, and validation are described in Turini et al. (2019, 2021).

Figure 2 shows the precipitation rates of the newly developed multispectral method compared to the MW-based precipitation rates of the independent validation data set of the IMERG product for Iran from February 2017 to February 2018. The validation results show promising performance of the new precipitation retrieval method, especially compared to the IR-based precipitation rates of the IMERG product.

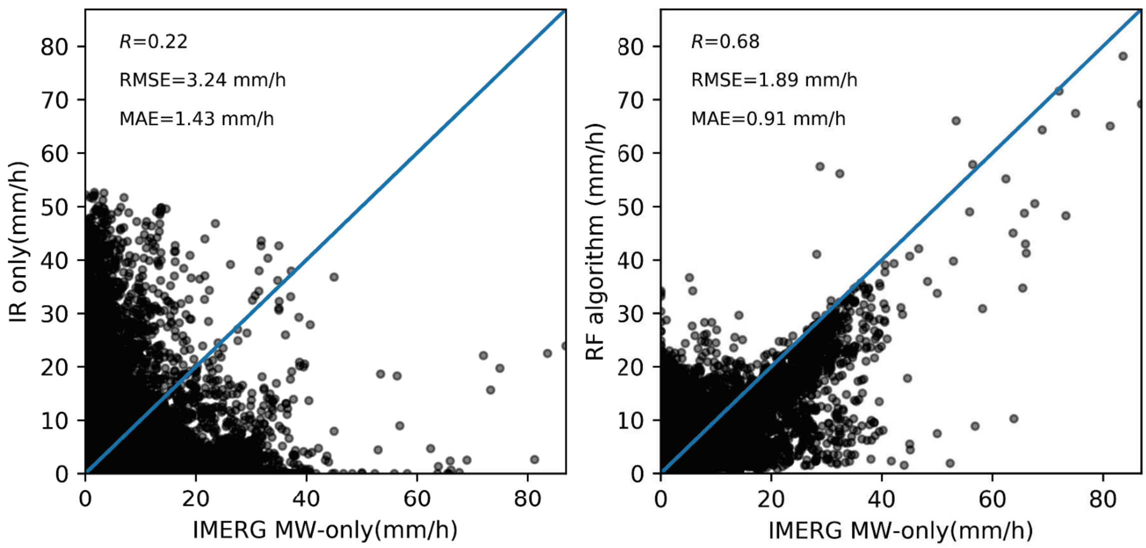

Figure 2: Rainfall rate comparison against independent GPM IMERG MW data for IR only (left) and the new multispectral algorithm (right) for Iran (February 2017-February 2018).

Figure 3 shows the validation results for the study period in Iran for the single months. Again, the good performance of the newly developed method can be seen, especially in comparison to the IR based precipitation rates. A sasionale dependence of the validation results is not to be recognized. The correlation coefficient shows a higher variability within the respective months compared to the IR based precipitation rates. The RMSE and MAE values indicate an overestimation of the precipitation rate by the newly developed method. Such overestimations by satellite-based precipitation methods are often found in semi-arid and arid areas. The cause is likely due to low humidity, which leads to evaporation of raindrops between the cloud base and the ground (Katiraie-Boroujerdy et al. 2013).

The validation results in comparison with ground measurements from Iran are shown in Figure 4. For the study period, there were 45 stations with 6 h temporal resolution and 32 stations with daily resolution available. The results show a monthly variability in the validation measures. The higher temporal aggregation does not improve the validation results. Overall, an overestimation of precipitation by the satellite-based method is also evident here, which is higher compared to the validation with the independent MW-based IMERG precipitation data. Here, the effect of low humidity described above could have a stronger impact. In addition to the problem of parallax shift (Vicente et al. 2002), which is particularly relevant for high range convection, wind drift could explain the larger discrepancies between the satellite retrieval and the ground measurements.

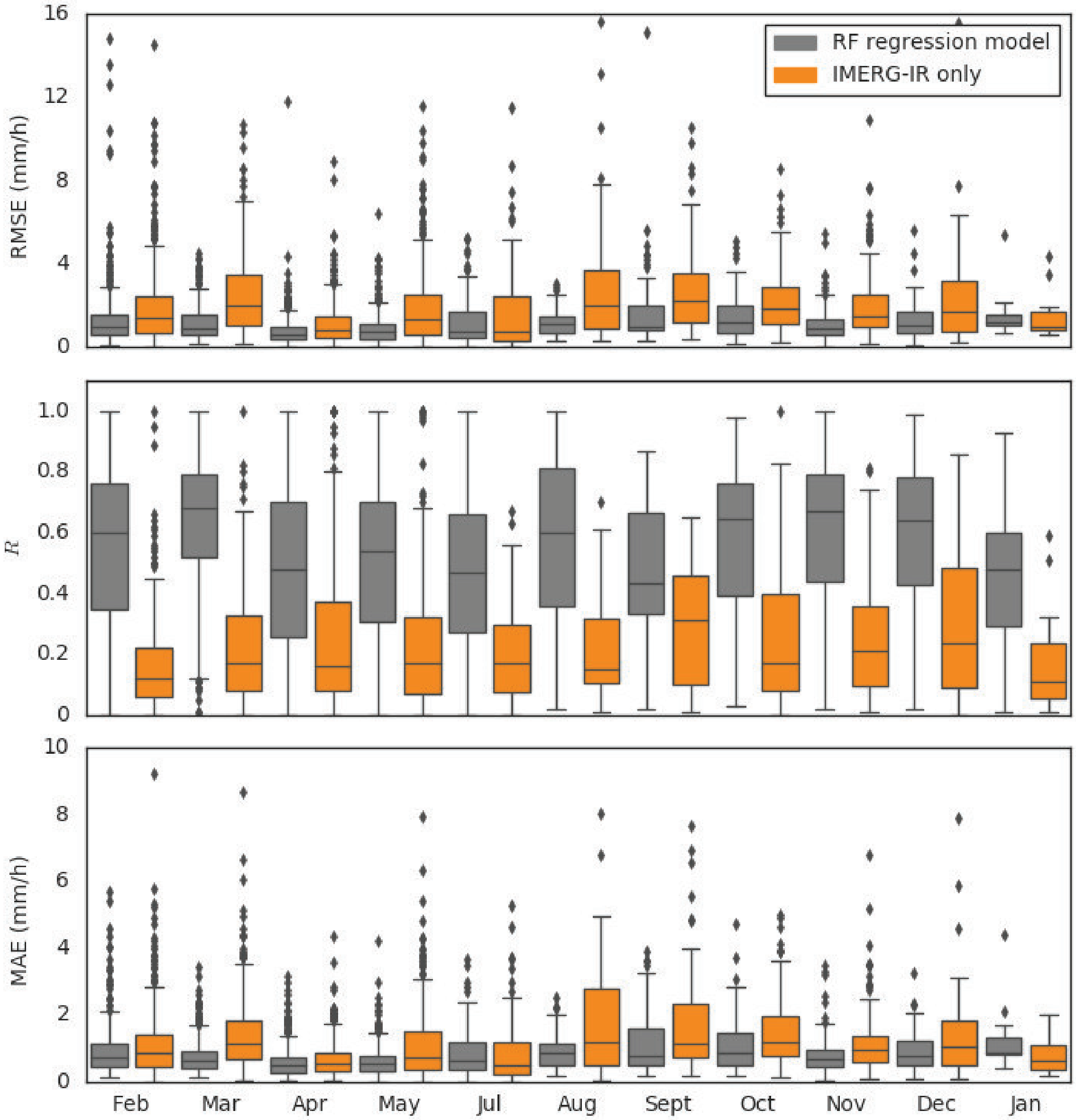

Figure 3: Standard validation scores for the new multispectral rainfall retrieval for Iran (February 2017 - February 2018): The scores were calculated on a scene basis in comparison with independent MW based rainfall information of the IMERG product. Boxes show 25th, 50th, and 75th percentiles. Whiskers extend to the most extreme data point between 75th and 25th percentile. Outliers are shown as points.

Within the SaWaM subproject remote sensing of precipitation, a new satellite-based rainfall retrieval technique was developed. For this purpose, multispectral data from GEO systems were combined with MW-based precipitation information from the GPM IMERG product using the machine learning method Random Forest. Validation with independent precipitation data show good performance of the new method. Thus, the provision of area-wide precipitation data in high spatio-temporal resolution in near real time for the regions of the SaWaM project is possible.

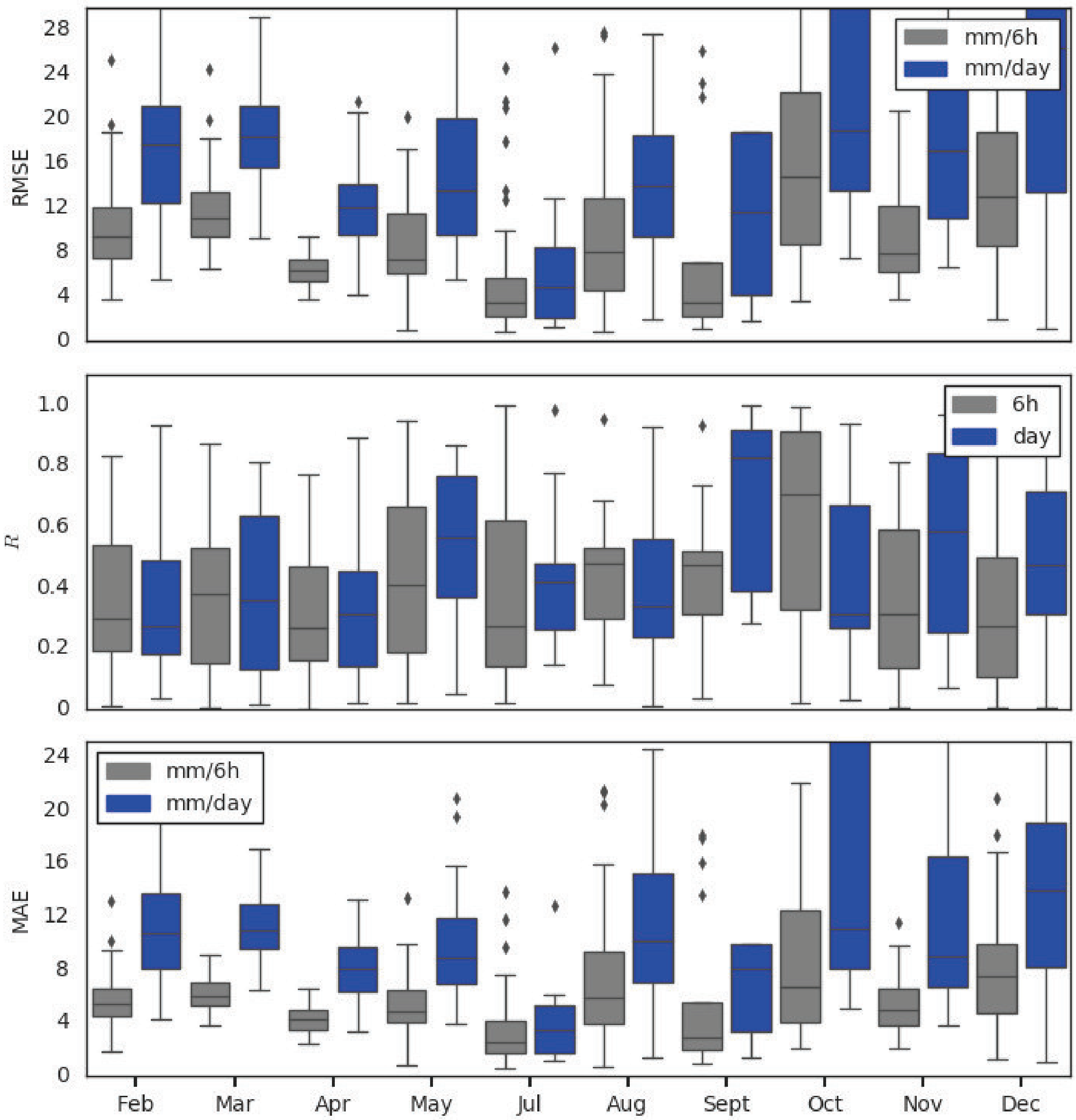

Figure 4: Standard validation scores for the new multispectral rainfall retrieval against gauge stations in Iran. The scores are based on the data pairs of 6 h/daily for the time period from February 2017 to December 2017. The gray boxes indicate the results for stations with 6-h resolution, and the blue boxes for stations with daily resolution. Boxes show 25th, 50th, and 75th percentiles. Whiskers extend to the most extreme data point between 75th and 25th percentile. Outliers are shown as points.

