European Commission

JRC SCIENTIFIC INFORMATION SYSTEMS AND DATABASES

e-NEXUS SENEGAL

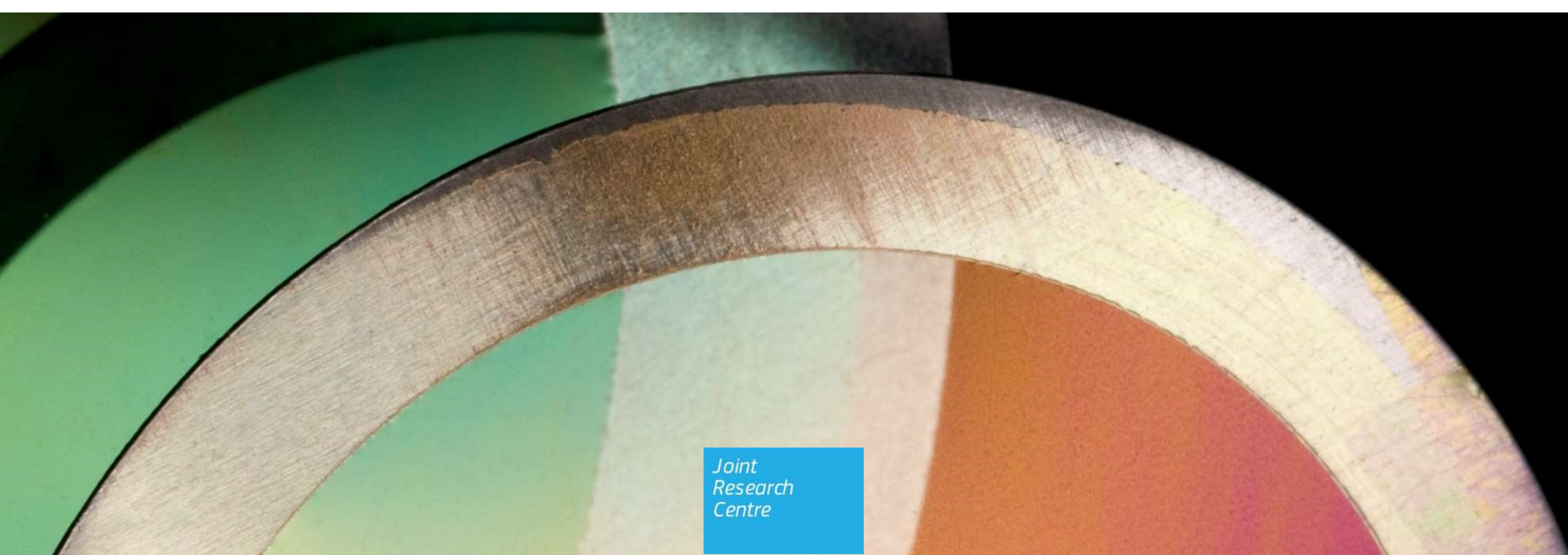
A DSS for the analysis of WEFE Nexus in the Senegal river basin

Climate Variability

Cattaneo L., Pastori M., Cordano E., Carmona, C.

Limited

2018



Joint Research Centre

Contact information
Name: César Carmona-Moreno
Address: Joint Research Centre, Via Enrico Fermi 2749, TP 440, 21027 Ispra (VA), Italy
Email: cesar.carmona-moreno[at]ec.europa.eu
Tel.: +39 0332 78 9654

EU Science Hub
https://ec.europa.eu/jrc

JRC115134

Ispra: European Commission, 2018

How to cite this report: Cattaneo L., Pastori M., Cordano E., Carmona, C., *Title e-Nexus Senegal A DSS for the analysis of WEFE Nexus in the Senegal river basin - Climate Variability*, European Commission, Ispra, 2018, JRC115134.

Printed in Italy

Contents

Acknowledgements

This work is a part of the WEFE-Sénégal project funded by the European Commission.

Authors

Cattaneo, L., Pastori M., Cordano, E., Carmona, C.

European Commission, Joint Research Centre (JRC), Ispra, Italy

Abstract

The E-Water tool has been initially developed in 2017 in the frame of Mékrou Basin Project, born from a collaboration between European Commission and African institutions as ABN and AGHRYMET. The E-Water tool was so identified as a valid operational system to be applied in the context of WEFE Senegal project. This imply a revision and an update of the working system in order to handle the increasing complexity and specificity of the WEFE Nexus approach. Indeed the new updated version of the tool, named e-NEXUS, should empower the capability to explicitly recognize water, energy, food and ecological systems as both interconnected and interdependent. This report gives a summary of the activities of the 1st year of the WEFE Senegal project aimed to the development of a Prototype of a Decision Support System for Environmental Monitoring through the detection of environmental trends and anomalies at the river basin level. The System was presented during the Workshop on Data and Models organized in Dakar in October 2018. During this workshop all partners presented models and data that are required for the development of the whole system. In this report a brief introduction to the whole DS system and the methodology of development is given. Then report is focused on the description of the Climate variability module that has been updated with data for Senegal river basin and also example of applications and analyses in the Senegal RB are described and summarized.

1 Introduction

Water, energy and food are essential for human well-being, poverty reduction and sustainable development. Water, Energy and Food systems are inextricably linked in the Water-Energy-Food Nexus (WEF), and all together are depends on and affect the environment.

The Senegal river basin is a transboundary basin shared among Senegal, Mali, Mauritania and Guinea (Figure 1). In this basin, agriculture is the predominant economic activity; it contributes to income generation and employment and it is critical for the identification of optimal development strategies. All 4 countries belonging to Senegal River Basin needs more energy and more food, and for both at least three of them strongly depend on the flows in the River Senegal. Indeed Guinea share a more limited area of the River Basin and this part is much more linked with environmental issue being included in the Fouta Djalon Massif. Power production in the Senegal river basin is largely hydro based. In addition climate studies predict a high likelihood of increasing variability of rainfall that need to be considered in combination of increasing demands for multi-purpose usage of water resources. Unfortunately, climate change (CC) is already hampering agricultural growth due to increased frequency and intensity of extreme events such as droughts and flooding (Cohn et al., 2017; FAO, 2016; Lesk et al., 2016; Lipper et al., 2014). It has been observed that climate change and variability have negatively impacted Western African Sahel rain-fed agriculture (Zougmoré et al., 2016), although agronomic studies suggest that low soil fertility management is the major limiting factor to agricultural production (Van Keulen and Breman, 1990). High rainfall variability and climate change can severely impact the management of water resources, particularly in water stressed transboundary river basins.

