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## Evolution future des débits des cours d'eau dans le bassin du Rhin en contexte de changement climatique - Une évaluation actualisée avec les simulations climatiques issues du 5ème rapport du GIEC

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# **FUTURE EVOLUTION OF RIVER DISCHARGE FOR THE FRENCH RHINE BASIN IN A CONTEXT OF CLIMATE CHANGE**

## **AN UPDATED EVALUATION BASED ON THE AR5 IPCC CLIMATE SIMULATIONS**

Evolution future des débits des cours d'eau dans le bassin du Rhin en contexte de changement climatique

Une évaluation actualisée avec les simulations climatiques issues du 5<sup>ème</sup> rapport du GIEC

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### **ABSTRACT**

*This paper presents the MOSARH21 (Evolution of the discharge of the Rivers MOselle, Sarre and tributaries of the River RHine in France during the 21<sup>st</sup> century) project funded by the Rhine-Meuse Water Agency, which aims at making an evaluation of the future impacts of climate changes on river discharge for the French tributaries of the River Rhine. The MOSARH21 project uses the most recent climate projections produced during the last IPCC climate modeling exercise. The assessment of the impacts of these new climate projections on the Rhine basin hydrology will help verifying to which extent they corroborate previous projections and how they could contribute to stakeholders decisions, e.g. in terms of adaptation strategies. This will be achieved by comparing the MOSARH21 results with those obtained from impact studies previously made in the French part of the Rhine basin. To do so, a prospective study is performed following a top-down ensemblist multi-model approach (using two hydrological models and several parameter sets) in conjunction with an ensemble of downscaled climate projections. The hydrological impacts of future climate changes will be quantified for different time slices (with a particular focus on the mid-21<sup>st</sup> century) based on indices of regimes, floods and low flows. The quantification of the uncertainties associated with the modelling chain will be a major aspect of this work.*

### **KEY WORDS**

Multi-model approach, hydrological impact, CMIP5 climate modeling experiment, Rhine basin, France

### **RESUME**

*Evolution future des débits des cours d'eau futurs sur dans le bassin du Rhin en contexte de changement climatique  
Une évaluation actualisée s'appuyant sur les simulations climatiques issues du 5<sup>ème</sup> rapport du GIEC  
Cet article présente le projet MOSARH21 (Evolution des débits de la Moselle, de la Sarre et des affluents du Rhin en France au cours du 21<sup>ème</sup> siècle), soutenu par l'Agence de l'Eau Rhin-Meuse, qui a pour ambition de réaliser une évaluation des impacts futurs des changements climatiques sur les débits de la partie française des affluents du Rhin, en utilisant les projections climatiques les plus récentes produites dans le cadre des travaux du GIEC. Il paraît en effet opportun d'évaluer les impacts de ces nouvelles projections climatiques sur l'hydrologie du bassin du Rhin, pour voir dans quelle mesure elles permettent d'affiner les précédentes projections et in fine d'éclairer la décision publique. Les résultats seront comparés à ceux obtenus dans le cadre d'études d'impact antérieures réalisées sur le bassin. Pour cela,*

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*une étude de prospective hydrologique sera effectuée dans une logique ensembliste et descendante grâce à la mise en œuvre d'une approche multi-modèles (exploitant deux modèles hydrologiques et un ensemble de paramètres) utilisée conjointement avec un ensemble de projections climatiques désagrégées à l'échelle d'intérêt. Les impacts hydrologiques du changement climatique futur seront quantifiés à différents horizons temporels (notamment celui de 2050) sur la base de divers indicateurs relatifs aux régimes, aux crues et aux étiages. Une attention particulière sera donnée à la quantification des incertitudes associées à la chaîne de modélisation.*

## MOTS-CLEFS

Approche multi-modèles, impact hydrologique, expérience numérique CMIP5, bassin du Rhin, France

## 1. INTRODUCTION

The fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) has recently been published [IPCC, 2014]. Summarizing the reports of three working groups (WGs), respectively dealing with physical science basis, impacts, adaptation and vulnerability and mitigation of climate change, the synthesis report provides a state-of-the-art view on scientific and socio-economic aspects of climate change. It qualifies the warming of oceans and atmosphere as unequivocal, and states that human influence is extremely likely to be the main cause of the observed warming. These conclusions strengthen the conclusions of the former report (AR4) published by the IPCC [2007].