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5.9. Water level time series from satellite altimetry

Sajedeh Behnia[1], Mohammad J. Tourian[1], and Nico Sneeuw[1]

[1]*University of Stuttgart, Institute of Geodesy (GIS)*

Monitoring water level variation is of unarguable importance in water management. The information has been traditionally provided by *in situ* gauging stations, the number of which has significantly decreased during the last few decades. Satellite altimetry has proved effective in filling this gap (Calmant et al., 2008) and more than that offering a much denser network of virtual gauging stations at a global scale. As part of the research project SaWaM, our group has focused on deriving water level time series by conducting inland altimetry.

Table 1. Specification of altimetric data

Mission	retracker	Period	revisit time [days]	Source	Version
Envisat	ICE-1	2002-2010	35 (30)	ESA	GDR-V3
SARAL/Altika	ICE-1	2013-2016	35	AVISO	GDR-t
Jason-1	ICE-1	2002-2010	9.9156	AVISO	GDR-d
Jason-2	ICE-3	2008-2017	9.9156	AVISO	PISTACH
Jason-3	ICE-1	2016-ongoing	9.9156	AVISO	GDR-d
Sentinel-3A	OCOG	2016-ongoing	27	COPERNICUS	O_NT_003 (_004)
Sentinel-3B	OCOG	2018-ongoing	27	COPERNICUS	O_NT_003 (_004)
CryoSat-2	retracker 1	2010-ongoing	369	ESA	Baseline D

In order to derive water level time series, virtual stations over lakes, rivers, and reservoirs were defined. A virtual station is the average position of intersection between an altimetry ground track and the inland water body of interest. In the case of lakes and reservoirs, measurements from various intersecting tracks were considered to belong to the same virtual station. All range measurements in a virtual station were corrected for geophysical effects (solid earth tide and pole tide) and path delays caused by the atmosphere (wet tropospheric, dry tropospheric and ionospheric). The water level was then calculated by subtracting the corrected range from the satellite altitude. After changing the reference height to the EGM2008 (Pavlis et al., 2012) geoid model, the median of orthometric heights during an overfly was chosen to be the representative height. Table 1 lists the main features of the altimetry missions considered for deriving water level time series in SaWaM.

One of the main challenges in deriving reliable altimetric information was the level of outliers contaminating the retrieved water level time series. The problem was further exacerbated by the fact that narrow rivers and seasonal reservoirs in the semi-arid basins of Karun, Blue Nile, Upper Atbara, and São Francisco, were more subject to land contamination. To tackle the problem, GIS developed an automated, data-driven outlier identification methodology designed within an iterative, non-parametric adjustment scheme. The algorithm comprises Singular Spectrum Analysis (SSA) for gap-filling, Savitzky-Golay filtering for smoothing, and a specially developed outlier identification method. The identification method benefits from applying a local kernel derived based on a local definition of an outlier. The outputs of the outlier identification algorithm were then used in developing a retracking algorithm based on Leading Edge Identification with Prior Information (LEIPI). Figure 1 shows water level time series derived from the Jason series over the rivers São Francisco and Karun. The latter example highlights the importance of outlier identification in narrow river crossings especially when they are surrounded by a mountainous area.

Within a lake or reservoir, the bias between time series of various missions and tracks needed to be estimated and compensated for. GIS developed a method to resolve relative biases in a rather generic and mission independent manner. For overlapping time series, the relative biases are estimated by minimizing a cost function for the merged time series. The cost function represents the difference between the power content of individual time series. For periods of no overlap or short overlap, remotely sensed surface area time series was used to minimize the biases within a Gauss-Helmert adjustment scheme. While the challenge of bias estimation in satellite altimetry has been generally discussed in the context of inter-satellite biases, our method goes beyond that and accounts for the inter-track biases which are mostly caused by inaccuracies in the geoid models. Figure 2 shows the multi-mission time series of lake Tana and the reservoir Sobradinho before and after bias correction.

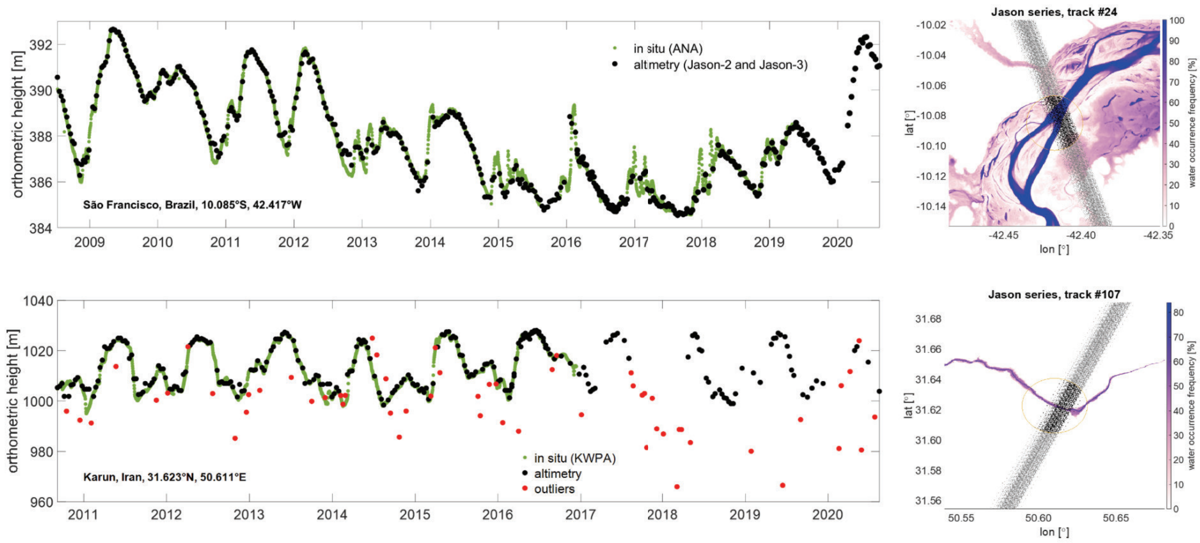

Figure 1. altimetric water level time series over the river São Francisco in Brazil and river Karun in Iran.

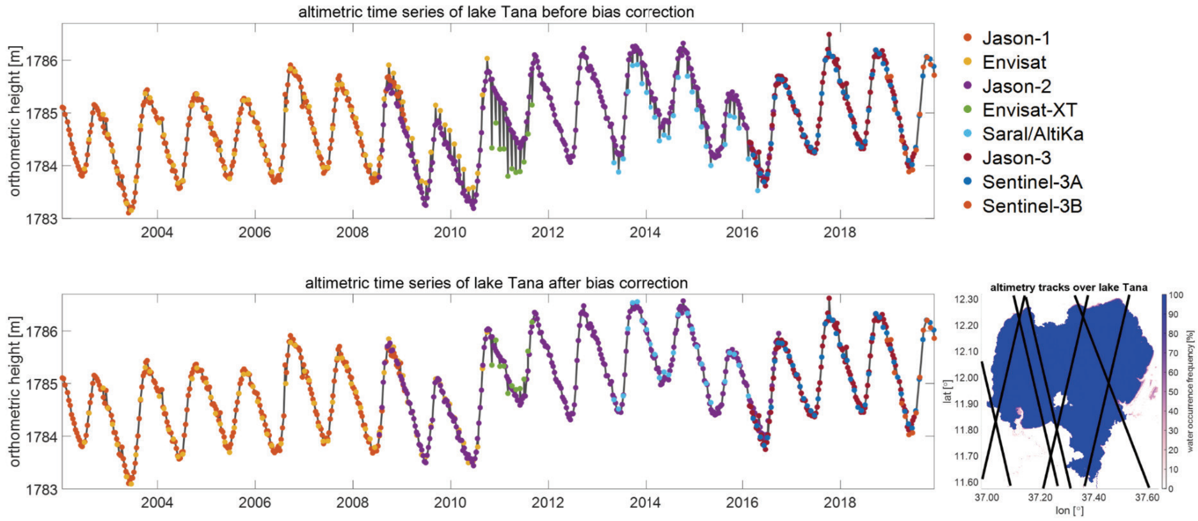

Figure 2. multi-mission altimetric time series of lake Tana before (top) and after (bottom) correcting for the inter-satellite and inter-track biases.

Within the SaWaM project, we generated water level time series for tens of altimetry gauging stations in São Francisco (Brazil), Karun (Iran), Blue Nile (Sudan), and Upper Atbara (Sudan) basins. We developed a data-driven outlier identification (rejection) scheme to remove the erroneous altimetric measurements at the level of time series analysis. Based on the output of the outlier identification analysis, a new retracking approach for inland applications, LEIPI, was developed. To deal with the inter-satellite and inter-track altimetric biases, we used a hybrid cost function minimization method.

Our research confirms that local water authorities can benefit from satellite altimetry data in order to establish virtual gauging stations over lakes, reservoirs, and rivers. This will enrich the water monitoring databases. Figure 3 shows an example of the established virtual gauging stations over the river São Francisco.

Satellite altimetry can also provide valuable information for hazard analysis. In such applications, however, it is important to consider all the limitations. From the 2019 flooding event in Iran we learned that the latency in data distribution renders satellite altimetry ineffective for an emergency response. Nevertheless, the same altimetry data can be of high value for post hazard mitigation and analysis.