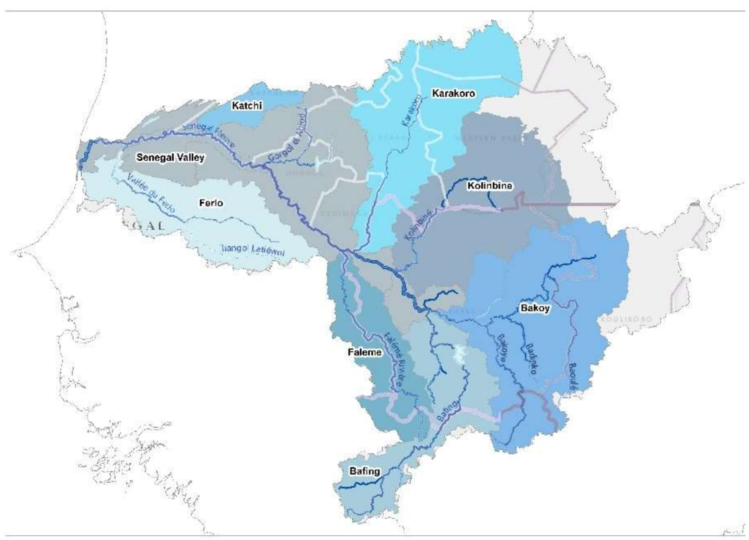


Figure 1. Senegal River Basin (and sub-basins) delineation.

There is need to identify the key factors that explain observed yield gaps (differences between current and maximum obtainable crop yields) to evaluate the impact of potential intensification on the environment and in general to support the development of local management plans for an effective management of natural resources (water, soils, land, tc.) to better achieve sustainable outcomes. Bio-physical models and Decision Support Systems (DSSs) are computer software packages that allow the development of site-specific recommendations for different purposes such as agricultural and livestock management, land management systems, environmental planning, multipurpose dam optimization, food security, etc.

Drivers that upset the WEFE Nexus assessment specifically in developing countries are: population growth and change of life quality standards and food demand; urbanization; energy demand increase; increasing competition for water demand by different sectors; climate change and specifically impact on water availability spatially and temporally.

Water resource use and management is a key aspect for all these aspect. Water is a driver for crop production, for intensive cropping system, for livestock and also for the energy sector. Energy production is linked with water management as for example for hydropower system based on water river's availability and on reservoirs. In addition energy is a crucial component for all activities linked with irrigation because of pumping and transport, as well as for water

2 The e-Nexus tool for the WEFE Senegal

2.1 Introduction of the system

The E-Water tool has been initially developed in 2017 in the frame of Mékrou Basin Project, born from a collaboration between European Commission and African institutions as ABN and AGHRYMET(Cattaneo et al., 2017). The e-Water DSS tool (Udias et al., 2018) was firstly developed in order to provide optimal agriculture management solutions at river basin level for local managers, solutions specifically design and identified in a context of food security. Despite it was initially developed for the specific needs of Mékrou basin area, its versatile attitude and design allows it to be easily fitted also for any other geographical domain with its distinct environmental features.

The E-Water tool was so identified as a valid operational system to be applied in the context of WEFE Senegal project. This imply a revision and an update of the working system in order to handle the increasing complexity and specificity of the WEFE Nexus approach. Indeed the new updated version of the tool, named e-NEXUS, should empower the capability to explicitly recognize water, energy, food and ecological systems as both interconnected and interdependent (Bazilian et al., 2011; Wolfe et al., 2016). The system must allow the possibility to take into account synergies and relation between the different WEFE components (such as Water, Energy, Ecosystem and environment, Food production and food security), should allow to identify how (methods) and where (spatially) maximize such synergies (mutually outcomes) and minimize trade-offs, improving resource use-efficiency, environmental impact, and socioeconomic aspect (Albrecht et al., 2018), (see also Figure 2).

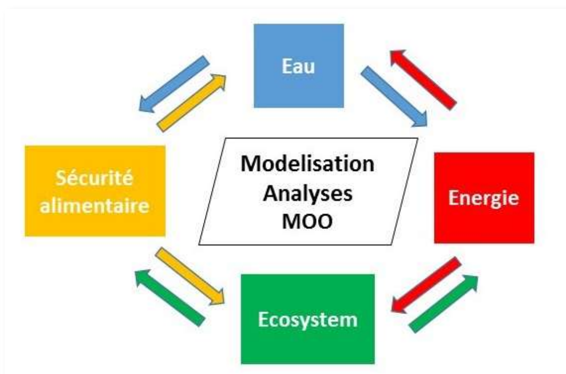


Figure 2. E-Nexus conceptual framework.

The design of the e- NEXUS system should enable user to manage and analyse data, scenarios and results at river basin and/or regional level in the WEFE context. The system need to be a system including the capability for information collection (input and output data) information processing (scripts modeling, stand alone models) and decision making (Output analysis and visualization, Graphs, Maps, Reports) (Wolfe et al., 2016). In this sense the design and the development of such a system must ensure:

- Inclusion of all components and issue as identified within the river basin;
- Allowing an interface across the components;
- Include in the development process of a range of disciplinary experts, stakeholders, local users, decision makers, etc.;
- Provide an accessible and clear interface to different modules and analysis in order to allow the use of the platform for a wide range of users, including researchers, policy makers, practitioners, technicians and sectorial experts

- Be flexible, in order to allow inclusion of feedbacks and suggestions, improvements and inclusion of new suggested elements, etc.
- Open for user data input updated and revision

More specifically 3 key dimensions need to be taken into account for the system design (Figure 4):

1. *Systems Informatics:* This refers to the data, information and in general knowledge system that is the base for addressing different WEFE Nexus issues. The system need to handle a large amount and distinct nature datasets: to allow an effective access to data from different users and applications (for example different modules) all data and information need to be gathered all into a Common dataset (for example PostgreSQL database used for the e-Nexus tool).
2. *Information analysis, methods and assessment:* This is the part providing analytical capability to process information and data mathematically, statistically and logically (indicators, models and optimization algorithms implemented in the system in the different modules). The software framework will enable decision makers to identify policy-relevant solutions, quantify the trade-offs between alternative strategies in different scenarios, flexibly explore alternative definitions of robustness, and identify key system factors to be monitored as triggers for future actions or additional planning.
3. *System analytics and decision support:* this is the part of the system/tool enabling the end users to delivery and analyse the issues and, finally, to product supporting information for the identification of optimal management solution. (Output section in Figure 4)

Following Figure 3 depicts the main features of the conceptual framework of the e-Nexus tool, as it is proposed for the Senegal WEFE project. The core part of the framework will be the Optimization module, which will include the capability to interact and get information and data from basic and thematic modules (hydrologic-*Water*, agriculture-*Food*, Energetic-*Energy*) and to combine these with an economic and environmental module in order to define tailored objective function and constraints.