Rising temperature together with modifications of precipitation regimes have an impact on water cycle at many scales. Surface hydrology may already be altered by these changes [Renard et al., 2006]. River discharge is one of the most important water sources for many water uses: hydro-electricity, agriculture, drinking water, power plants cooling, etc. It also represents a risk, during floods and droughts. Therefore assessing the long term (over the next decades) evolution of flows in a context of climate change is essential. Climate projections are usually designed through a forcing modelling chain: possible future emissions of greenhouse gases are established based on socio-economic and demographic scenarios, then these scenarios are used as inputs to General Circulation Models (GCMs). The outputs from GCMs are downscaled at finer spatial and temporal resolutions to be used for regional modelling purposes. To transform the climate projections into hydrological projections, a further step of hydrological modeling is implemented.

Such a top-down modeling chain has already been used for assessing the impact of climate change on hydrology for several large-scale areas in France [Chauveau et al., 2013], Germany [Görge et al., 2010], Europe [Forzieri et al., 2014] and Africa [Roudier et al., 2014]. These impact studies of climate change allow public water authorities, like e.g. the French « Directions Régionales de l'Environnement, de l'Aménagement et du Logement » (DREALs) or the German Länder, to get scientifically consistent estimations of relevant discharge indices that are useful to anticipate the management of water resources. However, each country making its own choices on climate scenarios, hydrological models and discharge indices (especially for low water), and data sharing being sometimes difficult between countries, the comparability of results and studies for transnational basins is usually limited. Yet the need for an international coordination within transboundary river basins is important for the identification of the likely impact of climate change on the occurrence of droughts or floods which shall be taken into account in the forthcoming review of the preliminary flood risk assessment for the purpose of the European Directive 2007/60/EC on the assessment and management of flood risks<sup>2</sup> and the review of the characteristics of the river basin district for the purpose of the European Directive establishing a framework for Community action in the field of water policy<sup>3</sup>. This requires a significant degree of coordination and harmonization of the existing regional tools and methodologies for producing hydrological scenarios [Bauwens et al., 2014]. Moreover, impact studies should be updated with the most recent generation of climate projections to better assess the adaptation measures.

This article presents the first outcomes of the MOSARH21 project (Evolution of the discharge of the Rivers MOselle, SARre and tributaries of the River RHine in France during the 21st century). The project is supported by the Rhine-Meuse Water Agency whose general objectives are to enhance water management in a broad sense in French parts of the Rhine and Meuse basins. By fostering the collaboration between hydrological modellers from France and Germany, and by setting up a common methodology to produce

<sup>2</sup> See article 14 of the Floods Directive / Reporting sheet for the implementation of the Floods Directive (2007/60/EC) Endorsed by Water Directors 30 November 2009 / Reporting sheets for the implementation of the Floods Directive (2007/60/EC) Endorsed by Water Directors: February 2011 /

<sup>3</sup> See article 5 of the Water Framework Directive and Technical Report n° 2009 – 040 for the Common Implementation Strategy for the Water Framework Directive (2000/60/EC) "Guidance Document n°24 - River basin management in a changing climate"

hydrological projections with the most recent climate projections, this project intends to give a new insight on water resources vulnerability to climate change during the 21<sup>st</sup> century. A link with previous impact studies made either on the French part or on the German part of the Rhine basin will be established. To this aim, hydrological projections will be produced by using both AR4 and AR5 climate projections. The comparison between impact studies is based on a common set of metrics.

The paper is organized as follows: first, previous studies including the French Rhine tributaries are analyzed and compared, with a focus on the methodological aspects. Then, the two hydrological models used in the MOSARH21 project are presented. The study area and the data are described in the third section. The last section focuses on the methodological aspects of the project.

## 2. SETTING THE SCENE: AN OVERVIEW OF RECENT HYDROLOGICAL IMPACT STUDIES IN THE RIVER RHINE BASIN

In this section, several studies assessing the impact of climate change on river discharges in areas including the French Rhine tributaries are presented. The expression “French Rhine tributaries“ will be used to refer to the French part of the River Moselle, the French part of the River Sarre, and the French tributaries of the section of the Rhine making the border with Germany (Ill, Moder and Sauer).

