Climate change impacts on water resources and hydrological extremes in northern France

Agnès Ducharne, Florence Habets, Christian Pagé, Eric Sauquet, P. Viennot, Michel Déqué, Simon Gascoin, A. Hachour, E. Martin, Ludovic Oudin, et al.

XVIII International Conference on Water Resources
CMWR 2010
J. Carrera (Ed)
CIMNE, Barcelona 2010

CLIMATE CHANGE IMPACTS ON WATER RESOURCES AND HYDROLOGICAL EXTREMES IN NORTHERN FRANCE

A. Ducharne [1], F. Habets [1,2], C. Pagé [3], E. Sauquet [4], P. Viennot [2], M. Déqué [5], S. Gascoin [1], A. Hachour [1,2], E. Martin [5], L. Oudin [1], L. Terray [3] and D. Thiéry [6]

[1] UMR Sisyphe, CNRS/UPMC
UPMC Case 105, 4 Place Jussieu, 75005 Paris, France
e-mail: agnes.ducharne@upmc.fr

[2] Centre de Géosciences, MINES ParisTech
35 rue Saint Honoré, 77305 Fontainebleau cedex, France

[3] CERFACS
42 avenue Gaspard de Coriolis, 31057 Toulouse cedex 01, France

[4] Cemagref, UR Hydrologie-Hydraulique
3bis quai Chauveau, CP 220, 69336 Lyon cedex 09, France

[5] CNRM, Météo-France
42 avenue Gaspard de Coriolis, 31057 Toulouse cedex 01, France

[6] BRGM, Service Eau
3 avenue Claude-Guillemin - BP 36009 - 45060 Orléans Cedex 2, France

Key words: Climate change, hydrological impacts, statistical downscaling, extreme events, irrigation, uncertainties

Summary. We downscaled 12 scenarios of anthropogenic climate change in the basins of the Seine and Somme Rivers (France). They were used as input to 5 different hydrological models. This framework allowed us to quantify the different sources of uncertainty. The resulting hydrological scenarios agree on a marked depletion of water resources during the 21st century with an annual mean decrease in both water table level and river discharge. At the seasonal scale, the reduction of river flow is more marked on low than on high flows, the decrease of which is also less robust. The response of extreme flows is even more contrasted, with a decrease of low-flow quantiles, whereas high-flow quantiles would not change significantly. In the Beauce region, one of the hotspots for irrigation in Europe, we show that the increase in potential demand for irrigation would have a lesser impact on water resources than the decrease in groundwater recharge directly caused by climate change, which is enough in itself to threaten the reliability of water resources.

1 INTRODUCTION

The anthropogenic increase in greenhouse gas concentrations is very likely causing a change in climate. It shall intensify during the 21st century, with manifestations concerning both mean climate and climate variability, which is likely to change compared to natural variability[1]. The potential impacts of such changes on river systems are the subject of active research, because of the importance of water for human activities, in terms of both resource and risk factor.

This paper summarizes the main results of the project RExHySS[2], which addressed the potential impacts of anthropogenic climate change in the basins of the Seine and the Somme rivers (78600 and 7400 km² respectively in northern France). They are characterized by an oceanic climate and the buffering influence of groundwater tables on river flow, so that water availability is presently not an issue under normal conditions. Yet, as most human impacted river basins, they are very vulnerable to hydrological extremes, as illustrated by the centennial floods of the Seine in 1910 and the Somme in 2001, or the recent droughts of 2003 and 2005.

After an overview of the novel methods used to downscale the climate change projections and the resulting conditions in the basins during the 21st century, the paper presents the subsequent impacts on water resources and hydrological regime, then on river discharge extremes. Given the robust trends towards water scarcity in the studied basins, the question of irrigation is eventually addressed, before discussing the main conclusions in light of the exercise's limits.

2 DOWNSCALED CLIMATE SCENARIOS FOR THE 21ST CENTURY

We constructed climate change scenarios in these basins based on projections by several large-scale climate models. To regionalize these scenarios, we benefited from two downscaling methods recently developed by the French scientific community. They are both calibrated to match the recent climate, as described by the Météo-France SAFRAN meteorological analysis[3].