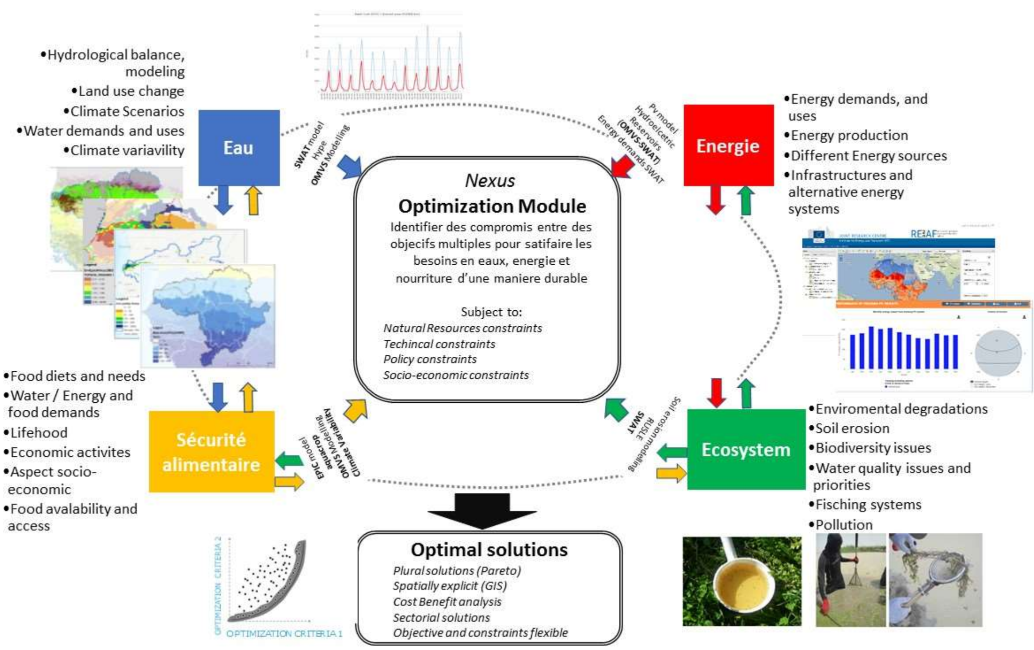


Figure 3. Schematic overview of E-Nexus conceptual framework.

Given the necessity of addressing the tool to the widest possible range of users, E-Nexus was designed as a stand-alone desktop application conceived for Windows OS mainly built using .NET languages (C#, Basic), but it also incorporates R libraries and scripts for internal processes involving statistics and algorithms. Since this module exclusively relies on open-source software, it is possible to use it without purchasing any particular license apart from Windows system.

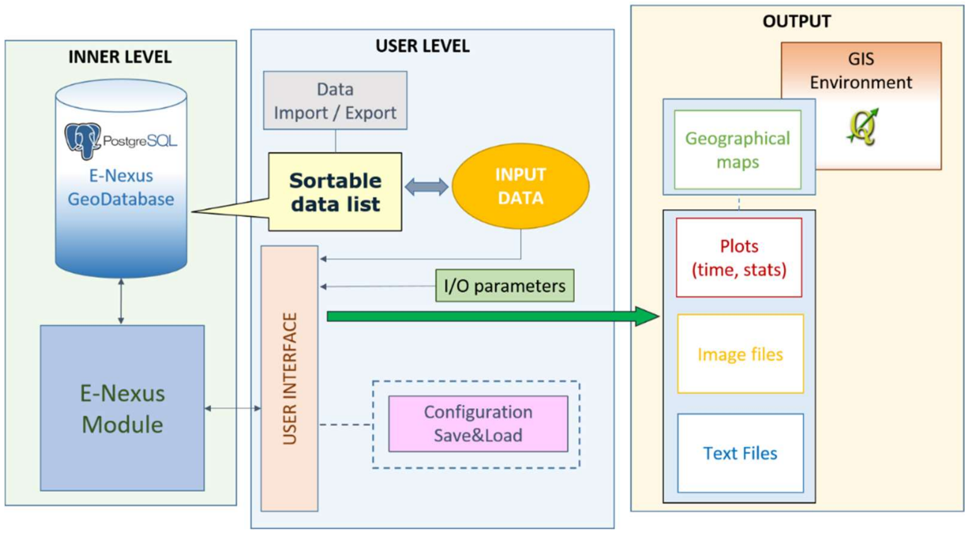


Figure 4. Schematic representation of the E-Nexus open source framework.

2.2 A modular system: DATA and models

E-Nexus was originally designed and developed by integrating several tools (Standalone models such as SWAT and EPIC; analysis tools such as L-Moments; and Optimization routines) in order to cope with heterogeneity of data, analysis and issues required by the sustainable management and analysis of environmental data (climate, hydrology, land use, etc.) at different scales (river basin level, regional ,national, continental, etc.).

In this way, it enables decision makers to identify policy-relevant solutions, quantify the trade-offs between alternative strategies in different scenarios, flexibly explore alternative definitions of robustness, and identify key system factors to be monitored as triggers for future actions or additional planning.

The modularity structure also enable the possibility to include different models and tools (if required by specific application or if requested by end-users).

In the framework of the WEFE-Senegal Project it is foreseen the strengthening of the Decision Support System (e-NEXUS) together with scientific and technical partners to enlarge tool capabilities and to allow a better assessment of all WEFE Nexus related components. To this scope it is indeed foreseen:

- To adapt current modules and functionalities to the Senegal River Basin (specifically this require the inclusion of new dataset for the Climate Module and the setup-calibration and validation for the Agriculture and Hydrological modules)
- The development of an Energy-Renewable Energy module (concretely Biogas and PV)
- Reinforce the water quality assessment.

- Reinforce the socio-economic module to provide policy makers with further accurate simulation scenarios in coherence with the environmental management policies.
- to expand the optimization module in order to be more dynamically linked with other Nexus components: for example including livestock (density, water and forage needs as derived by transhumance), dynamic economic elements (market, prices, specific costs) and socio-economic aspects in order to complement the Nexus assessment/scenarios.