Project	Rheinblick2050	VULNAR	Explore 2070	FLOW MS
Greenhouse gases emission scenario	AR4 A1B	AR4 A1B, A2 and B1	AR4 A1B	AR4 A1B
Number of GCMs	2	7	7	1
Downscaling method	Regional Climate Models	Statistical weather-type approach [Boé et al., 2007]	Statistical weather-type approach [Boé et al., 2007]	Regional Climate Model
Hydrological model(s)	HBV [Bergström, 1976]	MODCOU [Ledoux et al., 1989] et HPP-inv [Lecluse, 2014]	GR4J [Perrin et al., 2003] and Isba-Modcou [Habets et al., 2008]	LARSIM [Ludwig et Bremicker, 2006]
Reference period	1961-1990	1961-2000	1961-1990	1971-2000
Future period(s)	2021-2050 and 2071-2100	2046-2065 and 2081-2099	2046-2065	2021-2050

### 2.1 Rheinblick2050

This project took place from 2008 to 2010 and was initiated by the International Commission for the Hydrology of the Rhine basin (CHR). The objective of the project was to estimate the impacts of future climate change on discharge of River Rhine and its major tributaries, namely the Main and Moselle and associated institutions from France, the Netherlands, Switzerland, Luxembourg and Germany [Görgen et al., 2010]. The set up of the modelling exercise is described in Tab. 1.

Climate projections indicated rising temperatures up to 2.5°C for the near future and from 2.5 to 5.0°C for the far future. Precipitation is not expected to significantly change in the near future but could increase in winter and decrease in summer for the far future. A slight mean discharge increase was projected for the near future while for the far future opposite changes in winter and summer, in agreement with the precipitation changes. Low flows were studied through the calculation of the mean annual minimum 7-day flow. The only noticeable changes occurred for low flows with an increase during near future winters and a decrease during summers at the end of the century. Estimations of high flows change based on a weather generator approach did not lead to significant conclusions due to important uncertainties.

### 2.2 VULNAR

This project was funded by the French National Research Agency (ANR) from 2008 to 2012 (<http://www.cnrm.meteo.fr/spip.php?article278>). It aimed at studying the effects of climate change on the Upper Rhine aquifer layer (see its configuration in Tab. 1).

An increase of air temperature of 3°C and a decrease of precipitation around 15% are expected by the end of the century compared with a reference period set up as 1961-1990. Snow falls were projected to

drastically decrease by 70%. The impacts of climate change on aquifer levels was low, with a slight increase of the relative infiltration from rivers and a decrease of the average water recharge.

### **2.3 Explore 2070**

Within this project, ordered by the French Environment Ministry, the possible impact of climate changes on discharge was assessed over France [Chauveau et al., 2013]. The Isba-Modcou and GR4J models were applied on a common set of 543 gauge stations over France first forced by observed meteorological data and in a second step by climate projections [Chauveau et al., 2013] as detailed in Tab. 1.

An increase of air temperature in the future from 1.4°C to 3°C is the most robust result of climate projections over France. Regarding precipitation, trends are uncertain but may show a decrease of around 20% in summer with no significant trend for the rest of the year. Both hydrological models predict a decrease of around 10% of annual discharge for the Moselle and Sarre, and around 20% for the other Rhine tributaries. Low flows are predicted to significantly decrease for all Rhine tributaries but the intensities of this decrease are different for both models: around 20% for Isba-Modcou, and up to 60% for GR4J. This discrepancy shows the utility of adopting a multi-model approach to better quantify the uncertainty coming from hydrological modelling. Finally, the sign of flood change was shown to be very uncertain, which can be directly linked with the possible change of rainfall totals during the rainy season (winter). Floods may slightly increase for the Moselle and Sarre basins and slightly decrease for the other Rhine tributaries, but the dispersion of results is high. The metrics used were mainly based on discharge regimes, lowest monthly flow with a return period of 5 years, and maximum daily discharge with a return period of 10 years.

### **2.4 FLOW MS**

The “Floods and low flows management of the Moselle and Sarre basins – FLOW MS” project started in 2009 and was coordinated by the International Commissions for protection of Moselle and Sarre (Commissions Internationales pour la protection de la Moselle et de la Sarre, CIPMS). FLOW MS associated French, Luxemburgish and German institutions. The modelling chain was set up as described in Tab. 1. The study area of the FLOW MS project covered the Moselle basin, i.e. including its Luxemburgish and German parts, up to its confluence with the Rhine in Koblenz. A sample of 37 discharge gauging stations was selected.