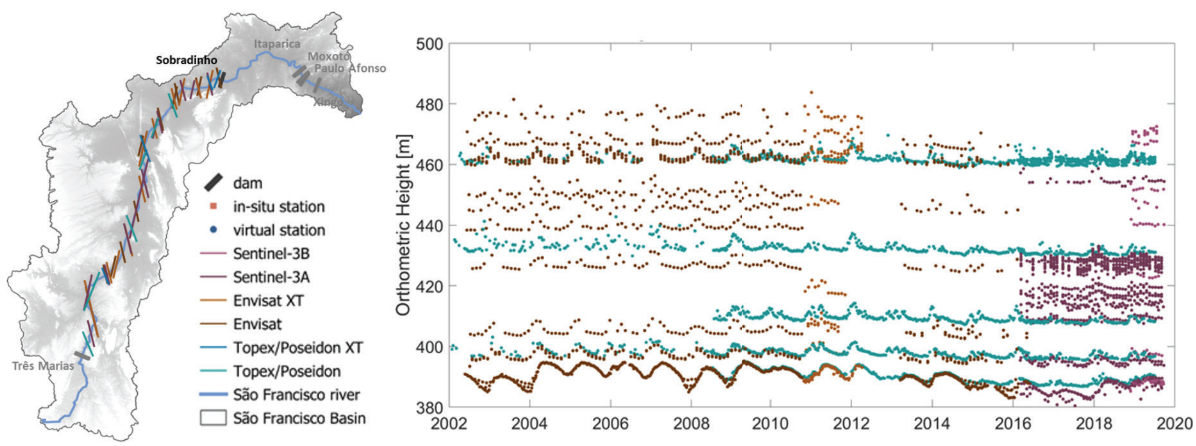

Figure 3. the established altimetry virtual stations over the river São Francisco, between Três Marias and Sobradinho dams.

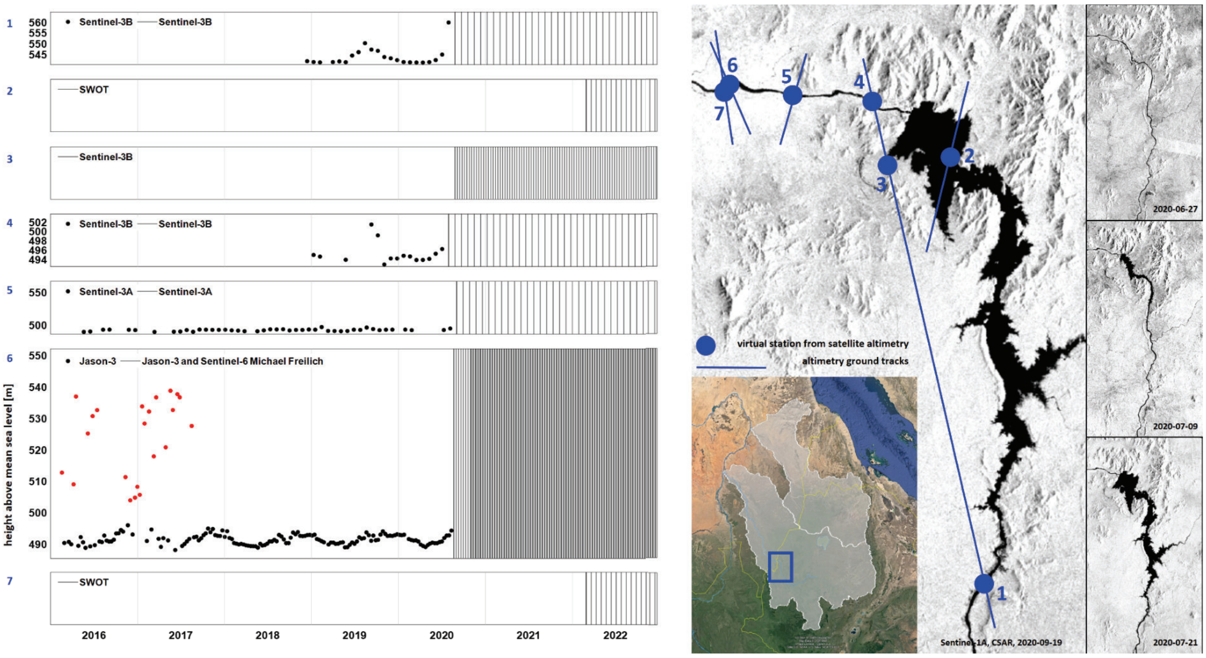

Figure 4. potential of satellite altimetry in monitoring the Grand Ethiopian Renaissance Dam. left) past, present, and future state of altimetry time series at different virtual stations and right) distribution of virtual gauging stations upstream and downstream of the dam

Another less emphasized application is the potential of satellite altimetry, and satellite imaging, in resolving transboundary water disputes (Biancamaria et al., 2011). Figure 4 shows the example of the Grand Ethiopian Renaissance Dam (GERD) as monitored by satellite altimetry (the Jason series, Sentinel-3A, Sentinel-3B, Sentinel-6 Michael Freilich, and the future SWOT mission) and satellite imaging (Sentinel-1A) missions.

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5.10. Seasonal Water Management – Online Prototype for Reservoir/Dam Management Support

Thomas Kukuk[1], Yasin Shafaghi[1], Enrique Caballero Mansilla[1]

[1]*GAF AG, Munich*

Providing stakeholders with meaningful information for dam and reservoir management is a challenge. The SaWaM project provides a number of complex information products which are not easy to understand. Therefore the goal was to develop and provide an „Online Prototype" for decision support to help stakeholders to use and understand the delivered geo-information and compare information from past seasons and events to the coming months. Accuracy measures must be easily understandable for different levels of users, especially decision makers.

Main information presented in the Online Prototype are the seasonal forecasts and historical data – so-called hindcasts – to help decision makers in dam management in planning the next month‘s strategy. Users are now able to compare and retrieve decision support information on future water availability through modelled hydro-meteorological and hydrological information like precipitation, temperature and inflow together with further information on ecological information.

User needs assessment

SaWaM had a number of meetings in the study regions where users were asked on the key information needs related to dam and reservoir management related to the inform layers that are developed in the different work packages. These needs were then summarized during project mid term meetings and the basic layout of the system was presented.

The organisation and planning of reservoir operations is managed in different administrative ways including a number of (state) entities in the target and perspective areas, but the parameters of main interest for the users are the following (collected mainly during the midterm review of the project in February 2019): precipitation, temperature, streamflow respectively Inflow and outflow to/from dams, evapotranspiration and sediments.

A number of additional parameters especially hydrological and ecological parameters can be offered, but focus was put on the main parameters.

Online prototype architecture

The online prototype is based on a microservices architecture using GeoServer technology to provide the spatial information and retrieves the data, mainly NetCDF data, through a THREDDS-Server where the scientific data is ingested in a controlled manner using a dedicated Meta-data tool to help scientists and data specialists to provide these complex data sets in a standardized way.

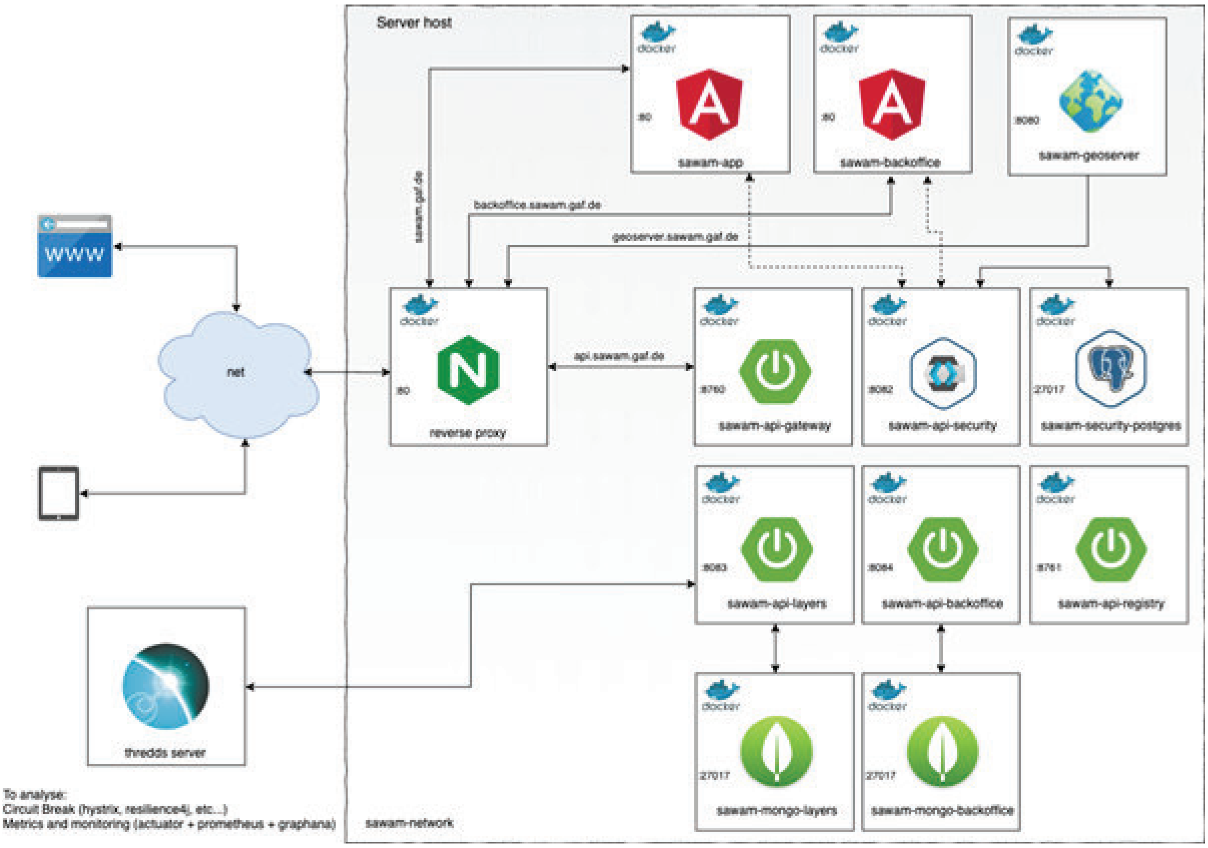


Figure 1: SaWaM Online Prototype architecture (GAF AG 2020)

The presentation of the data sets is split into historical and forecast data and provides absolute and categorical value presentations of the model outputs. A timeline provides dynamic views on the development of the situation in the respective river basins or subbasins relevant for dam management.

Graphical presentation of the values together with different confidence value presentations help decision makers to understand the information.