The first method combines a dynamical downscaling using a regional climate model with a correction of the simulated cumulative-density functions[4], at the scale of the SAFRAN analysis (8 km x 8 km). The second one is a statistical downscaling method based on weather typing[5]. The idea is to statistically link the large-scale circulation, here defined by the mean sea-level pressure and the temperature averaged over Western Europe (predictors), to local-scale climate variables (predictants). The statistical model is established over a learning period (1981-2005), when the predictors are extracted from the daily NCEP reanalysis, while the predictants are taken from the SAFRAN analysis. The downscaling then consists of conditional resampling, by matching the day of the large-scale climate scenario to the day of the SAFRAN analysis with the same weather type and the closest mean-sea level pressure and Western Europe averaged temperature. The four standard seasons are processed separately, as they are characterized by different large-scale weather types.

These two downscaling method offer the advantage to satisfactorily describe the regional climate variability at daily to inter-annual time scales, as shown for instance by the distributions of precipitation[2]. Under the assumption that the model errors are stationary, they allow us to account for the changes in climate variability in addition to mean climate change, and thus to tackle the evolution of hydrological extremes. This is not the case of the simpler perturbation method, kept here as a reference with previous impact studies[6].

To address the uncertainties related to the downscaled climate scenarios, we classically multiplied the latter ones to generate an ensemble of scenarios. We used 12 of them, characterized by 8 different large-scale climate models, forced by one or two SRES emission scenarios, and downscaled by one to three different methods. In the following, we will mostly focus on two future time slices, 2045-2065 and 2080-2100, referred to as 2050 and 2100, and analyzed by comparison to a reference period spanning 1970-2000.

The downscaled scenarios all agree on a warming during the 21st century (+1.5 to +3 °C by 2050, and +2 to +4 °C by 2100), with an increase in potential evapotranspiration and a marked decrease in summer precipitation. The sign of winter precipitation change is uncertain, but the annual mean precipitation decreases (-6% and -12% on average over the studied scenarios, by 2050 and 2100 respectively, with only one exception corresponding to a +2% increase by 2100).

3 EVOLUTION OF THE WATER RESOURCES

The above 12 downscaled scenarios were analyzed by 5 state-of-the-art hydrological models (MODCOU[7], SIM[8], CLSM[9], EROS/GARDENIA[10], GR4J[11]). They are representative of the main types of hydrological models (lumped *vs.* distributed, physically-based *vs.* conceptual, land-surface *vs.* hydrogeological) and were all validated against recent observed discharge with good performances, using the SAFRAN meteorological analysis[3] as input. We also verified that the different hydrological scenarios (i.e. combinations of climate model / downscaling method / hydrological model) reproduced, for the reference period, the main features of observed discharge. This is illustrated in Figure 1, where the observed discharge falls within the standard error of the different reference hydrological scenarios.

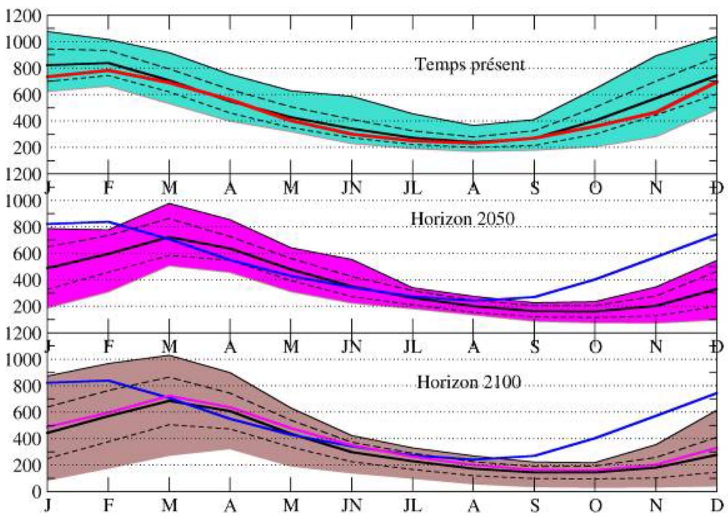

Figure 1. Evolution of the Seine monthly discharge at Poses (m^3/s) following the ensemble of hydrological scenarios. The enveloppes define the monthly min and max values, and the thick and dotted lines give the monthly ensemble mean and standard deviations respectively. TOP: Reference period (1970-2000); the red line gives the monthly mean observed discharge over 1970-2003. MIDDLE: Period 2045-2065; the blue line gives the monthly ensemble mean for the reference period. BOTTOM: Period 2080-2100; the blue and pink lines give the monthly ensemble means for the reference period and 2045-2065 respectively.