Climate projections indicated an increase of air temperature of 1°C until 2050 for the basin, with drier summers and wetter winters. From a hydrological perspective, the FLOW MS project concluded to likely lower flows during summers and to significantly higher floods for winter. The metrics used to obtain these conclusions were mainly based on monthly mean, minimal and maximal discharge values.

As it is clear from the reading of Tab. 1, the hydrological projections realized within these four projects highly differ in their settings: GCMs, downscaling methods, hydrological models and time periods differ. Moreover, the indices used to assess the evolution of discharge differed a lot between the models. As a consequence, the MOSARH21 project is necessary to update and homogenise the hydrological projections and indices. This MOSARH21 project is presented in the following.

## **3. THE HYDROLOGICAL MODELS USED IN THE MOSARH21 PROJECT**

### **3.1 The conceptual semi-distributed GR5J daily model (GRSD)**

GRSD is a daily semi-distributed rainfall-runoff model. Based on the daily lumped GR5J model, mainly composed of a production reservoir and of a routing reservoir [Le Moine, 2008], the GRSD model was developed by Lobligeois [2014]. Instead of considering input data as uniform on each basin like in GR5J, GRSD spatially distributes input data on sub-basins (Fig. 1). The sub-basin discretization scheme can either correspond to the gauging stations network or to the modeller’s choice based for example on a specific contributing area. Therefore this semi-distributed model explicitly accounts for the heterogeneity of basins characteristics. In addition to the five free parameters of GR5J calibrated against observed discharge series, the GRSD model, has two parameters related to its hydraulic propagation scheme. Within the MOSARH21 project, the GRSD discretization corresponds to the selected gauged sub-basins. Hence, the rainfall-runoff GRSD model is calibrated at each gauge station.

A degree-day snow accumulation and melting module, CemaNeige [Valéry et al., 2004], is used together with GRSD. Each sub-basin is cut into five zones of equal area on which the snow accumulation and melting are calculated. Its two parameters are set up at fixed median values for this project.

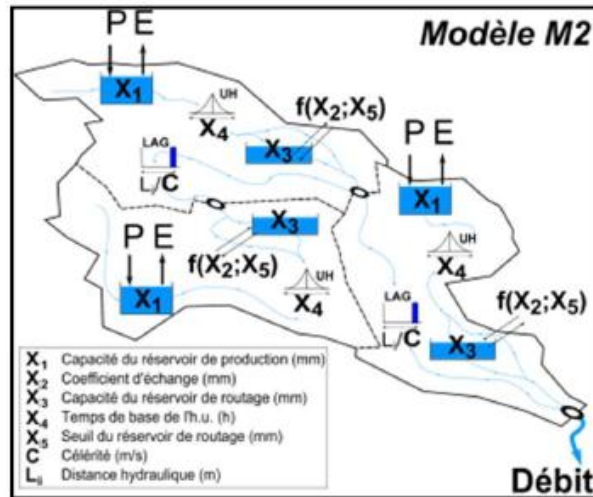
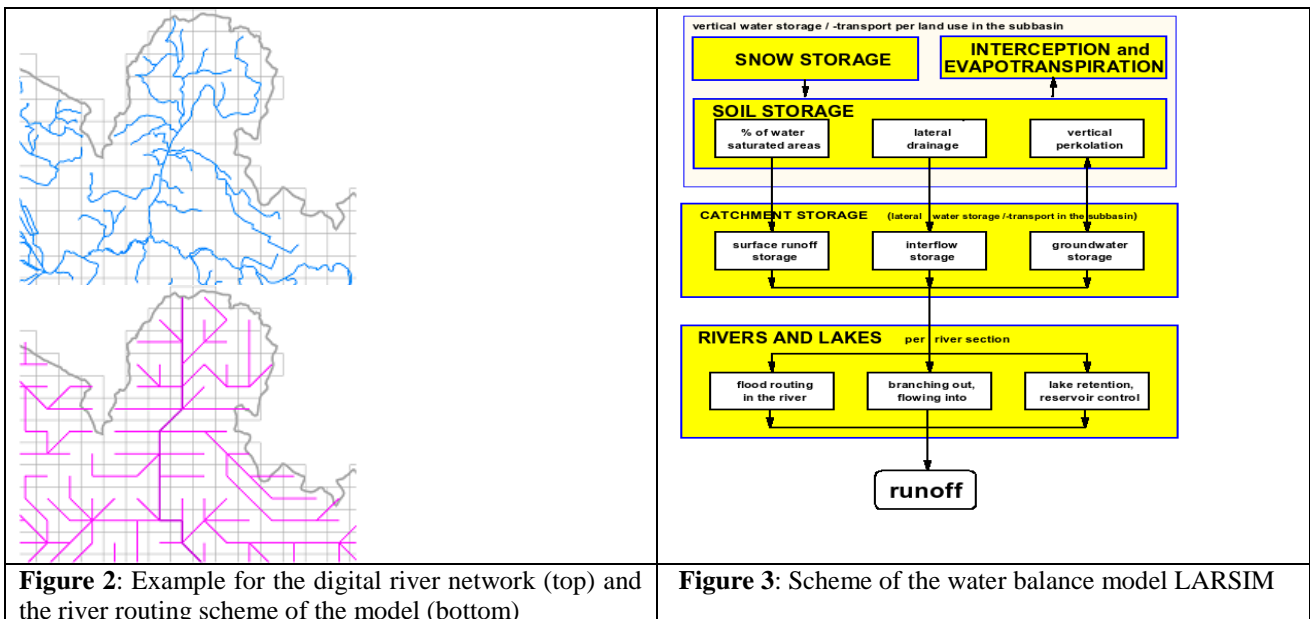