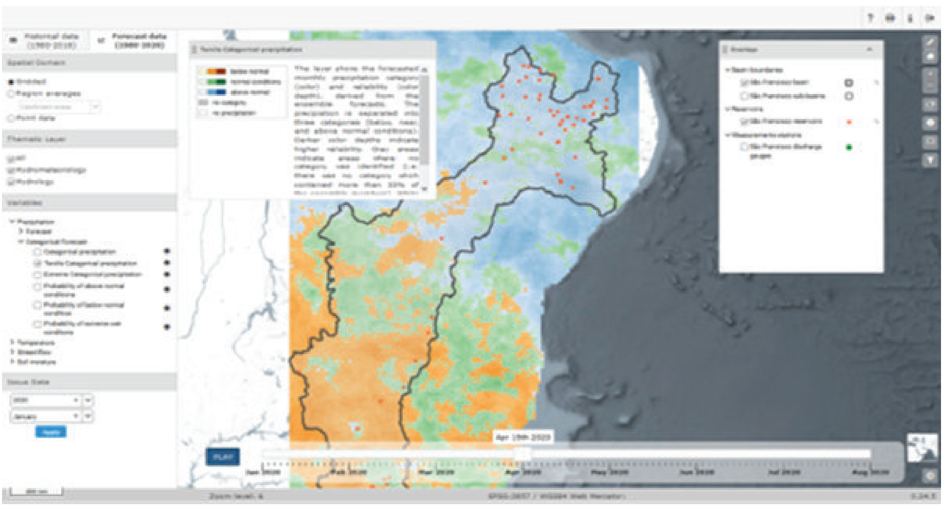


Figure 2: SaWaM Online Prototype view for Sao Francisco Basin, Brazil showing categorical precipitation forecast (issue date Jan 2020 – next 7 months) (forecast source KIT / Prototype GAF AG 2020)

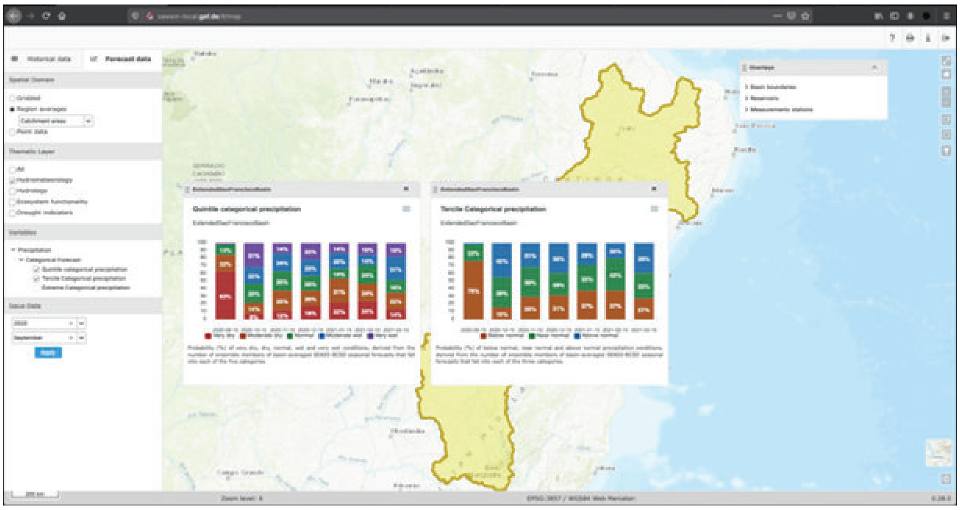


Figure 3: SaWaM Online Prototype view for Rio Sao Francisco, Brazil. Comparison of historical and forecast categorical precipitation (basin average) (source KIT / Prototype GAF AG 2020)

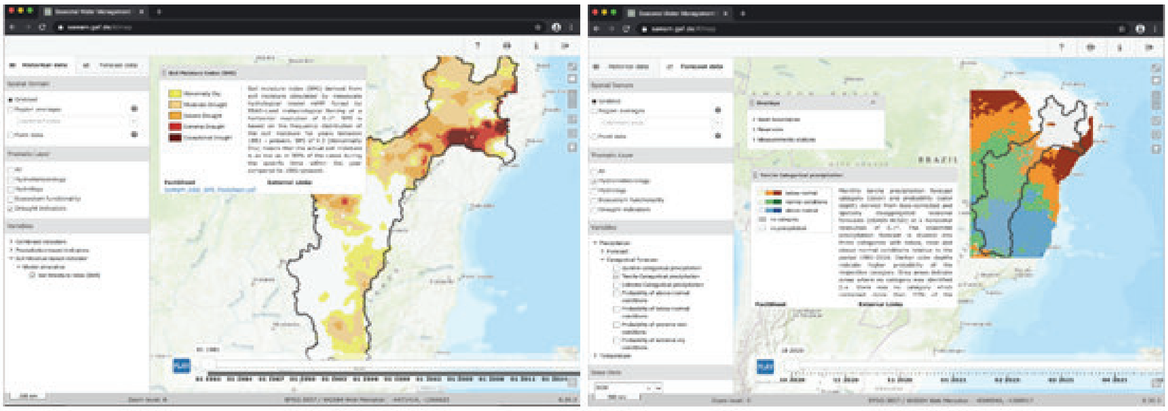


Figure 4: SaWaM Online Prototype: Categorical Soil moisture index (historic view /left) and tercile categorical precipitation forecast (right) San Francisco (Brazil) (forecast source KIT / Prototype GAF AG 2020)

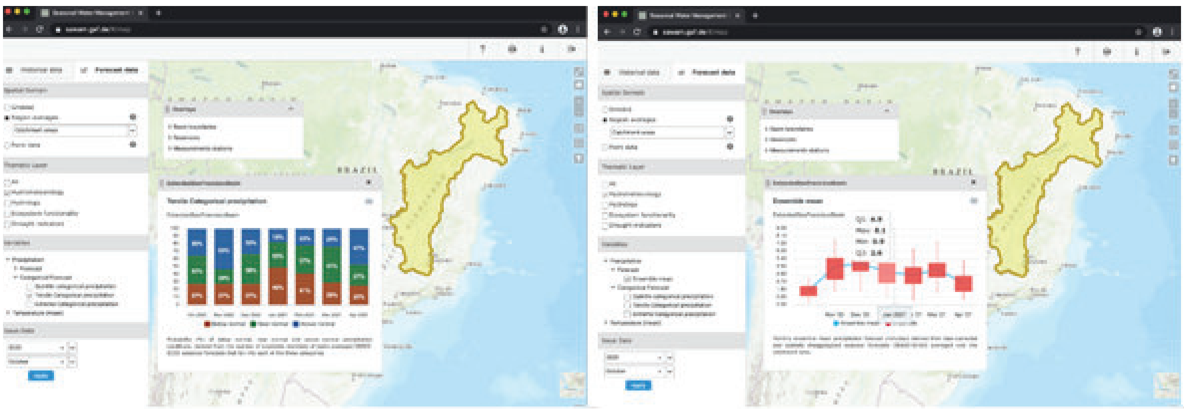


Figure 5: Categorical presentation of model results and confidence information for results (forecast source KIT / Prototype GAF AG 2020)

Initially it was planned that the system should present all the information especially of the seasonal forecasts and its uncertainties as geospatial layers. Discussions with data providers and users based on their usual information “consumption” showed that this presentation was too complex for understanding and easy decision making. So the data itself was presented as spatial timelines and graphs of e.g. area averages showing the situation in the relevant part of the basins having influence on the reservoir or dam.

The possibility to compare the forecast to past situations together with fact sheets and scientific background information provided together with the data, supports the interpretation of the forecast data and decision making in a comprehensive way. Further available layers and feedback from users based on the growing experience can be implemented permanently to improve the system.

The system is available online under http://sawam.gaf.de .

The SaWaM Online Prototype is under further integration into other software products of GAF AG and forms part of upcoming offers for water information management on national and basin level, mainly tendered by WorldBank and other international development cooperation programmes.

References:

Docker hub (2020): https://docker.hub.com (last visited on 15th June 2021)

GeoServer (2020): https://docs.geoserver.org (last visit on 15th June 2021)

Keycloak (2020): https://www.keycloak.org/ (last visited on 15th June 2021)

MongoDB (2020): https://www.mongodb.com/ (last visited on 15th June 2021)

PostgresSQL (2020): https://www.postgresql.org (last visit on 15th June 2021)

THREDDS Data Server (2020): https://www.unidata.ucar.edu/software/tds/ (last visited 15th June 2021)

5.11. User-oriented application of developed methods and tools

Berhon Dibrani[1]

[1]*Tractebel Engineering GmbH*

Tractebel Engineering GmbH (Tractebel) is a worldwide operating engineering company that provides services for project-related development stages, in fields such as hydropower, irrigation and food security. It is due to this ability that Tractebel has a deep understanding of how information shall be provided to ensure a practical utilization of seasonal forecasted data.

Tractebel's main goal within this project was the assessment of the scientific results for the purpose of practical application. This process takes place in close cooperation with local decision makers to combine user-oriented and scientific information with the goal of contributing to specific decision support in these regions.

The tool collating these results is an online prototype that facilitates access and use of the outcomes of the project in the form of methods and data including a seasonal forecast for water resources management. Tractebel assists in the development of this tool to ensure its practical utilization. The functionality of the online tool has been tested during various development stages and options for improvement were discussed within the team.

Tractebel participated in stakeholder workshops for assessing user-oriented needs indicating necessary features of the online tool. Hydrometeorological and sedimentological data of the study region Upper Atbara (Sudan) were collected, processed and provided to the project team for calibration of hydrological models. In order to assess benefits of a seasonal forecast for an existing reservoir, a spreadsheet model was developed for Upper Atbara Dam that considers reservoir operating rules for the maximization of electrical energy production.

The significance of the practice-oriented methodology was examined by applying two examples of the Upper Atbara Dam. The reservoir operation of Upper Atbara Dam comprises an annual drawdown from a full supply level of 521.0 m asl to a level of 510.0 m asl, which is maintained for six weeks between 1 July and 15 August for the purposes of sediment conveyance and removal. For the subsequent filling, it must be ensured that the reservoir reaches the full supply level latest by end of December of the same year.

It is assumed in the first example that the information of the seasonal forecast would be available and thus the discharge time series is known. For the dry year 2015 (Fig. 1), the reservoir operation was carried out first as for an average year without considering information of a seasonal forecast. In a second step, the reservoir operation was amended based on the seasonal forecast outputs.

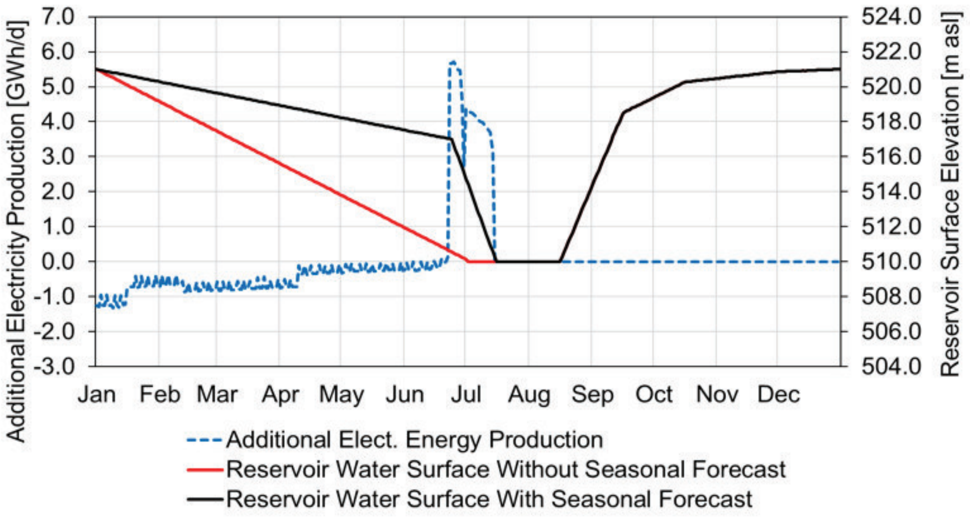


Figure 1: Benefits of a seasonal forecast for 2015

Results indicate that a reservoir operation adapted to the seasonal forecast can generate for the year 2015 additional electricity worth about 1.3 million US$. On the other hand, an incorrect seasonal forecast (forecast of a dry year, but an average year occurs) may lead to losses of about 0.3 million US$.