A key aspect to be taken into account is the collection of DATA required specifically for the setup of models used within the hydrological and agriculture modules. The collection of public available data has been concluded and a preliminary setup of models has been developed. Anyway in order to make the system more attractive and acceptable by final end users, models should use (when possible) local data. Currently local data collection is an ongoing activity that is foreseen to be finalized by the end of 2018. After local data analysis and integration with the system Agriculture and hydrological modules will be setup and calibrated (2019 activity).

An important aspect for water management in developing countries is clearly related with climate change and variability and there is a strong need to understand climate variability and above all its interaction with environment at different scales (from regional to global). The analysis of climate variability, the identification of extreme events intensity and recurrence (for precipitation, temperature, heat waves, surplus/deficit) are required to support the sustainable development and planning process. In addition for such analysis long time series are required and the data are open access data public available.

For this reason the first improvement of the tool was focused on the climate variability module, and its development and application in the Senegal river basin is described in the following section.

2.3 The Climate module

The objective of Climate module is to process and analyze climatic series of data in order to generate spatially explicit products based on L-moment statistics and to identify the recurrence of extreme events (for precipitation, temperature, heat waves, surplus/deficit).

Indeed, given the increasing awareness in the field of Climate Variability and Climate Change (CV - CC) and its consequences on food security, a number of indicators and analysis were included to characterize precipitation and temperature patterns and their spatiotemporal characteristics. Although long-term effects of climate change are still largely unknown, the impacts of some of these phenomena have some obvious short-term effects that can lead to, for example, agricultural productivity decrease, harming of crops due to floods, thus, food supply shortages, drier soils due to warmer weather, etc.

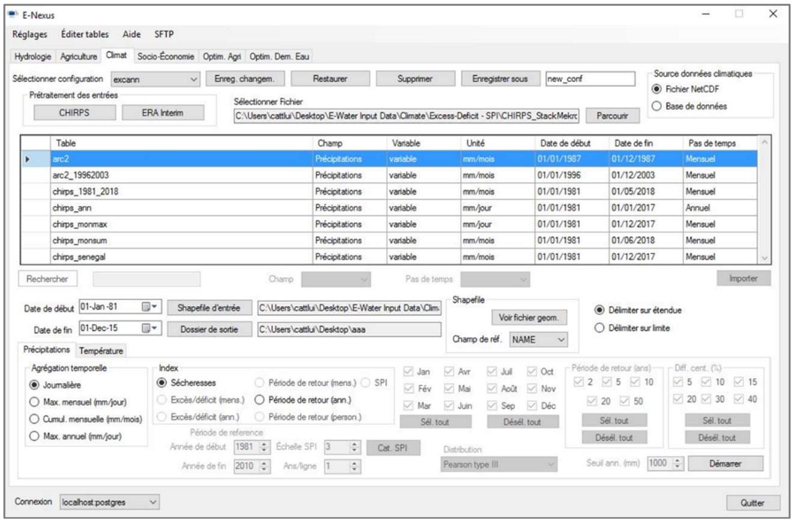


Figure 5. Climate Module Interface.

2.3.1 Data Input

The original source of data are for this modules are:

- **Temperature**: ERA-INTERIM (Berrisford, 2011) is a global atmospheric reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA-Interim is available from 1979, and it is continuously updated in real time. The data assimilation system used to produce ERA-Interim is based on a 4-dimensional variational scheme (4D-Var) with a 12-hour analysis window. The spatial resolution of the data set is approximately 80 km. ERA-Interim allows having a consistent spatial and temporal resolution over 3 decades, incorporating millions of observations into a stable data assimilation system that would be nearly impossible for an individual to collect and analyse separately.
- **Precipitation**: Climate Hazards Group InfraRed Precipitation with Station data (monitoring (Funk, C.C., 2014) is a 30+ year quasi global rainfall dataset. Spanning 50ºS-50ºN and all longitudes. It starts in 1981 to near-present and incorporates 0.05º resolution satellite imagery with in-situ station data to create gridded rainfall time series for trend analysis and seasonal drought.

The original data were processed and spatially clipped over the Senegal River Basin window to be quickly analysed within the tool. The input data can be of daily, monthly or yearly frequency and the standard format used is the NetCDF, while the information on the geographical domain is inserted with a .shp file.

2.3.2 Application and analysis

The indices of climatic variability (return time, heat waves, excess and deficit, SPI, droughts) are provided from modelled temperature and precipitation data collected over a period of around 30 years. In the case of monthly data, it is possible to choose between the 12th month of interest for the evaluation of the indices.

The occurrence of extreme events (precipitations and heatwaves)

The main aspects and methodology used to characterize extreme events lies on the so called Extreme Value Theory in one hand and on the Heat Wave Magnitude Index computation in the other. To assess the probability of occurrence and then return periods of such extreme events, the L-Moments methodology is applied on a basis of 35-year time series using a R package called "lmom" (Hosking, 2017) available in the online CRAN repository.

The monthly and annual cumulated precipitation have been modelled using the Pearson-III distribution, setting in this way the "lmom" package. The Pearson-III distribution is a good choice for describing cumulated precipitation values because being more flexible and allowing a better fit to any number of rainfall regimes with reasonable accuracy. All these calculations are performed for each 0.05-degree by 0.05-degree grid cell in the rainfall CHIRPS data array using the R package "rasterList" (Cordano, 2017).

One of the interesting outputs of this method are the return period maps of precipitation values (deficit and excess) that can be defined as the average time interval in which two equal events occur. For instance, Figure 6 shows different annual statistics that can be calculate with e-Nexus *Climate module*.