These hydrological scenarios project a marked depletion of the water resources in the two basins during the 21st century, with an annual mean decrease in both water table level and river discharge. The discharge at the outlet of the Seine River (Poses) is a representative example (Figure 1). It decreases according to 97% of the hydrological scenarios, and the mean change (-150 m^3/s by 2100, i.e. -28% of the reference discharge) is much larger than the uncertainty, estimated as the related standard deviation (50 m^3/s). This decrease is largely realized by 2050, and is visible on high and low flows, but with larger uncertainties on the former. One can also note a lag of the mean hydrograph of one to two months.

We also attempted to rank the different uncertainty sources, following[12]. The smallest uncertainties are related to the emission scenarios and time horizon of the climate projections, what is consistent with impacts that are largely realized by 2050. Thus, uncertainties mostly arise from the large-scale climate models, closely followed by the hydrological models and downscaling methods. This novel result shows that neglecting these last two uncertainty sources, as in many older impact studies, may lead to biases in the projected impact. This generalizes the widely accepted recommendation that an impact study cannot be limited to a unique climate projection. To avoid unjustified uncertainties, however, we excluded the hydrological scenarios simulated with the CLSM, because of doubts regarding its response to soil moisture stress, which is markedly enhanced during the 21st century in our scenarios[2].

4 EVOLUTION OF RIVER DISCHARGE EXTREMES

We used classical frequency analysis methods to characterize the extremes of river discharge[13]. We focused on the *QMNA5* low-flow quantile (annual monthly minimum with a mean return period of 5 years, equivalent to *30Q5* in the US) and the *QJXA*10 high-flow quantile (annual daily maximum with a mean return period of 10 years, equivalent to *Q10* in the US). They were deduced assuming that the corresponding annual extremes followed a log-normal and Gumbel distribution respectively, based on 20-year time series (restricted to 1980-2000 for the reference simulations), all assumed to be stationary.

These two variables are operationally used as alert thresholds and for infrastructure design, and are thus relevant for water management issues. They were also easy to process automatically. This was critical given that the different hydrological scenarios were multiplied by the number of gauging stations considered by each hydrological model (from 23 to 125, with 9 shared stations), defining *ca.* 8000 time series.

We first compared the simulated quantiles to the observed ones over the recent period. The match was far from perfect but satisfactory. No hydrological model clearly surpassed the others in this exercise. Logically, the biases were larger when the latter were forced by the downscaled reference scenarios than with the SAFRAN meteorological forcing, and the relative bias were larger for the low-flow quantile.

Given these imperfections, we analyzed the future evolution of these quantiles relatively to their simulated values during the reference period. By 2050 (Figure 2), the low-flow quantiles would decrease in all the studied gauging stations, whereas the high-flow quantiles would not change significantly (they change by ±10% in most cases, when the 95% confidence intervals around the reference quantiles range between -12 to +25%). Similar results are found by

2100, except that the decrease of the low-flow quantile is more pronounced. Note that the low-flow quantile reduction goes along with a decrease in water supply reliability (estimated as the probability of stream flow to exceed the reference quantile).