Figure 1: Spatial discretization and functioning of the GRSD model. From Lobligeois [2014].

### 3.2 The physically-based distributed LARSIM daily model

The water balance model LARSIM (Large Area Runoff Simulation Model; [Ludwig & Bremicker, 2006]) is a so-called conceptual model, i.e. the complex processes in the natural system are reproduced by simplified model concepts. The water balance model LARSIM is often applied with quadratic grid cells (subareas) of 1 km for the representation of the real river network (Fig. 2). Alternatively, a subarea structure based on hydrologic subareas is possible as well as any other grid cell size than 1km<sup>2</sup>. For each cell, the following hydrological sub-processes are described: interception, evapotranspiration, snow accumulation, compaction and thaw, soil water replenishment, storage and lateral water transport within the area and translation and retention in channels and lakes (see LARSIM model schema, Figure 3).



LARSIM combines well-tried deterministic hydrological model components, which are as far as possible generally applicable and are based on accessible system data for the land surface. Emphasis is laid on the reliable determination of evapotranspiration by using the Penman-Monteith equations. Evapotranspiration and the soil water budget are calculated separately for different land uses and field capacities of the soils. Up to 16 different land uses with their specific evapotranspiration and run-off properties were recorded for each individual grid area (Figure 3).

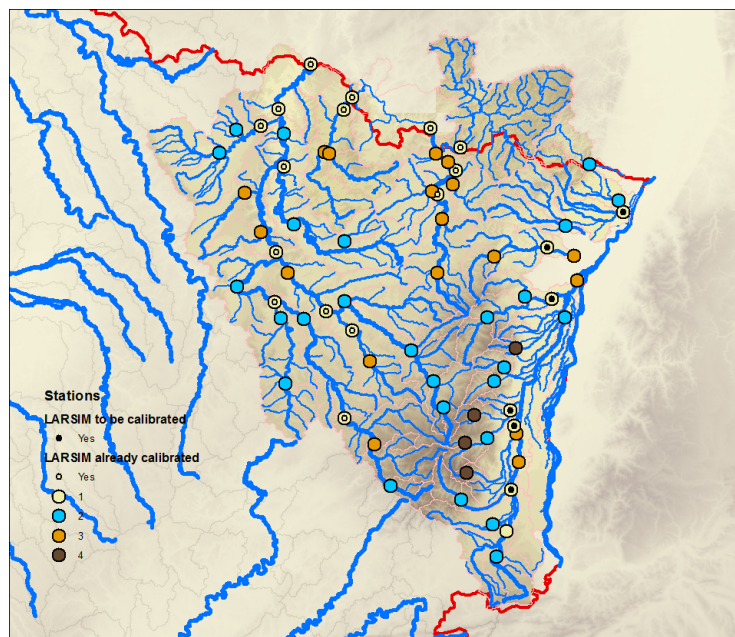


The LARSIM model is widely used for operational flood forecast centres [Bremicker et al. 2013]. LARSIM has originally been developed for the French Rhine tributaries for hourly calculation time intervals for the purpose of flood forecast for the operational flood warning centres Meuse-Moselle and Rhin-Sarre of the French DREALs Lorraine and Alsace. LARSIM has hence been adapted to daily calculation time intervals for the purpose of the FLOW MS and MOSARH21 projects.

## 4. STUDY AREA AND DATA OF THE MOSARH21 PROJECT

### 4.1 The study area and monitoring discharge stations network

The French part of the Rhine basin represents 12 % of the whole Rhine catchment basin and includes two sub-districts: the River Rhine itself and its direct tributaries located in the Alsace region (8,160 km<sup>2</sup>) and the Moselle and Saar basins up to the German and Luxemburgish borders (15,360 km<sup>2</sup>). The eastern part comprises the 214 kilometres of the Rhine from the Swiss border at Basel (South) to the German border at Lauterbourg (North) and its tributaries which take their spring in the Vosges mountains (Moder, Sauer, Lauter, Bruche, Zorn, Lauch, Doller) and in the Jura mountains (River Ill). The western part comprises the Rivers Moselle and Saar and their tributaries. The Moselle has a total length of 313 kilometres between its spring in the Vosges Mountains and the border with Germany and Luxembourg. Its main tributary is the River Meurthe. The Saar also has its spring in the Vosges Mountain and flows to Germany at Saarguemines.