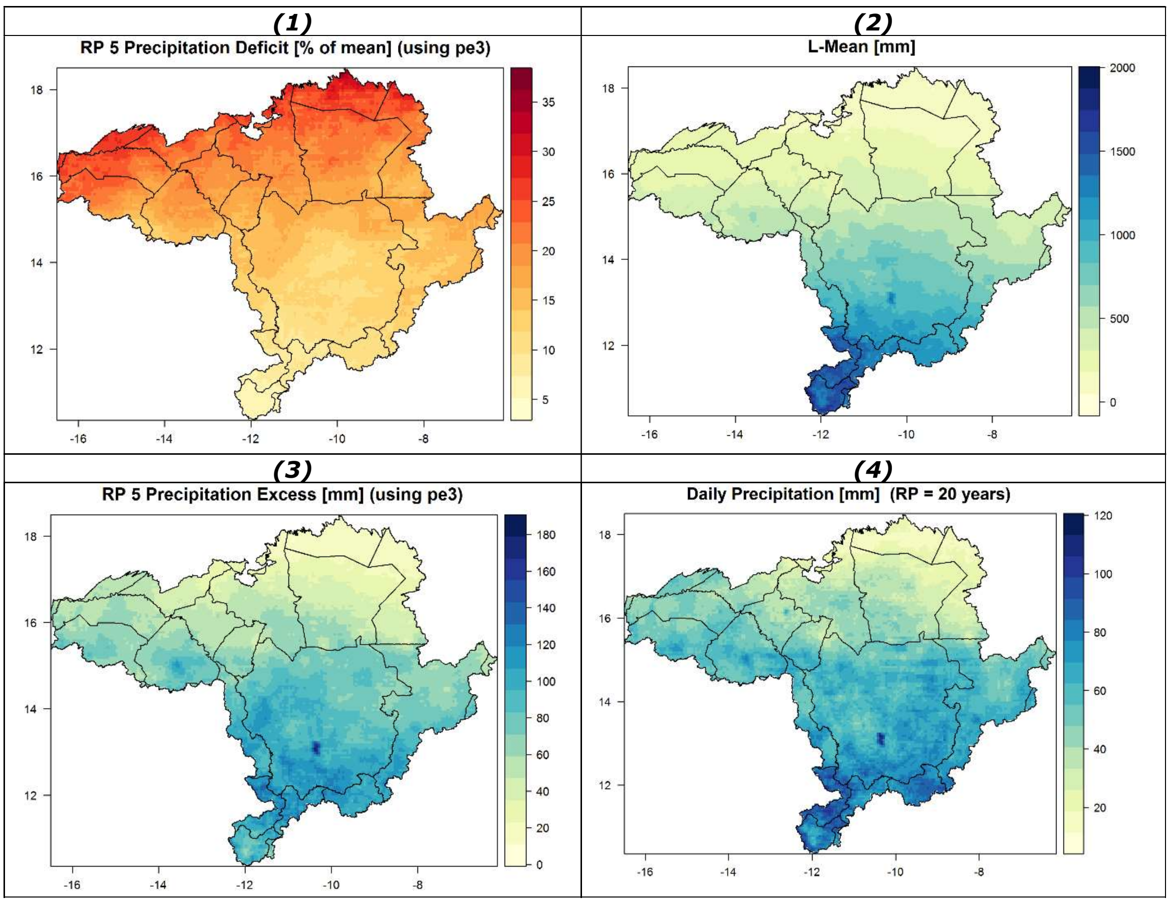


Figure 6. Example of annual statistics calculated in the Senegal River Basin (1): Annual deficit of monthly precipitation (%) with a return period of 5 years. (2): 1st L-Moment (Average) of annual precipitation. (3): Annul excess of precipitation (mm) with a return period of 5 years. (4) Daily precipitation (mm) with a return period of 20 years.

In Figure 6(3) indicates, for example, that the southern area of the river basin is expected to have an additional 100-140 mm in a 5 year period. On the opposite, deficits related to a given return period can be also mapped. **Error! Reference source not**

found. Figure 6(1) shows the precipitation deficits given as a percentage respect to the mean for a 5 year return period. In other words, the northern zone, for example, will be affected by precipitation shortages of about the 20-30% of the mean once every 5 years. Southern areas with higher annual and monthly precipitation values are less affected by this deficit events (values below 15% of the mean).

Figure 6(2) shows the average precipitation in mm over the analysed period, and it is evident the high variation of the annual precipitation across the river basin (range is from 0 to about 2000 mm/yr), and highlight the importance of the southern part of the river basin (in the Guinean part) that is the most important region contributing to water input (indeed it is in the Fouta Djallon highland region in the centre of Guinea).

Figure 6(4) shows the estimated daily precipitation in each cell with a return period of 20 years.

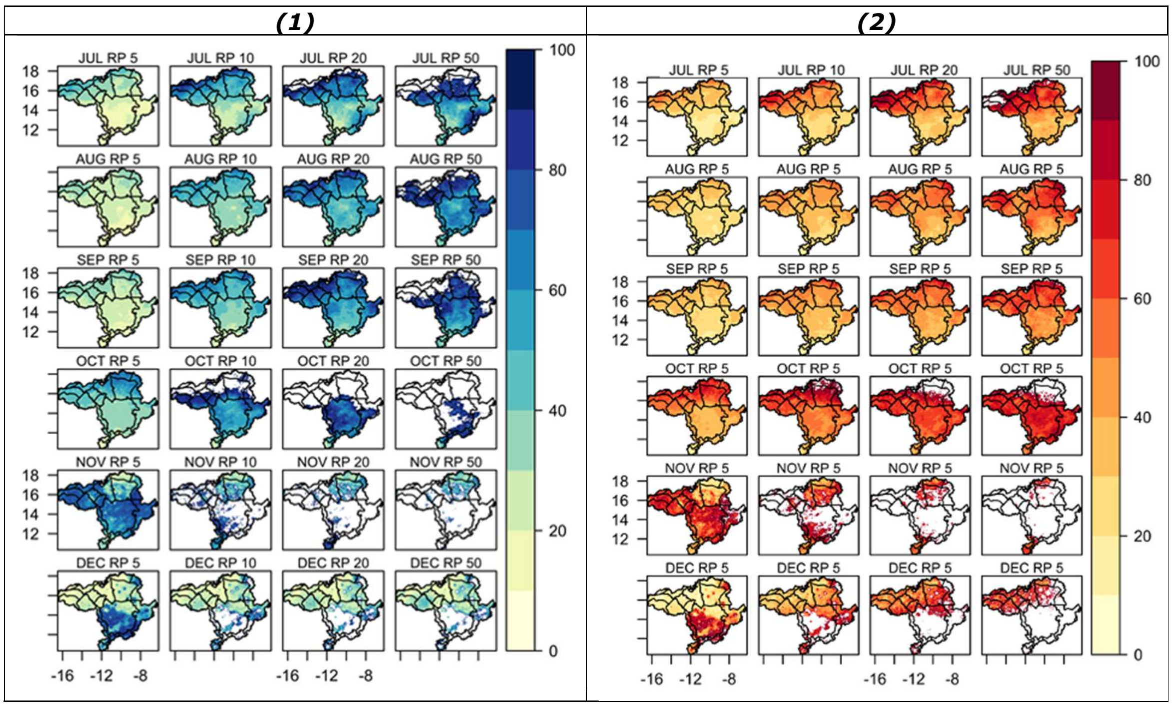


Figure 7. Example of <u>monthly statistics </u>calculated in the Senegal River Basin. Excess (1) and deficit (2) of monthly precipitation (period showed from Monthly to December) with different return periods (RP: 5, 10, 20 and 50 years)

Figure 7 reports the monthly excess (%) and deficit (%) of monthly precipitation estimated by considering different return periods. It can be observed how increasing the return period analysis correspond to an increase of variability and intensity of the excess/deficit across all the river basin. Anyway the region with the highest precipitation (south part) is more affected by high variability in the last months of the year.