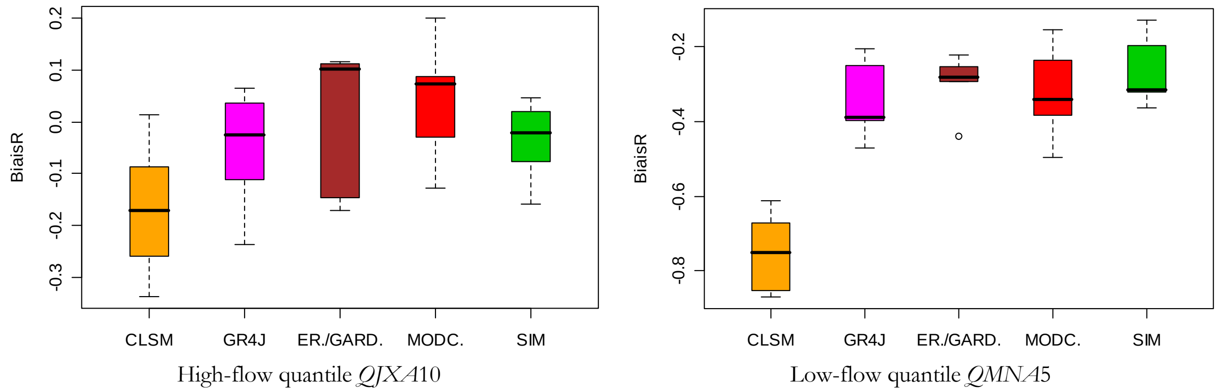

Figure 2. Relative changes in high and low flow quantiles between 2045-2065 and the reference period (Q_{2050}/Q_{REF} -1). For each hydrological models, we consider the distribution of relative changes for the different downscaled climate change scenario and the different stations simulated by the hydrological model in the Seine et Somme basins. The bottom and top of the box-plots define the 1st and 3rd quartiles and the inside line gives the median. The ends of the whiskers represent the lowest and highest values within 1.5 interquartile range, and the remaining data are represented by dots.

5 IRRIGATION

Given the above results, the socio-economic impacts of climate change will probably be dominated in the studied basins by the enhancement of low-flows and droughts, which threatens the balance of the different water uses against water supply. A particularly sensitive use is irrigation, which was studied using the hydrogeological model MODCOU coupled to the crop model STICS[7].

At the scale of the Seine river basin, for the time being, irrigation only concerns 3% of agricultural land, and amounts to 5% of the total water withdrawals (*ca.* 3000 Mm^3/yr), almost exclusively from groundwater. It may seem negligible, but more than half of this withdrawals are concentrated in the Beauce region, which combines intensive cash crop farming and small precipitation amounts (*ca.* 500 mm/yr). Based on recent records, the withdrawals can be estimated to 100 mm/yr on average in the irrigated plots, which cover 16% of the total area (4610 km^2). Using the SAFRAN meteorological forcing, we achieved in this area realistic simulations of both irrigation demand by the crop model STICS and groundwater recharge by the hydrogeological model MODCOU (*ca.* 125 mm/yr).

We further used these models to address the evolution of groundwater sustainability under climate change. To this end, we focused on one downscaled climate scenario for 2100, corresponding to a SRES emission scenario A2, with larger warming and precipitation reduction than average (+3.6°C and -23% respectively, on average in the Seine river basin).

Assuming that the crop rotations remain the same, we projected a 60% increase of the potential demand for irrigation using the crop model STICS. We modified the reference withdrawals accordingly, what reduces the mean net influx to the water table of 10 mm/yr. The resulting drop of water table level in the Beauce aquifer, simulated by the hydrogeological model MODCOU without any other influence of climate change, can locally exceed 3 m, with an average of 1 m over the area.

But the main driving factor is the decrease in groundwater recharge directly caused by climate change. It reaches 37% of the reference value, what is consistent with the 33% decrease found on average over the entire Seine basin, over the ensemble of studied downscaled scenarios by 2100. Based on a Student test, this average drop is statistically significant at the risk α = 2% compared to the dispersion between the different downscaled scenarios.

The related decrease of the mean net influx to the Beauce aquifer (50 mm/yr) is five times larger than the one related to irrigation demand increase, with similar order relationships regarding the mean water table level (-4.6 m *vs.* -1 m) and the maximum local depletions (-15 m *vs.* -3 m). As a result, the combined impact of these two driving forces is dominated by the direct effect of climate change on groundwater recharge, as illustrated on the low-flow quantile *QMNA*5 of the different regional streams (Figure 3).