**Figure 4:** Monitoring discharge stations selected for the MOSARH21 project.

In order to make a link between past projects carried out on the French part or on the German part of the Rhine basin, and new projections produced in the MOSARH21 project, a set of gauging stations has been selected (Fig. 4). Calibrating the LARSIM model being time consuming, gauging stations where LARSIM was already calibrated and applied within the FLOW MS project are included. For Alsace, six other stations will be calibrated in the MOSARH21 project. All these stations were included in a priority dataset (category 1 in Fig. 2; 22 stations) for which a thorough analysis of models performance and hydrological projections will be made. A second category (category 2; 26 stations) for which only GRSD will be calibrated was established for operational purposes. These stations are of interest for the Water Public Authorities for either flood or drought monitoring. A detailed analysis of results for the LARSIM simulations will not be done on them. Finally, additional stations included within the Explore 2070 project were put in categories 3 and 4 (22 stations). These stations will not necessarily be subject to a detailed analysis. The quality of measured discharge and the potential anthropic influence was taken into consideration for selecting the stations.

### 4.2 Climate data

Daily meteorological data are derived from the gridded SAFRAN reanalysis [Vidal et al., 2010]. This dataset consists in an 8-km resolution atmospheric reanalysis over France from 1958. The atmospheric variables are rainfall, snowfall, mean air temperature, specific humidity, wind speed, solar and infrared radiation. The hydrological data were retrieved from the Banque Hydro website: <http://www.hydro.eaufrance.fr>. For the four stations located in Germany, data were obtained from the German federal Waterways and Shipping Administration (Wasser- und Schifffahrtsamt) and the Institute for Environment and Workerprotection in Saarland (Landesamt für Umwelt- und Arbeitsschutz Saarland).

The climate projections from four distinct sources will be used (Tab. 2). First, the projections from the two former projects, Explore 2070 and FLOW MS will be used. To have homogeneous hydrological projections, the Explore 2070 climate projections will be used as an input of both LARSIM and GRSD (a lumped version of the model, GR4J, was indeed used in Explore 2070). Regarding FLOW MS, GRSD will be fed with its projections, while LARSIM will be fed only on the Alsace region (projections were made only on the rest of the basin during the FLOW MS project).