In addition to this precipitation analysis, a method and a code to calculate **Heat Wave Magnitude Index** was also applied in the Senegal River Basin. This index (HWMId), recently defined by Russo et al. (2015) is a numerical indicator that takes both the duration and the intensity of the heat wave into account, and it was also applied in the African context (Ceccherini et al., 2017). Basically, the magnitude index sums excess temperatures beyond a certain normalized threshold and merges durations and temperature anomalies of intense heat wave events into a single indicator. The HWMId is an improvement on the previous Heat Wave Magnitude Index and it is able to overcome its underestimation of extreme events. The Index can be classified into different categories from normal behaviour to moderate, severe and extreme temperature conditions Table 1.

Table 1. Classification of heat waves (i.e. HWMI) scale categories

Classification	**Heat Wave Magnitude Index**
Normal	1 ≤ HWMI < 2
Moderate	2 ≤ HWMI < 3
Severe	3 ≤ HWMI < 4
Extreme	4 ≤ HWMI < 8
Very extreme	8 ≤ HWMI < 16
Super extreme	16 ≤ HWMI < 32
Ultra extreme	HWMI ≥ 32

Figure 8 shows for example the incidence of Heatwaves in the Senegal river basin over the period 1981 - 2017. The values range from normal conditions (most of the years) to extreme and very extreme heatwaves (just in specific years, 1998 for example and in specific areas of the river basin). The central southern part of the Senegal basin in 1998 for example was affected by a Heatwave with values above 10, corresponding to a very extreme heatwave, and in 2016 with extreme heatwave. Another representation is showed in the figure on the side (b): this map shows the number of heatwaves during the 1981-2017 period above a certain value, in this case “extreme” heatwave or above value” (>value 4). The central and eastern part of the Senegal river basin are most affected by extreme heatwaves.

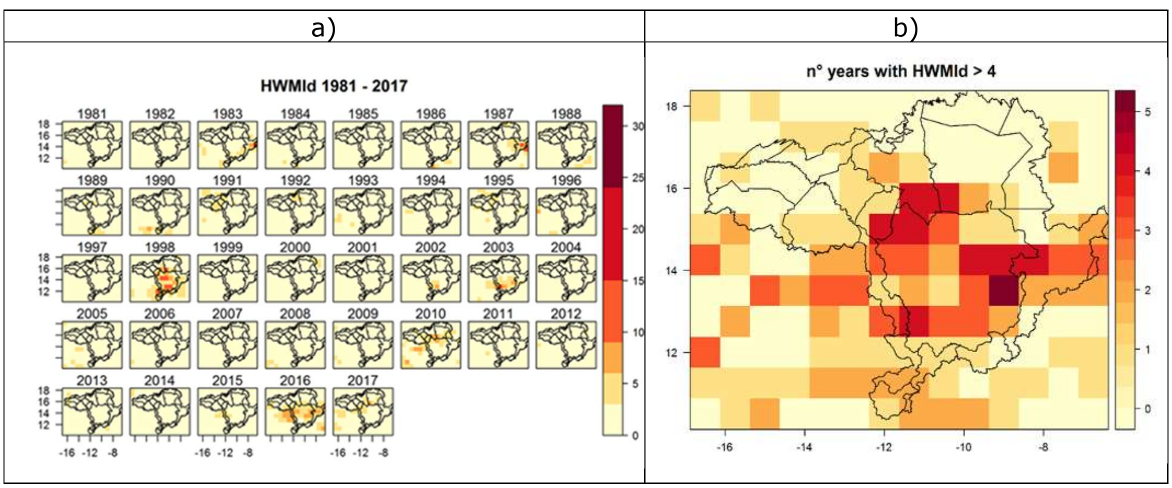


Figure 8. (a) Yearly Heat Wave Magnitude Index between 1981 and 2017 in the Senegal River Basin and (b) number of years within 1981 and 2017 with HWMI exceeding values of 4 (classification of heat waves extreme or more severe).

Assessment of Precipitations anomalies (droughts and excess)

The **S**tandardized **P**recipitation **I**ndex was applied to the Senegal river basin to analyse the meteorological droughts:

- This indicator allows determining the anomaly on rainfall compared to the historic time series at a given time scale of interest.

It is a gaussianization of moving average of monthly average of precipitation, it derives from the cumulative probability of a given rainfall event occurring in a given pixel and the rolling average is calculated for different temporal windows (n = generally 1-36 months). Operatively the numerical values of the output represent the number of standard deviations from the mean at which an event occurs. Thus, the ***SPI*** depends on the amount of rainfall over a given time scale but gives information in relation with the normal. The SPI index is classified as qualitative indicators for meteorological droughts or meteorological wet periods:

Table 2. SPI-n classification.

Wet/dry class	SPI values (Mckee et al., 1993)	SPI values (Agnew, 2000)
Extremely Dry	< -2	< -1.64
Severely Dry	[-2, -1.5]	[-1.64, -1.28]
Moderately Dry	[-1.5, -1]	[-1.28, -0.84]
Moderate	[-1, 1]	[-0.84, 0.84]
Moderately Wet	[1, 1.5]	[0.84, 1.28]
Severely Wet	[1.5, 2]	[1.28, 1.64]
Extremely Wet	> 2	> 1.64

Figure 9 depicts an example of SPI-3 (3 months) calculated for 2 different periods: the first figure (left) is referred to January 1991 and related to the 2 months periods (Nov-Jan) indicating important negative anomalies all over the whole river basin. The second figure (right side) allows to identify high precipitations events, above all in the southern part of the river basin.