The second example assesses how a seasonal forecast of meteorological parameters may be implemented practically in the reservoir operation procedure. The inflow time series of the dry year 2005 (Fig. 2) was selected since the reservoir inflow has been influenced since 2007 by the erection of the upstream located Tekeze Dam. The seasonal forecast is updated every second month, but validated with observed data every month. The reservoir drawdown and rise of the reservoir level is amended based on the forecast and the actual observations.

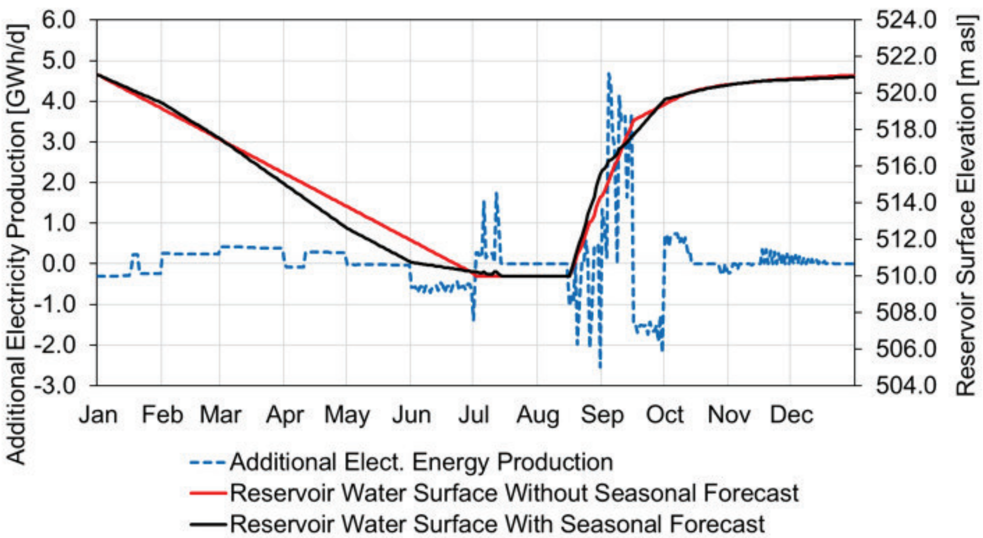


Figure 2: Benefits of a seasonal forecast for 2005

As a result, the benefit from the generation of electrical energy for the year 2005 amounts to approximately 4.2 million US$. The main reason for the monetary benefits is the reduction of the sluicing operation from six to four weeks, which reduces spillage (from 667 Mm^3 to 513 Mm^3) and in turn provides more water for the generation of the electrical energy.

The seasonal forecast offers not only noticeable benefits for electrical energy production, but also improves the water resources management for irrigation, potable water and flood retention in reservoirs.

6. Synthesis: Integration of results into DSS

Within SaWaM we developed the prototype of an online decision support system (DSS) to explore the praxis transfer of the methods and datasets created within the project for regional water management in semi-arid regions. The tool provides data from the fields hydrometeorology (e.g. precipitation, temperature), hydrology (e.g. streamflow, soil moisture) and ecosystem functionality (e.g. NPP, ecosystem water usage, remote sensing-based vegetation indices NDVI and EVI as well as FAPAR und LAI maps) for the study regions in Iran, Brazil and Sudan/Ethiopia. In addition, drought indicators that are based on one or a combination of multiple indicators are depicted in the tool. Historic timelines start in 1981 until 2018 to 2020 (depending on the dataset). Latest forecast data (updated frequently) currently being included run from June 2021 to January 2022. Data are gridded, provided as region averages or point data depending on the type of dataset. Access to the DSS prototype is for free and provided to partners of the study regions, as well as to guests via guest logins for the regions (https://sawam.gaf.de).

The DSS ensures good outreach promoting the usability by the end users. For instance, the categorical forecasts provided by the DSS are relative quantification and thus are intuitive. The forecasts are probabilistic based on 51 ensemble members providing users with uncertainty quantification as well. The spatial requirement of various end users of the DSS could be varied. For instance, a reservoir operator requires point data at the reservoir, a city mayor would be interested in regional average data for the city extent, and a regional development team might be interested in the distribution of gridded values over the entire region. Keeping this in consideration, DSS generates forecast indicators at three spatial categories - grid, points, regional averages - fulfilling a wide range of spatial requirements which ensures a good user base.

Operationalization of the developed tools and their dissemination in the DSS were important prerequisites for the increased integration of SaWaM's advanced solutions. In particular, the provision of SaWaM's improved hydrometeorological seasonal forecasts was operationalized, which required the establishment of a web server for online data access (THREDDS data server) and an operational workflow for the calculation of bias-corrected and spatially disaggregated forecasts for the regions. SaWaM’s forecasts in the DSS are thus updated each month only 1-2 days after the official release of the original seasonal forecasts by ECMWF. Decision makers are therefore able to integrate SaWaM's hydrometeorological seasonal forecasts into their planning and management from the current to the next seven months in a timely manner.

Concluding, the products, tools and methods developed in SaWaM provide a benchmark for the application of seasonal forecasting, remote sensing and modeling data for regional water management and thus contribute to climate proofing, especially in semi-arid regions. The provision of the DSS also actively contributes to the final transfer to practice and ensures that SaWaM research and technology results can be directly used by local decision makers and stakeholders.

7. Utilization of the results

7.1. Publications with review process

2021

Title	Authors	Type
Seasonal forecasts offer economic benefit for hydrological decision making in semi-arid regions, Scientific Reports, https://doi.org/10.1038/s41598-021-89564-y	T. C. Portele, C. Lorenz, B. Dibrani, P. Laux, J. Bliefernicht, H. Kunstmann	Research article
Ensemble-Tailored Pattern Analysis of High-Resolution Dynamically Downscaled Precipitation Fields: Example for Climate Sensitive Regions of South America. Frontiers in Earth Science, https://doi.org/10.3389/feart.2021.669427	T. C. Portele, P. Laux, C. Lorenz, A. Janner, N. Horna, B. Fersch, M. Iza, H. Kunstmann	Research article
Bias-corrected and spatially disaggregated seasonal forecasts: along-term reference forecast product for the water sector in semi-arid regions, Earth System Science Data, https://doi.org/10.5194/essd-2020-177	C. Lorenz, T.C. Portele, P. Laux, H. Kunstmann	Research article
Intraseasonal Oscillation Indices from Complex EOFs, *Journal of Climate*, 34, 107–122, https://doi.org/10.1175/JCLI-D-20-0427.1	G. Bürger	Research article
A drought monitoring tool for South Asia, Environment Research Letters, https://iopscience.iop.org/article/10.1088/1748-9326/abf525	T. R. Saha, P. K. Shrestha, O. Rakovec, S Thober, L Samaniego	Research article

2020

Title	Authors	Type
A semi-objective circulation pattern classification scheme for the semi-arid Northeast Brazil. *International Journal of Climatology,* 1 – 22, doi: 10.1002/joc.6608	P. Laux, B. Böker, E. S. Martins, F. C. V. Junior, V. Moron, T. Portele, C. Lorenz, A. Philipp, H. Kunstmann	Research article

A seamless filter for daily to seasonal forecasts, with applications to Iran and Brazil, *Quarterly Journal of the Royal Meteorological Society*, **146**, 240 – 253, doi: 10.1002/qj.3670	G. Bürger	Research article
Mesoscale Mapping of Sediment Source Hotspots for Dam Sediment Management in Data-Sparse Semi-Arid Catchments, *Water*, **12**(2), 396, doi: 10.3390/w12020396	A. Smetanová, A. Müller, M. Zargar, M. A. Suleiman, F. R. Gholami, M. Mousavi	Research article
A Random Forest based rainfall retrieval for Ecuador using GOES-16 and IMERG-V06, European Journal of Remote Sensing, 54(1), 117-139, http://dx.doi.org/10.1080/22797254.2021.1884002	N. Turini, B. Thies, N. Horna, J. Bendix	Research article

2019

Title	**Authors**	**Type**
Estimating High Spatio-Temporal Resolution Rainfall from MSG1 and GPM IMERG Based on Machine Learning: Case Study of Iran, *Remote sensing*, **11**, 2307, doi: 10.3390/rs11192307	N. Turini, B. Thies, J. Bendix	Research article
Ground surface response to continuous compaction of aquifer system in Tehran, Iran: Results from a long-term multi-sensor InSAR analysis. - *Remote Sensing of Environment*, 221, 534-550. doi: 10.1016/j.rse.2018.11.003	M. Haghshenas Haghighi, M. Motagh	Research article

In preparation/review

Title	**Authors**	**Type**
A high-resolution regional climate simulation physics ensemble for Sub-Saharan Africa	P. Laux, D. Dieng, T. C. Portele, J. Wei, S. Shang, Z. Z., J. Arnault, C. Lorenz, H. Kunstmann	Artikel (in review)
Seamless seasonal prediction skill for two semi-arid regions, using two downscaling methods	G. Bürger, C. Lorenz, T. C. Portele, F. C. Vasconcelos Junior, and H. Najafi	Artikel (in preparation)
The Significance of Reservoir Sedimentation for Water Security in Semi-arid Regions, *Water Security*	A. Müller, A. Bronstert, M.A. Suleiman	Artikel (in preparation)
Hydro-sedimentological modelling of the Karun and Dez catchment, Iran	A. Müller, A. Bronstert, T. Francke, J. Diether, M. Zargar, M. Mousavi	Artikel (in preparation)

Modelling of hydro-sedimentological processes and irrigation management of the Rio São Francisco catchment, Brazil	A. Müller, P. Voit, A. Bronstert, T. Francke, J. Diether	Artikel (in preparation)
Validation of satellite-based rainfall products over Ecuador using a ground based radar network	N. Turini, B. Thies, R.Rollenbeck, A. Fries, F. Pucha-Cofrep, J. Orellana Alvear, N. Horna, R. Célleri, J. Bendix	Artikel (in preparation)
Vegetation and land cover dynamics under increasing water scarcity in Iran. Scientific reports.	R. Behling, Roessner, T. C. Portele, C. Lorenz, P. Saemian, N. Sneeuw, M. Tourian, M. Zargar, S. Foerster	Artikel (in preparation)
The mHM Lake Module mLM v1.0: Reservoir regulation parameterization for hydrological models using real world operating language	P. K. Shrestha, L. Samaniego, O. Rakovec, R. Kumar, S. Thober	Article (in preparation)
Impartially resolving reservoirs for scalable hydrological modeling across 1 km to 100 km	P .K. Shrestha, L. Samaniego, O. Rakovec, R. Kumar, S. Thober	Article (in preparation)
Regionalization of reservoir regulation parameters using physiographic and climatological predictors.	P. K. Shrestha, S. Thober, L. Samaniego	Article (in planning)
Towards scale independent hydrological forecasting in regulated semi-arid regions.	P. K. Shrestha, S. Thober, O. Rakovec, H. Najafi, C. Lorenz, L. Samaniego	Article (in planning)
Leading Edge Identification with Prior Information (LEIPI): a new approach to retracking inland water altimetry waveforms	S. Behnia, M.J. Tourian, and N.Sneeuw	article (in preparation)