New projections based on AR5 are made available by National Meteorological Services. Due to the availability of downscaled projections for most of the variables required by LARSIM, our choice should move towards the datasets available on the French Drias portal (<http://drias-climat.fr/>). Two climate modelling procedures are available. The first one, produced by the Pierre-Simon Laplace Institute (IPSL) is based on the IPSL-CM4 GCM, dynamically downscaled by the WRF model and corrected using a Cumulative Distribution Function – Transform (<http://drias-climat.fr/accompagnement/section/180>) for RCPs 4.5 and 8.5. The second climate modelling procedure, produced by the National Centre for Meteorological Research (CNRM), is based on the Arpege-global GCM, dynamically downscaled using the Aladin-Climat limited area model (LAM) and corrected with the quantile-quantile method (<http://drias-climat.fr/accompagnement/section/179>) for RCPs 2.6, 4.5 and 8.5. Both chains provide data at an 8-km resolution respectively from 1971-2100 and 1950-2100. Due to time computation, the MOSARH21 project will mainly focus on the 2021-2050 period and the RCP8.5 scenario for producing LARSIM simulations, while the other RCPs and the period 2071-2100 will be considered only for GRSD simulations.

Additional downscaled climate projections will be available for the project. They come from the use of a simpler statistical method, the Advanced Delta-Change [van Pelt et al., 2012]. These projections will be made available for the climate forcing of the GRSD rainfall-runoff model.

Origin of projection dataset	Explore 2070	Flow MS	Drias	Advanced-Delta Change
Scenario	AR4 A1B	AR4 A1B	RCP8.5 (RCPs2.6 & 4.5)	RCPs2.6, 4.5, 6.0 & 8.5
Number of GCMs	7	1	2	~ 20
Downscaling	Statistical weather-type approach	Regional Climate Model	Regional Climate Models	Statistical method
Unbiasing	-	Linear scaling & quantile-quantile	Distribution fitting-based methods	-
Spatial resolution	8x8 km	7x7 km	8x8 km	8x8 km
Hydrological models to run	LARSIM & GRSD	GRSD	LARSIM & GRSD (GRSD)	GRSD

Table 2: Overview of the hydrological projections realized within MOSARH21.

## 5. METHODS

### 5.1 Incorporating sources of uncertainties in the hydrological projections through an ensemblist approach

Throughout the complete modelling chain set up to produce hydrological projections, many sources of uncertainties exist: greenhouse gaz emission scenarios, GCMs, downscaling methods and hydrological models. In order to take into account these sources of uncertainties, the common approach is to consider several options for each step. This approach was adopted in MOSARH21: several RCPs will be considered, as well as two GCMs, two downscaling methods and two hydrological models.

An additional specific task will be performed on the parameterization of the hydrological models. Indeed, this source of uncertainty is most of the time neglected in climate change impact studies. However, it



has been shown that hydrological model errors, regardless to the mathematical structure of the model, suffer from a dependence to the hydro-climatic conditions of the calibration period [Coron et al., 2012; Thirel et al., 2015]. In order to take into account this source of uncertainty, the models will be calibrated over different climate contrasted periods.

## 5.2 Making projections of very high flows

Stochastic rainfall generators are tools that use statistical properties of rainfall observations time series (typically mean, variability, extreme values, spatial and temporal correlations, and successions of days with or without rainfall [Aubert, 2011]) to produce very long rainfall time series. These tools are largely used for providing inputs to hydrological models when the knowledge of extreme flows is necessary (e.g. dams design).

Within MOSARH21, a stochastic rainfall generator will be calibrated first on the statistical properties of rainfall time series obtained from a reference period, and then on the statistical properties of future conditions coming from the climate projections. Up to a thousand years of rainfall will be produced for both periods. Two sets of runs of GRSD (and possibly LARSIM) will then be produced. From the discharge time series obtained for both runs, 100-yr and 1000-yr floods will be calculated.

## 5.3 Common metrics to assess floods and low flows occurrences

One of the aims of the project is to assess the discharge projections on our study area on a common basis for both AR4 projections and the new AR5 projections. This needs to design an experimental protocol relying on a selected set of metrics. A review of the metrics used in the past studies will be made in order to select the adequate metrics for this project. A particular focus will be made on high and low flows, as well as on regimes.

## 6. CONCLUSIONS

The MOSARH21 project is still in its preliminary phase, therefore only the general context and the methodological aspects were presented here. Its aim is to update the expected discharge modifications related to future climate change on a set of stations with interests for the operational stakeholders, and to homogenise the indices used to assess the future changes taking into account the uncertainties of the modelling chain.

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