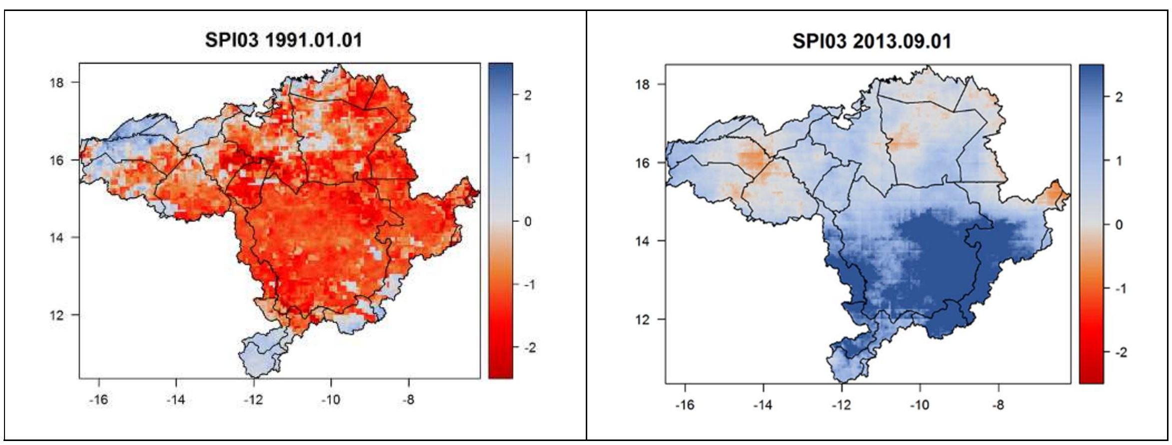


Figure 9. Examples of SPI-03 for January and September

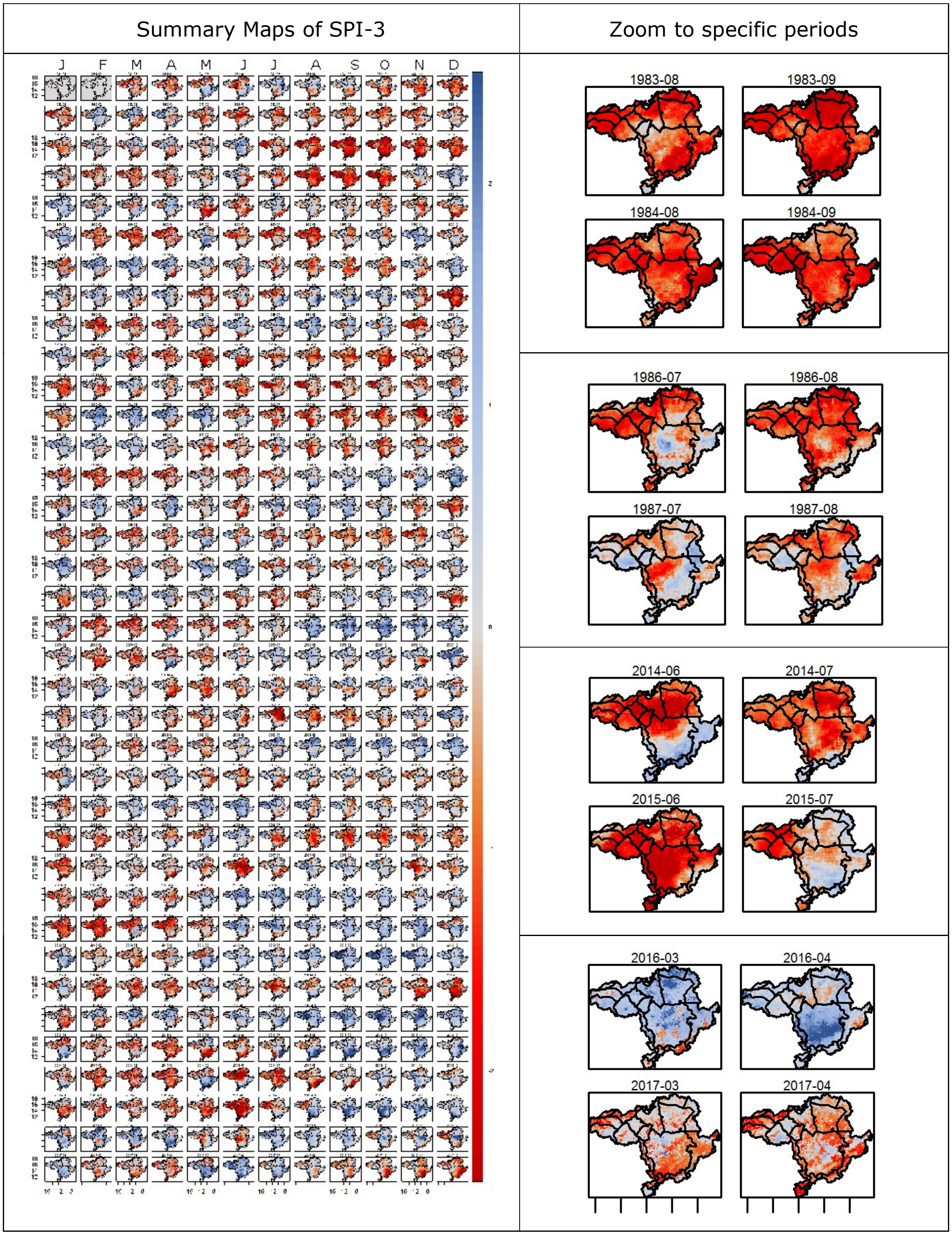


Figure 10. Summary Maps of SPI-3 for all period as resulting from e-Nexus climate module.

One output of the e-Nexus Climate module is the summary for all the analysed period (reference period of the analysis is 1981-2010). This map is useful to identify quite easily the dry periods in the Senegal river basin. In this application, it is possible for example to identify an important negative anomaly in the second half of 1983 and 1984. The identification of moderately to extremely dry periods versus the normal is particularly important when potentially near to the crop harvest period or during the main growing cycle as can potentially affects and reduce crop yield quantity and quality if not mitigated (for example by target irrigation).

Specific regional analysis can also be used. In this case, it is possible to estimate the surface of each administrative region that is affected by a specific anomaly. It is so possible to identify which regions (spatially) and in which period (temporally) are more affected by anomalies. In the following Figure 10 the example of Trarza (in Mauritania in the North-West of the Senegal river basin) is reported: in the 1984 (1) the most part of the Trarza commune is affected by negative anomalies (dry), above all in the first months of the year, but even the rest of the year is affected by extreme drought conditions.

Conversely, the municipality was affected by a rain more abundant in 2011, or more precisely a large part of its surface was high-extremely wet (2).