These results show that the direct impact of climate change is by itself enough to cast doubts on the sustainability of the water supply in the Beauce area, and thus on the one of the present water uses, including cash crop irrigation as it is presently performed.

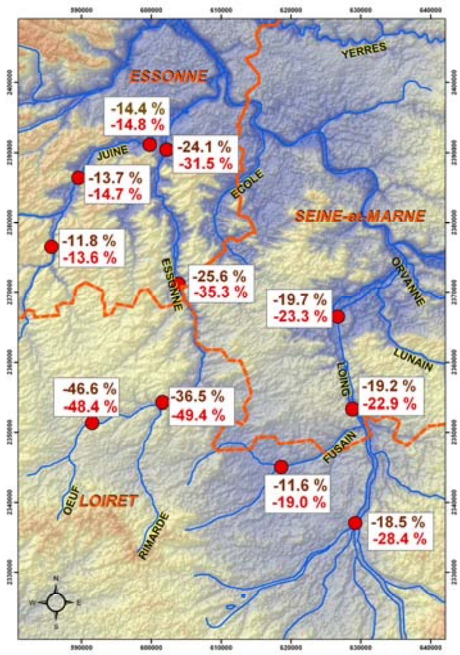

Figure 3. Relative change of the low-flow quantile *QMNA*5 in the main streams of the Beauce area between 2080-2100 and the reference period (in % of the reference value), under one specific A2 climate change scenario. Values in brown give the impact of the reduction in groundwater recharge directly caused by climate change, assuming unchanged withdrawals fo rirrigation. Values in red give the combined impact of groundwater recharge reduction and increased withdrawals to satisfy increased irrigation demand under climate change.

6 CONCLUSIONS

According to the hydrological scenarios elaborated in this study, the main hydrological impact of climate change in the Seine and Somme basins during the 21st century is a robust decrease of water resources in summer, when they are mostly solicited. In contrast, we found a moderate change of the flood regime. These results have important socio-economic implications, in particular to guide adaptation strategies in water-dependent sectors. They are limited, however, to the potential impact of climate change, and do not account for other change factors, which can either be independent anthropogenic pressures (but they will probably enhance the water scarcity issue), or the above-mentioned adaptation strategies.

Another limit of these results is their inherent uncertainties, which is always a key question in this type of impact studies integrating complex models. Comparison with other studies in Northern-European basins[6,14,15] confirms both the robustness of the summer response and the high uncertainty of future high-flows in winter. The latter is tightly related to the large uncertainty margin of precipitation change, which is very likely the most uncertain component of climate change projections. Yet, the decrease of annual mean precipitation that is projected in this study can be seen as the best available projection in the Seine and Somme river basins, because it is consistent for many different state-of-the-art global climate change projections[1] and two downscaling methods based on different principles and validated against observations in the studied basins.

7 ACKNOWLEDGEMENTS

The work was supported by the research program “Gestion et Impacts du Changement Climatique” of the French Ministère de l'Ecologie, de l’Energie, du Développement Durable et de la Mer. We also thank Météo-France for the SAFRAN meteorological analysis.

REFERENCES

[1] IPCC, Working Group I, *Climate change 2007: the physical science basis*. 4th Assessment Report, Genève, (2007).

[2] A. Ducharne, F. Habets, M. Déqué, L. Evaux, A. Hachour, A. Lepaillier, T.Lepelletier, E. Martin, L. Oudin, C. Pagé, P. Ribstein, E. Sauquet, D. Thiéry, L. Terray, P. Viennot, J. Boé, M. Bourqui, O. Crespi, S. Gascoin and J. Rieu, *Impact du changement climatique sur les Ressources en eau et les Extrêmes Hydrologiques dans les bassins de la Seine et la Somme*, Rapport final du projet RExHySS, Programme GICC, 62 pp, (2009). http://www.sisyphe.jussieu.fr/~agnes/rexhyss/documents_rapport.php

[3] P. Quintana-Seguí P. Le Moigne, Y. Durand, E. Martin, F. Habets, M. Baillon, L. Franchisteguy, S. Morel and J. Noilhan, “The SAFRAN atmospheric analysis: Description and validation”, *J. Applied Meteorol. Climatology*, **47**, 92–107 (2008).