7.2. Publications without review process

2021

Title	Authors	Type
SaWaM region averages for SREP, doi: 10.1038/s41598-021-89564-y	T. C. Portele, C. Lorenz	Dataset-Publication
Statistische Analyse und Vergleich globaler und regionaler Niederschlagsdaten für die hydro-sedimentologische Modellierung des Dez- & Karun-Einzugsgebiets, Iran, Bachelorarbeit, Institut für Umweltwissenschaften und Geographie, Universität Potsdam	J. Geißler	Bachelor thesis
Hydrological modelling of the Rio São Francisco catchment, Brazil, with WASA-SED, Masterarbeit, Institut für Umweltwissenschaften und Geographie, Universität Potsdam	P. Voit	Master thesis

2020

Title	Authors	Type
Sensitivity analysis and case studies for hydrological modelling with WASA-SED in selected sub-basin areas of Karun-Dez catchment, Iran, Bachelorarbeit, Institut für Umweltwissenschaften und Geographie, Universität Potsdam	J. Diether	Bachelor thesis
Evaluation of long-term and seasonal trends of modelled and monitored vegetation variables in two semi-arid catchments	C. Mihalyfi-Dean	Bachelor thesis
Seasonal Water Resources Management for Semiarid Areas: Bias-corrected and spatially disaggregated seasonal forecasts for the Karun Basin (Iran), https://doi.org/10.26050/WDCC/SaWaM_D01_SEAS5_BCSD	C. Lorenz, T. C. Portele, P. Laux, H. Kunstmann	Dataset-Publication
Seasonal Water Resources Management for Semiarid Areas: Bias-corrected and spatially disaggregated seasonal forecasts for the Rio São Francisco Basin (Brazil), https://doi.org/10.26050/WDCC/SaWaM_D02_SEAS5_BCSD	C. Lorenz, T. C. Portele, P. Laux, H. Kunstmann	Dataset-Publication
Seasonal Water Resources Management for Semiarid Areas: Bias-corrected and spatially disaggregated seasonal forecasts for the Tekeze-Atbara and Blue Nile Basins (Sudan and Ethiopia), https://doi.org/10.26050/WDCC/SaWaM_D03_SEAS5_BCSD	C. Lorenz, T .C. Portele, P. Laux, H. Kunstmann	Dataset-Publication
Seasonal Water Resources Management for Semiarid Areas: Bias-corrected and spatially disaggregated seasonal forecasts for the Catamayo-Chira Basin (Ecuador and Peru), https://doi.org/10.26050/WDCC/SaWaM_D04_SEAS5_BCSD	C. Lorenz, T. C. Portele, P. Laux, H. Kunstmann	Dataset-Publication

2019

Title	Authors	Type
Large Area Precipitation and Vegetation Dynamics in the Republic of Sudan from Remotely Sensed Time Series, GFZ Potsdam/TU Dresden	E. H. Amegashie	Master thesis

Development of an objective weather classification for statistical downscaling and drought prediction - Feasibility study for the Sao Francisco catchment area, Universität Augsburg	B. Böker	Master thesis
Seasonal basin scale runoff forecast: Development of a Kalman filter based system within an operational online framework, Masterarbeit, IMK-IFU, Karlsruher Institut für Technologie	M. Borne	Master thesis
Geoökologische Charakterisierung des Rio São Francisco Einzugsgebiets, Brasilien, inklusive aktueller Wasserbewirtschaftungsmaßnahmen, Bachelorarbeit, Institut für Umweltwissenschaften und Geographie, Universität Potsdam	J. K. P. Hurtig	Bachelor thesis
WASA-SED Modell, Modellcodeerweiterung zur Einbeziehung von Stauseen in großskaligen Einzugsgebieten, Software-Publikation (Fortran-Code), Institut für Umweltwissenschaften und Geographie, Universität Potsdam. GitHub: https://github.com/TillF/WASA-SED	T. Francke, A. Müller	Software-Publication

2018

Title	Authors	Type
GRoW position paper on SDG 6: Strengthening the evidence base for the SDG process. An. High Level Political Forum. 2018	C. Pahl-Wostl, U. Eid, F. Schmidt, H. Kunstmann, A. Smetanová, F.A. Weber, M. Hagenlocher, L. Wolf	Publication
SWAT Analysis of the Urmia watershed - Iran. Effects of land use on water scarcity and increasing salination in the Urmia Lake	A. Bertram	Master thesis
Erfassung von Vegetationsdynamiken in semi-ariden Regionen basierend auf der Analyse multitemporaler Fernerkundungsdaten im Rahmen eines Wassermanagement-Projekts, GFZ-Potsdam/UniPotsdam.	M. Lins	Master thesis
WASA_Clim-Q-Sed_Input-Plot-Stats, Software-Publikation (R-Skripte), Institut für Umweltwissenschaften und Geographie, Universität Potsdam. GitHub: https://github.com/A-Mue/WASA_Clim-Q-Sed_Input-Plot-Stats	A. Müller, J.M. Delgado, T. Francke	Software-Publication

SoilDataPrep, Software-Publikation (R-Skripte), Institut für Umweltwissenschaften und Geographie, Universität Potsdam. GitHub: https://github.com/TillF/SoilDataPrep	T. Francke, S. Dobkowitz	Software-Publication
Validierung satellitengestützter Niederschlagsprodukte in semiariden Gebieten	S. C. Kämpfert	Bachelor thesis

7.3. Presentations, poster and talks

2021

Title	Authors	Type
Results from SAWAM Project for Northeast Brazil, XXIII International Workshop on Climate Assessment for the Northeastern semi-arid Brazil, January, 19-20 of 2021 - Fortaleza – Ceará	C. Lorenz, T. Portele, H. Kunstmann	Conference talk
Monitoring stability of embankment dams in response to 2019 Iran Flood event, EGU 2021, doi: 10.5194/egusphere-egu21-14308	M. Haghshenas Haghighi, M. Motagh	Conference talk
Regionalization of Reservoir regulation parameters using physiographic and climatological predictors. EGU 2021. https://meetingorganizer.copernicus.org/EGU21/EGU21-5030.html	Shrestha PK, Thober S, Samaniego L	Conference talk

2020

Title	Authors	Type
Seasonal Hydrometeorological Forecasts for Water Management in Northeast Africa: Development, Operationalisation and Performance of a Regional Prediction System, EGU 2020, 4. – 8.5.2020, Vienna, Austria; https://meetingorganizer.copernicus.org/EGU2020/EGU2020-16534.html	H. Kunstmann, C. Lorenz, T. Portele, J. Bliefernicht, S. Salack, A. Gaber, Y. Mohammad	Conference talk

Satellite time series analysis of vegetation dynamics for water resources management in semi-arid regions, EGU 2020, doi: https://doi.org/10.5194/egusphere-egu2020-16520	R. Behling, S. Roessner, S. Foerster	Conference talk
Retrieving high resolution rainfall data for Ecuador using GOES-16 and IMERG data, EGU 2020, 4. – 8.5.2020, Vienna, Austria, doi: 10.5194/egusphere-egu2020-6594	N. Turini, B. Thies, R.Rollenbeck, A. Fries, F. Pucha-Cofrep, J. Orellana Alvear, N. Horna, R. Célleri, J. Bendix	Conference talk
Towards improved disaster preparedness and climate proofing in semi-arid regions: development of an operational seasonal forecasting system, EGU 2020, 4. – 8.5.2020, Vienna, Austria, doi: 10.5194/egusphere-egu2020-20290	C. Lorenz, T. C. Portele, P. Laux, H. Kunstmann	Conference talk
Proactive Drought and Extreme Event Preparedness: Seasonal Climate Forecasts offer Benefit for Decision Making in Water Management in Semi-arid Regions, EGU 2020, 4. – 8.5.2020, Vienna, Austria, doi: 10.5194/egusphere-egu2020-16179	T. C. Portele, C. Lorenz, B. Dibrani, P. Laux, J. Bliefernicht, H. Kunstmann	Conference talk
A physically-based ensemble of high-resolution regional climate simulations for Sub-Saharan Africa, EGU 2020, 4. – 8.5.2020, Vienna, Austria, doi: 10.5194/egusphere-egu2020-18552	P. Laux, D. Dieng, T. C. Portele, J. Arnault, C. Lorenz, J. Bliefernicht, H. Kunstmann	Conference talk
Impartially resolving reservoirs of all sizes for seamless hydrological forecasting using multiscale Lake Module (mLM), AGU 2020, 7 -- 14 Dec 2020, Online. https://agu.confex.com/agu/fm20/meetingapp.cgi/Paper/695085	P. K. Shrestha, S. Thober, O. Rakovec, H. Najafi, C. Lorenz, L. Samaniego	Conference Poster
Towards scale independent hydrological forecasting in regulated semi-arid regions. EGU 2020, 4. – 8.5.2020, Online, doi: https://presentations.copernicus.org/EGU2020/EGU2020-6047_presentation.pdf	P. K. Shrestha, C. Lorenz, H. Najafi, S. Thober, O. Rakovec, L. Samaniego	Conference talk
Retrieving high resolution rainfall data for Ecuador using GOES-16 and IMERG data. EGU 2020, 4. – 8.5.2020, Vienna, Austria, doi: https://doi.org/10.5194/egusphere-egu2020-6594	N. Turini, B. Thies, R. Rollenbeck, A. Fries, F. Pucha-Cofrep, J. Orellana Alvear, N. Horna, R. Célleri, J. Bendix	Conference poster