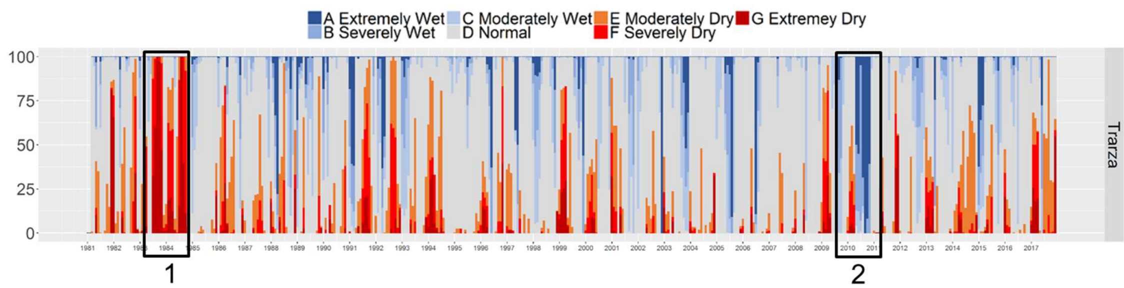


Figure 11. Spatiotemporal statistics for Trarza province in the Senegal river basin. Extremely wet to Severely dry anomalies can be easily identified for the entire time series (1981-2017).

3 Future steps

This report gives a summary of the activities of the 1st year of the WEFE Senegal project aimed to the development of a Prototype of a Decision Support System for Environmental Monitoring through the detection of environmental trends and anomalies at the river basin level. The System was presented during the Workshop on Data and Models organized in Dakar in October 2018. During this workshop all partners presented models and data that are required for the development of the whole system.

In this report a brief introduction to the whole DS system and the methodology of development is given. Then report is focused on the description of the Climate variability module that was already updated with data for Senegal river basin and also example of applications and analyses in the Senegal RB are described and summarized.

As local data and models available within the research community in the Senegal river basin is still under development the prototype will be updated in the next year of the project (2019).Specifically the update of SWAT model (for Hydrological module) and of EPIC (for agricultural module) is under development and will be finalized as soon the local data collection (required for model setup, refinement and calibration/validation) will be completed.

The Optimization module, that is the core of the Nexus assessment is an activity that will require the local data but even more the feedback and contribution of local stakeholders: for example for the design of economic module, for the identification of constraints to be included, and in general for the identification of priorities and interconnection between components. In addition, the potential inclusion of new tools, analysis script and models - if available and required - will be taken into account.

References

Agnew, C.T., 2000. Using the SPI to Identify Drought. Drought Netw. News 1.

Albrecht, T.R., Crootof, A., Scott, C.A., 2018. The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. Environ. Res. Lett. 13, 043002. https://doi.org/10.1088/1748-9326/aaa9c6

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R.S.J., Yumkella, K.K., 2011. Considering the energy, water and food nexus: Towards an integrated modelling approach. Energy Policy 39, 7896–7906. https://doi.org/10.1016/J.ENPOL.2011.09.039

Ceccherini, G., Russo, S., Ameztoy, I., Marchese, A.F., Carmona-Moreno, C., 2017. Heat waves in Africa 1981-2015, observations and reanalysis. Nat. Hazards Earth Syst. Sci. 17, 115–125. https://doi.org/10.5194/nhess-17-115-2017

Cohn, A.S., Newton, P., Gil, J.D.B., Kuhl, L., Samberg, L., Ricciardi, V., Manly, J.R., Northrop, S., 2017. Smallholder Agriculture and Climate Change, Annual Review of Environment and Resources. https://doi.org/10.1146/annurev-environ-102016-060946

Cordano, E., 2017. RasterList. R package, URL: https://cran.r-project.org/package=rasterList.

FAO, 2016. The State of Food and Agriculture: Climate Change, Agriculture and Food Security. https://doi.org/ISBN: 978-92-5-107671-2 I

Hosking, J.R.M., 2017. L-Moments. R package, version 2.6. URL: https://CRAN.R-project.org/package=lmom.

Lesk, C., Rowhani, P., Ramankutty, N., 2016. Influence of extreme weather disasters on global crop production. Nature 529, 84–87. https://doi.org/10.1038/nature16467

Lipper, L., Thornton, P., Campbell, B.M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D., Henry, K., Hottle, R., Jackson, L., Jarvis, A., Kossam, F., Mann, W., McCarthy, N., Meybeck, A., Neufeldt, H., Remington, T., Sen, P.T., Sessa, R., Shula, R., Tibu, A., Torquebiau, E.F., 2014. Climate-smart agriculture for food security. Nat. Clim. Chang. 4, 1068–1072. https://doi.org/10.1038/nclimate2437

Mckee, T.B., Doesken, N.J., Kleist, J., 1993. The Relationship of Drought Frequency and Duration Times Scales, in: American Meteorological Society. 8th Conference on Applied Climatology 17-22 Janvier, Anaheim. pp. 179–184.

Russo, S., Sillmann, J., Fischer, E.M., 2015. Top ten European heatwaves since 1950 and their occurrence in the coming decades. Environ. Res. Lett. 10, 124003. https://doi.org/10.1088/1748-9326/10/12/124003

Udias, A., Pastori, M., Dondeynaz, C., Carmona Moreno, C., Ali, A., Cattaneo, L., Cano, J., 2018. A decision support tool to enhance agricultural growth in the Mékrou river basin (West Africa). Comput. Electron. Agric. 154, 467–481. https://doi.org/10.1016/J.COMPAG.2018.09.037

Van Keulen, H., Breman, H., 1990. Agricultural development in the West African Sahelian region: a cure against land hunger? Agric. Ecosyst. Environ. 32, 177–197.

Wolfe, M.L., Ting, K.C., Scott, N., Sharpley, A., Jones, J.W., Verma, L., 2016. Engineering solutions for food-energy-water systems: it is more than engineering. J. Environ. Stud. Sci. 6, 172–182. https://doi.org/10.1007/s13412-016-0363-z

Zougmoré, R., Partey, S., Ouédraogo, M., Omitoyin, B., Thomas, T., Ayantunde, A., Ericksen, P., Said, M., Jalloh, A., 2016. Toward climate-smart agriculture in West Africa: a review of climate change impacts, adaptation strategies and policy developments for the livestock, fishery and crop production sectors. Agric. Food Secur. 5, 26. https://doi.org/10.1186/s40066-016-0075-3

List of figures

List of tables

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

Joint Research Centre

EU Science Hub

Publications Office