[4] M. Déqué, “Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: Model results and statistical correction according to observed values”, *Global Planet. Change*, **57**,16-26, doi:10.1016/j.gloplacha.2006.11. 030 (2007).

[5] J. Boé, L. Terray, F. Habets and E. Martin, "A simple statistical-dynamical downscaling scheme based on weather types and conditional resampling", *J. Geophys. Res.* **111**, D23106 (2006).

[6] A. Ducharne, C. Baubion, N. Beaudoin, M. Benoit, G. Billen, N. Brisson, J. Garnier, H. Kieken, S. Lebonvallet, E. Ledoux, B. Mary, C. Mignolet, X. Poux, E. Sauboua, C. Schott, S. Théry, and P. Viennot, "Long term prospective of the Seine river system: Confronting climatic and direct anthropogenic changes", *Sci. Total Environ.*, **375**, 292-311, doi:10.1016/j.scitotenv.2006.12.011 (2007).

[7] E. Ledoux, E. Gomez, J.M. Monget, C. Viavattene, P. Viennot, A. Ducharne, M. Benoit, C. Mignolet, C. Schott and B. Mary, "Agriculture and Groundwater Nitrate Contamination in the Seine Basin. The STICS-MODCOU modelling chain", *Sci. Total Environ.*, **375**, 33-47, doi:10.1016/j.scitotenv.2006.12.002 (2007).

[8] F. Habets, A. Boone, J.L. Champeaux, P. Etchevers, L. Franchistéguy, E. Leblois, E. Ledoux, P. Le Moigne, E. Martin, S. Morel, J. Noilhan, P. Quintana-Segui, F. Rousset-Regimbeau and P. Viennot, "The SAFRAN-ISBA-MODCOU hydrometeorological model applied over France", *J. Geophy. Res. D*, **113**, D06113(2008)18 (2008).

[9] S. Gascoin, A. Ducharne, P. Ribstein, M. Carli and F. Habets, "Adaptation of a catchment-based land surface model to the hydrogeological setting of the Somme River basin (France)", *J. Hydrol.* **368**(1-4), 105-116, doi:10.1016/j.jhydrol.2009.01.039 (2009).

[10] D. Thiéry and C. Moutzopoulos, "Un modèle hydrologique spatialisé pour la simulation de très grands bassins : le modèle EROS formé de grappes de modèles globaux élémentaires". In : *VIIIèmes journées hydrologiques de l'ORSTOM "Régionalisation en hydrologie, application au développement", Le Barbé et E. Servat (Eds.),* ORSTOM Editions, pp. 285-295 (1995).

[11] C. Perrin, C. Michel, and V. Andréassian, "Improvement of a parsimonious model for streamflow simulation", *J. Hydrol.*, **279**(1-4): 275-289 (2003).

[12] M. Déqué, D.P. Rowell, D. Lüthi, F. Giorgi, J.H. Christensen, B. Rockel, D. Jacob, E. Kjellström, M. de Castro and B. van den Hurk, "An intercomparison of regional climate simulations for Europe: assessing uncertainties in model projections", *Clim. Change*, doi:10.1007/s10584-006-9228-x (2007).

[13] E. Sauquet, M.H. Ramos, L. Chapel, and P. Bernardara, "Stream flow scaling properties: investigating characteristic scales from different statistical approaches", *Hydrol. Proc.*, **22**(17), 3462-3475, doi: 10.1002/hyp.6952 & Erratum doi: 10.1002/hyp.7192 (2008).

[14] P. Goderniaux, S. Brouyère, H.J. Fowler, S. Blenkinsop, R. Therrien, P. Orban, and A. Dassargues, "Large scale surface–subsurface hydrological model to assess climate change impacts on groundwater reserves", *J. Hydrol.* **373**, 122-138, doi:10.1016/j.jhydrol.2009.04.017 (2009).

[15] R. Dankers and L. Feyen, "Climate change impact on flood hazard in Europe: An assessment based on high-resolution climate simulations", *J. Geophys. Res.* **113**, D19105, doi:10.1029/2007JD009719 (2008).