2019

Title	Authors	Type
Ensemble-Based Seasonal Predictions for Semi-Arid Regions: Value of Bias Correction. International Union of Geodesy and Geophysics (IUGG) General Assembly. 8 – 18 Jul 2019, Montreal.	H. Kunstmann, C. Lorenz, T. C. Portele	Conference talk
Seasonal Water Resources Management for Semi-Arid Areas: Transferring Regionalized Global Information into Practice, European Geosciences Union General Assembly (EGU) 2019. 7 - 12 Apr 2019, Vienna. https://meetingorganizer.copernicus.org/EGU2019/EGU2019-10303.pdf	H. Kunstmann, C. Lorenz, T. C. Portele	Conference talk
São Francisco as monitored by Radar Altimetry, SatellitesSouth America water from Space II, Manaus, Brazil https://www.gis.uni-stuttgart.de/forschung/doc/Behnia_2019.pdf	S. Behnia, M.J. Tourian, A. Ribeiro Neto, and N. Sneeuw	Conference poster
Climate-proofing for the hydropower sector: Opportunities and challenges using state-of-the-art seasonal predictions, 6th International Conference on Energy and Meteorology, Copenhagen, Denmark	C. Lorenz, T. C. Portele, P. Laux, M. Borne, L. Samaniego, P. K. Shrestha, T. Kukuk, Y. Shafaghi, H. Kunstmann	Conference talk
Global information. For the regional water management: opportunities and challenges, International River Engineering Conference, Ahvaz, Iran	C. Lorenz, T. C.Portele	Conference talk
Operational seasonal forecasting for improved disaster preparedness in semi-arid regions, Ahvaz, Iran	C. Lorenz, T. C. Portele	Conference talk
Regionalized global and seasonal information for the transboundary water management: Examples from the Tekeze-Atbara and Blue Nile Basins, Tekeze-Atbara Conference on Water Related Studies, Khartoum, Sudan	C. Lorenz, T. C. Portele, P. K. Shrestha, M. A. Hassan, M. Osman, L. Samaniego, P. Laux, H. Kunstmann	Conference talk
Using seasonal forecasts to support climate proofing and water management in semi-arid regions, GRoW Status Conference, Frankfurt, Germany	C. Lorenz, SaWaM-Team	Conference talk
Seasonal Forecasts for Water Management in Semi-arid Regions: Evaluation of Performance Metrics, IUGG General Assembly 2019, Montréal, Canada	T. C. Portele, C. Lorenz, H. Kunstmann	Conference talk

One-way Coupled Model Chain for Seasonal Predictions of Hydrometeorological Extreme Events: Concept and Focus on Meteorological Regionalization, EGU 2019, Vienna, Austria	T. C. Portele, C. Lorenz, P. Laux, H. Kunstmann	Conference poster
Ensemble-basierte saisonale Vorhersagen für die Unterstützung des Wassermanagements in semi-ariden Regionen – von globaler zu regionaler Information, DACH 2019, Garmisch-Partenkirchen, Germany	T. C. Portele, C. Lorenz, P. Laux, H. Kunstmann	Conference poster
Comprehensible modeling of reservoir regulation effect on streamflow with a scalable lake-hydrology model. American Geophysical Union General Assembly (AGU) 2019. 9 - 13 Dec 2019, San Francisco. AGU abstract book - https://agu.confex.com/agu/fm19/meetingapp.cgi/Paper/534735	P. K. Shrestha, L. Samaniego, O. Rakovec, R. Kumar, F.V. Junior, E. Martins, S. Thober	Conference poster
Towards Scale Independent Lake/Dam-hydrology Modelling in Seasonal Forecasting of Semi-arid Regions. International Union of Geodesy and Geophysics (IUGG) General Assembly. 8 – 18 Jul 2019, Montreal. IUGG abstract book - http://iugg2019montreal.com/assets/iugg2019-abstracts.zip	P. K. Shrestha, L. Samaniego, S. Thober, C. Lorenz, S. Behnia, T. C. Portele, P. Laux, R. Kumar, O. Rakovec	Conference talk
Towards scale independent lake-hydrology modeling in semi-arid regions: mHM lake module (mLM). European Geosciences Union General Assembly (EGU) 2019. 7 - 12 Apr 2019, Vienna. https://meetingorganizer.copernicus.org/EGU2019/EGU2019-8054.pdf	P. K. Shrestha, L. Samaniego, S. Thober, R. Kumar, S. Behnia, F. V. Junior, E. Martins, O. Rakovec	Conference talk
Satellite remote sensing for better understanding of Earth surface dynamics in relation to extreme hydro-meteorological events – Introduction, National Conference on 2019 Flood; Will it happen again?, Ahvaz, Iran.	S. Roessner, R. Behling, S. Foerster	Conference talk
Optical Remote Sensing Analysis of Surface Cover Dynamics, National Conference on 2019 Flood; Will it happen again?, Ahvaz, Iran.	R. Behling, S. Roessner, S. Foerster	Conference talk
Estimating high spatiotemporal resolution rainfall from MSG-1 and GPM IMERG based on machine learning: case study for Iran, 38. Jahrestagung des Arbeitskreis Klima, 2019, Hamburg	N. Turini, B. Thies, J. Bendix	Conference poster

2018

Title	Authors	Type
Performance of global seasonal precipitation forecasts across semi-arid regions	P. Laux, C. Lorenz, T. C. Portele, L. Samaniego, P. Shrestha, S. Thober, G. Bürger, A. Bronstert, J. Bliefernicht, H. Kunstmann, E. Martins	Conference poster
Ensemble subsetting for dynamical downscaling of global seasonal climate predictions: Evaluation for selected semi-arid regions, Using ECMWF's Forecasts (UEF2018), June 5th to 8th, Reading, UK.	P. Laux	Conference poster
Seasonal Predictions for Water Management – From Global to Regional Information, EnviroInfo 2018, Garching, Germany, ISBN 978-3-8440-6138-3	T. C. Portele, P. Laux, C. Lorenz, H. Kunstmann	Conference talk
Augmenting mesoscale hydrological model (mHM) for seasonal forecasting of lake-hydrology systems. European Geosciences Union General Assembly (EGU) 2018. 8 - 13 Apr 2018, Vienna. https://meetingorganizer.copernicus.org/EGU2018/EGU2018-12940-1.pdf	P. K. Shrestha, L. Samaniego, O. Rakovec, S. Thober, R. Kumar	Conference poster
Kartierung von Studiengebieten für Sedimentmanagement in großen datenarmen Einzugsgebieten. Tag der Hydrologie, 2018, Dresden	A. Smetanova, E. Paton	Conference talk
Satellite-based remote sensing of rainfall in semi-arid regions, 37. Jahrestagung des Arbeitskreis Klima, 2018, Bayreuth	N. Turini, B. Thies, J. Bendix	Conference poster

7.4. Workshops and trainings

The goal of SaWaM was to assess the performance and suitability of global freely available information as decision support for the regional water management in semi-arid regions. Here, our strength was the development of methods and tools that can be applied in very different regions. However, water management issues can only be solved by profound expertise in the local systems and management strategies. The concrete provision of needed information has to be developed in close coordination with local stakeholders and special user needs are to be identified. On-site workshops, including methods training, e.g. for dynamical or statistical downscaling and hydrological modeling, allowed the direct cooperation with the local decision makers and stakeholders to actively foster the transfer and uptake of developed information and methods into practice and the exchange of local knowledge with the German consortium. The organized on-site workshops in Iran, Brazil, Sudan and Ecuador allowed the exchange of developed methods in SaWaM, and were gratefully acknowledged by the partners in the study regions. With up to 100 participants, the workshops showed great interest not only in our tools and methods, but in seasonal forecasts and climate proofing approaches in general. The partners appreciated the German research consortium financed by the German Federal Ministry of Education and Research (BMBF) in developing solutions jointly for water issues in each of the regions.

SaWaM kickoff workshop in Brasilia, Brazil, in October 2017

The SaWaM kickoff workshop for the Rio São Francisco target region was hosted by the National Water Agency (Agência Nacional de Águas, ANA) in Brasilia, Brazil, from Oct. 31 - Nov. 1, 2017. Together with about 50 participants from the Research Institute for Meteorology and Water Resources (Fundação Cearense de Meteorologia e Recursos Hídricos, FUNCEME), the Universidade de Brasília (UnB), the Universidade da Integração Internacional da Lusofonia Afro- Brasileira (UNILAB) and the Instituto Federal de Educação, Ciência e Tecnologia do Ceará (IFCE) concrete steps to improve the regional water management of the Rio São Francisco were discussed. At the workshop, initial analyses were presented regarding the performance of seasonal forecasts (ECMWF S4 and NCEP CFSv2) in the target regions. Expert groups were defined for the main topics meteorology and atmospheric modeling, hydrology and hydrological modeling, ecosystems and ecosystem modeling, sediments, end-users and data. This was done to facilitate the exchange of methods and information. The successful cooperation with the Brazilian partners was shown in several scientific publications. A close thematic networking of experts from Brazil and Germany is intended even beyond the project period.

Picture 1. Group picture at the SaWaM kickoff workshop in Brasilia.

Picture 2. (Left) Brazilian partner presents the São Francisco river basin. (Right) Presentation of SaWaM's hydrological modeling.

Picture 3. Group excursion to Pirenópolis, Rio das Almas.

SaWaM kickoff workshop in Ahvaz, Iran, in December 2017

The SaWaM kickoff workshop for the Karun River basin was held at Khuzestan Water and Power Authority (KWPA) from 10 - 11 December 2017. About 100 people from KWPA, Tarbiat Modares University Tehran, Shahid Chamran University of Ahvaz, Ministry of Energy and Tehran University participated in the workshop. The definition of expert groups for the main topics within SaWaM was analogous to the Brazilian workshop. The workshop significantly facilitated the exchange of information and data with Iranian partners.

Picture 4. Group picture at the SaWaM kickoff workshop in Ahvaz.

Picture 5. Group picture at the SaWaM kickoff workshop in Ahvaz.

Picture 6. Iranian partner presents water management and irrigation strategies.


Picture 7. SaWaM team and partners at the Karun river dam complexes.

Picture 8. Shushtar Historical Hydraulic System in the Khuzestan province.

SaWaM dynamical downscaling training workshop in Ahvaz, Iran, in December 2017

In addition, first training courses on dynamic downscaling (P. Laux, KIT) and statistical downscaling (G. Bürger, Uni Potsdam) were conducted during the workshop in Iran. All participants were extremely grateful and excited.

Picture 9. Group picture at the SaWaM dynamical downscaling training workshop in Ahvaz.

SaWaM kickoff workshop in Khartoum, Sudan, in May 2018

The SaWaM kickoff workshop for the Upper Atbara River target region was held from June 21-22, 2018 in Khartoum, Sudan. Together with about 50 participants from the Dams Implementation Unit (DIU, Minister of Water Resources, Irrigation and Electricity), the Nile Water Directorate, the Upper Atbara Dams Complex Project (UADCP), the Hydraulics Research Center (HRC), the University of Khartoum - Water Research Center (WRC), the Sudan Meteorological Authority (SMA), the National Water Research Center (NWRC) and the Regional Center for Research and Capacity Development on Water Harvesting (RCWH), concrete steps to improve regional water management of the Atbara and Blue Nile catchments were discussed. At the workshop, first analyses regarding the performance of the new seasonal ECMWF forecast (SEAS5) in the Atbara catchment were presented. The workshop completed the expert groups initiated at the previous workshops in Brazil and Iran for the main topics of meteorology and atmospheric modeling, hydrology and hydrologic modeling, ecosystems and ecosystem modeling, sediments, end-users, and data. Further close cooperation between experts from Sudan, Ethiopia and Germany is also planned beyond the project period, especially for the Blue Nile catchment area, where a new dam, the Ethiopian Grand Renaissance Dam, is currently being completed and filled.

Picture 10. Group picture at the SaWaM kickoff workshop in Khartoum.

Picture 11. SaWaM team and partners at the Upper Atbara Dam Complex.

Picture 12. (Left) Upper Atbara Dam Complex in Sudan. (Right) Sudanese partners explain to the SaWaM team the operation of the Upper Atbara Dam Complex.

SaWaM kickoff workshop in Loja, Ecuador, in May 2019

The kickoff workshop for the Catamayo-Chira study region was held in Loja, Ecuador from 14-16 May 2019. Here, the participation of colleagues from the Ecuadorian Meteorological Service must be highlighted in particular. During a field trip to Catamayo-Chira Reservoir, a meeting with the dam operator took place, where the different SaWaM methods and products were presented. Especially with the Ecuadorian Meteorological Service a good cooperation with data exchange and publications in international journals was established.

Picture 13. Group picture at the SaWaM kickoff workshop in Loja.

Picture 14. Visit of the Poeches Dam in Peru in the Catamayo-Chira basin.

Picture 15. Poeches Dam in Peru in the Catamayo-Chira basin.

Challenges and Insights

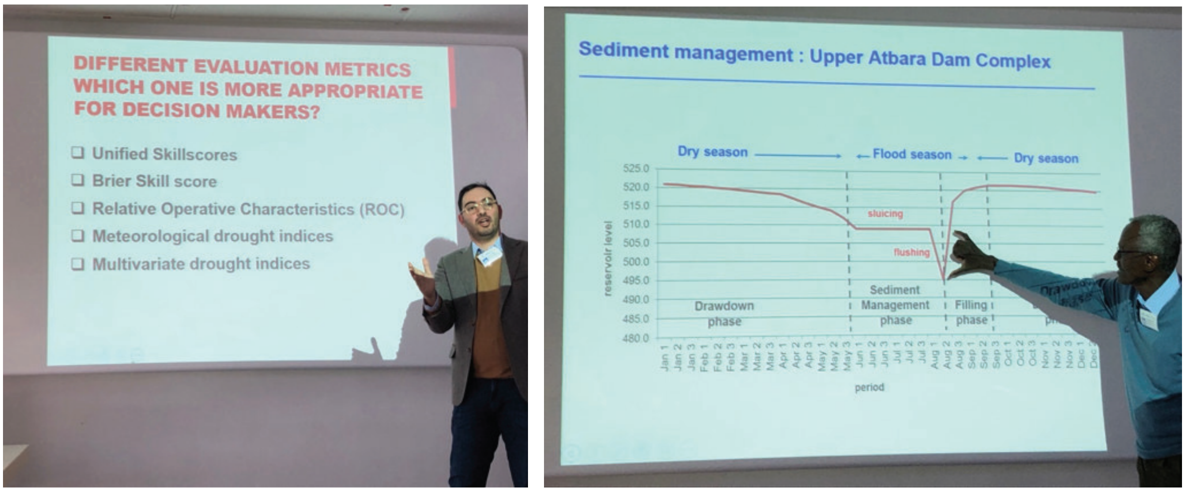
For countries like Sudan and Iran considerable international sanctions apply, posing special challenges in the cooperation and complicating the organization of workshops on-site. In particular, the financial transaction turned out to be challenging as Sudan and Iran are not allowed to be part of the classical international monetary system. Workshops needed to be paid in cash, credit cards were unserviceable.

With the on-site workshops, the German consortium not only gained valuable insights in local water management, but also special intercultural experiences in the study regions. Different hierarchies could be acknowledged and the close cooperation provided a better understanding of the local governance structures and management systems. This allowed a commensurate work flow and effective exchange with local authorities.

SaWaM mid-term workshop in Garmisch-Partenkirchen, Germany, in February 2019

From 11 - 14 February 2019, the SaWaM Midterm Workshop took place at the Institute for Meteorology and Climate Research in Garmisch-Partenkirchen. Bringing together all partners from Sudan, Iran, and Brazil, as well as other international colleagues during the mid-term workshop in Garmisch-Partenkirchen, Germany, valuable exchange of experiences in water management of different countries was enabled. Common issues were addressed, challenges in the different countries discussed and differences assessed. German representatives of the water management sector shared their positive experiences in transboundary water management especially with the Sudanese partners that are facing increasing problems in the transboundary water management of the Nile river basin.

Picture 16. Group picture at the SaWaM mid-term workshop in Garmisch-Partenkirchen.



Picture 17. Iranian (left) and Sudanese (right) partners present at the SaWaM mid-term workshop.

Picture 18. SaWaM-Team (left) and Iranian partner (right) present at the SaWaM mid-term workshop.

2020

Title	Authors	Type
Online training for SaWaM Online DSS: metadata tool, 10.07.2020	SaWaM / GAF Team	Online training for data providers
Online training course DSS (Online Prototype) with Brazilian partners, 02.09.2020	SaWaM / GAF Team	Training course
Online training course DSS (Online Prototype) with Sudanese partners, 30.11.2020	SaWaM / GAF Team	Training course
Online training course DSS (Online Prototype) with Iranian partners, 01.12.2020	SaWaM / GAF Team	Training course
Online training course DSS (Online Prototype) at the GROW final conference, 20.-21.10.2020	SaWaM / GAF Team	Training course
SaWaM Mid-Term Meeting, 10.12. – 11.12.2017, Garmisch-Partenkirchen, Germany	SaWaM / GAF Team	Training course

2019

Title	Authors	Type
Seasonal Water Resources Management in semi-arid Regions: Application-oriented Transfer of Regionalized Global Information, SaWaM Kickoff-Meeting, 12.05. – 20.05.2019, Loja, Ecuador	SaWaM-Team	Workshop
Processing climate data, SaWaM Kickoff-Meeting, 12.05. – 20.05.2019, Loja, Ecuador	C. Lorenz	Training course
Dynamical downscaling with WRF, SaWaM Kickoff-Meeting, 12.05. – 20.05.2019, Loja, Ecuador	T. C. Portele	Training course

Introduction to the Global Precipitation Measurement Mission, 12.05. – 20.05.2019, Loja, Ecuador	N. Turini	Training course
Introduction to mHM and Drought monitoring, 14.05.2019, Loja, Ecuador	L. Samaniego	Training course
SaWaM Mid-Term Meeting, 10.12. – 11.12.2017, Garmisch-Partenkirchen, Germany	SaWaM-Team	Workshop

2018

Title	Authors	Type
Seasonal Water Resources Management in semi-arid Regions: Application-oriented Transfer of Regionalized Global Information, SaWaM Kickoff-Meeting, 21. – 22.06.2018, Khartoum, Sudan	SaWaM-Team	Workshop

2017

Title	Authors	Type
Seasonal Water Resources Management in semi-arid Regions: Application-oriented Transfer of Regionalized Global Information, SaWaM Kickoff-Meeting, 10.-11.12.2017, Ahvaz, Iran	SaWaM-Team	Workshop
Dynamical downscaling with WRF, 10.-11.12.2017	P. Laux	Training course
Statistical downscaling, 10.-11.12.2017	G. Bürger	Training course
Seasonal Water Resources Management in semi-arid Regions: Application-oriented Transfer of Regionalized Global Information, SaWaM Kickoff-Meeting, 31.10. – 1.11.2017, Brasília, Brazil	SaWaM-Team	Workshop

7.5. Public outreach

Special highlights have also been the presentation of SaWaM at side events both at the *8th World Water Forum* in Brasília, Brazil, the *24th Conference of the Parties* (COP24) in Katowice, Poland, and the Keynote Speech at the *United Nations Secretary-General's Advisory Board on Water and Sanitation*, UNSGAB+5 Conference

8th World Water Forum in Brasilia, Brazil 2018

The SaWaM project was represented at the 8th World Water Forum. Together with Brazilian colleagues from FUNCEME, a side event was organized to present application-oriented aspects of the project. In addition, a joint workshop with ANA was held at the Brazilian pavilion.

Picture 20. SaWaM team at the World Water Forum in Brasilia.

COP24 in Katowice, Poland 2018

The SaWaM project was presented at the UN Climate Change Conference 2018 (COP24) in Katowice, Poland. Together with Polish colleagues from Retencja as well as Ms. Romy Durst from PTKA, a side event was organized in the EU pavilion. In this context, Prof. Dr. Kunstmann and Dr. Lorenz presented and discussed SaWaM's contribution to climate proofing.

Picture 19. SaWaM team together with Ms. Romy Durst from PTKA at the European Union Side Event of the COP24.

United Nations Secretary-General's Advisory Board on Water and Sanitation, UNSGAB+5 Conference, 2021

On February 12, 2021, the former members of the UN Advisory Board on Water and Sanitation (UNSGAB) met to discuss current challenges in the water and sanitation sector. Prof. Dr. Harald Kunstmann, coordinator of the GRoW project SaWaM, was one of the participants. As the voice of science, he presented some of the research results achieved in GRoW in his input lecture, and also highlighted the role of science on the way to sustainable water resource management.
(https://bmbf-grow.de/de/grow-stimme-wissenschaft-treffen-united-nations-secretary-generals-advisory-board-water-sanitation)

2018

Title	Authors	Type
Seasonal predictions for the water management: from global data to regional decision support – First results for the Rio São Francisco basin from the SaWaM-project, 8th World Water Forum, Brasília, Brazil	C. Lorenz, SaWaM-Team	Conference talk
Water management in semi-arid regions using seasonal predictions, 8th World Water Forum, Brasília, Brazil	C. Lorenz, SaWaM-Team	Conference talk
Seasonal predictions for the water management: from global data to regional decision support, 8th World Water Forum, Brasília, Brazil	C. Lorenz, SaWaM-Team	Conference talk
Climate Proofing: Seasonal Predictions and Options for Water Resources Management in semi-arid regions, COP24, 3. – 14.12.2018, Katowice, Poland	H. Kunstmann, C. Lorenz	Conference talk

7.6. Newspaper and internet articles

2017

Title	Authors	Type
Besseres Wassermanagement in trockenen Gebieten, May 2017 https://www.kit.edu/kit/pi_2017_062_besseres-wassermanagement-in-trockenen-gebieten.php	H. Kunstmann, C. Lorenz	Press release

2021

Title	Authors	Type
Mehr Klimaresilienz durch verbesserte saisonale Vorhersagen, May 2021 https://www.kit.edu/kit/pi_2021_046_mehr-klimaresilienz-durch-verbesserte-saisonale-vorhersagen.php	H. Kunstmann, C. Lorenz, T. Portele	Press release

7.7. Further dissemination of results

2020

Title	Authors	Type
Model chain for radar-based drought monitoring for Ecuador. April 2020	L.S. Quinônes, P.K. Shrestha, S. Thober, A. Koppa, L. Samaniego	Collaboration, transfer to practice
How seasonal forecasts improve water management and disaster preparedness in semi-arid regions, Nov 2020 https://www.youtube.com/watch?v=6---v06-U0I	SaWaM-Team	Youtube project image video
SaWaM – GroW Final Conference 2020, Dec 2020 https://www.youtube.com/watch?v=pGKpMCxGr5Y	H. Kunstmann and SaWaM-Team	Youtube presentation video