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CLIMATE CHANGE IMPACT ASSESSMENT FOR A SMALL RIVER BASIN USING A PROCESS-BASED NUMERICAL MODEL OF COUPLED SURFACE WATER/GROUNDWATER FLOW

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ABSTRACT We present an assessment of the sensitivity of hydrologic response (river discharge, aquifer recharge, and soil water storage) to future climate conditions using a fully coupled numerical model of surface and subsurface flow. The study area is the Des Anglais River basin located in southwestern Quebec, Canada. The future climate projection (2041-2070) is constructed by applying to an observed daily dataset (1961-1990) a monthly deviation factor extracted from projections generated by the Canadian Regional Climate Model (CRCM). Results comparing projections obtained with the land surface scheme that is coupled to the CRCM model to those obtained with the coupled surface/subsurface model are also presented for both past and future periods.

Keywords: Climate change, groundwater modeling, surface/subsurface interactions, land surface models.

INTRODUCTION Assessing climate change impacts on freshwater resources requires analysis of important hydrodynamic feedbacks between the land surface, soil, and groundwater zones. This analysis is best addressed with detailed, distributed-parameter numerical models that represent the feedbacks in a physically consistent manner. In this work a coupled, process-based model of surface water and groundwater flow is applied to a medium-sized catchment (690 km^2) in order to investigate climate change impacts on both aggregated and distributed measures of hydrologic response.

STUDY AREA The des Anglais river basin (Figure 1) has a drainage area of 690 km^2 and an average discharge of 300 x 10^6 m^3 per year at its outlet. It is the largest sub-catchment of the transboundary Chateauguay River watershed, and has an elevation range from 30 m to 400 m. The aquifer system is part of the St. Lawrence Lowlands and consists of Cambrian to Middle Ordovician sedimentary rocks that are slightly deformed and fractured. Unconsolidated sediments of glacial and post-glacial origin overlie the bedrock aquifer and are of varying thickness, reaching 40 m in the northernmost portion.

These sediments are in turn overlain by Quaternary deposits of silty till (Côté et al., 2006). The study area belongs to the Great Lakes and St. Lawrence climate region, characterized by a semi-humid climate with cold winters and humid summers. The annual mean temperature is 6.3 °C, with monthly variations from -10°C in January to 20°C in July (Environment Canada, 2004). The average annual precipitation is 958 mm.

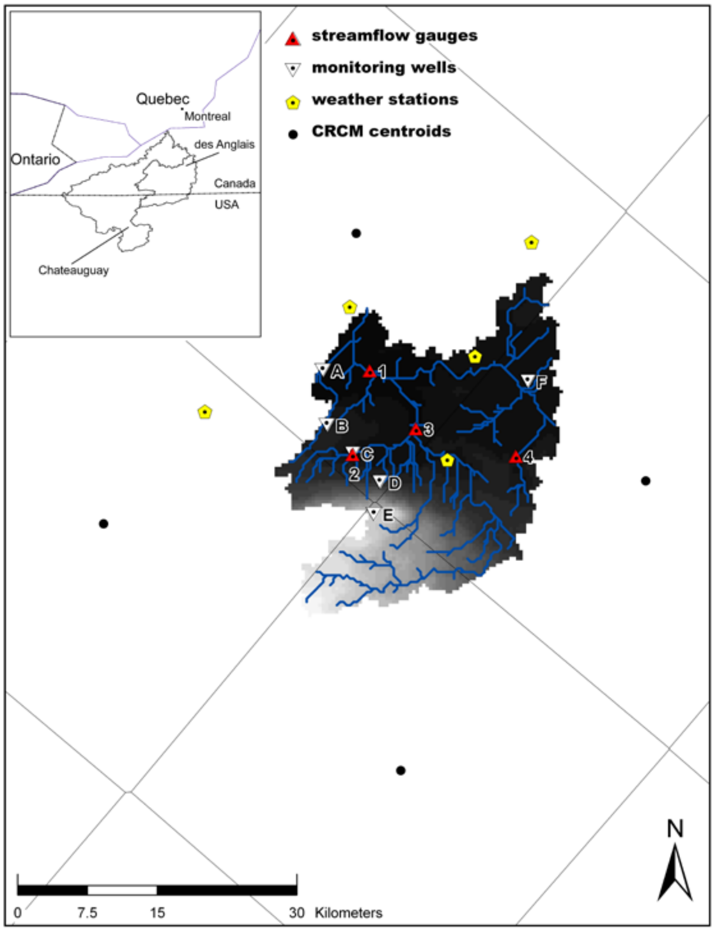

Figure 1. Topographic map of the des Anglais river basin (highest elevations in light grey) showing the network of weather stations, streamflow gauges, and monitoring wells, and the centroids of the CRCM grid with their Thiessen polygons.

SIMULATION MODELS CATHY (CATchment HYdrology; Camporese et al., 2010) is a coupled groundwater/surface water model based on resolution of a one-dimensional diffusion wave approximation of the St. Venant equation for overland and channel routing nested within a solver for the three-dimensional equation for subsurface flow in variably saturated porous media (i.e., Richards equation). Surface runoff is propagated through a 1D drainage network of rivulets and channels automatically extracted by a digital elevation model (DEM)-based pre-processor and characterized using hydraulic geometry scaling relationships. A boundary condition switching procedure is used to partition potential (atmospheric) fluxes into actual fluxes across the land surface and changes in surface storage. This scheme resolves the coupling term in the CATHY equations that represents the interactions between surface and subsurface waters.

The Canadian Regional Climate Model (CRCM) is a limited area, three-dimensional, nested grid–point atmospheric model based on the fully elastic nonhydrostatic Euler equations (Music and Caya, 2007). The model is run over a regional domain (on typical scales of 100s to 1000s of kilometers) cast on a horizontal grid that is uniform on a polar stereographic projection. A typical horizontal resolution is 45 km. Time-dependent data are provided at the lateral boundaries of the regional domain by reanalyses of observational data or GCM output at coarser horizontal resolutions. The vertical resolution is variable and uses a Gal-Chen scaled terrain following vertical coordinate.

Within the CRCM, turbulent exchanges of energy, water, and momentum at the surface–atmosphere interface are computed by the Canadian LAnd Surface Scheme (CLASS), a physically-based soil–snow–vegetation land surface scheme (Verseghy et al., 1993). CLASS uses an explicit representation of temperature and liquid and frozen soil moisture for three soil layers (a 10 cm surface layer, a 25 cm vegetation root zone layer, and a 3.75 m deep soil layer). CLASS solves the one-dimensional Darcy equation for vertical fluid flow in porous media and thermal conduction equations for soil temperatures. When the infiltration capacity is exceeded, water is considered to be ponded at the surface up to a maximum surface retention capacity, which varies according to land cover, and beyond which surface runoff occurs. Subsurface runoff is simulated as a "bottom drainage" from the deepest soil layer, parameterized via an empirical power relation linking the saturated hydraulic conductivity and volumetric liquid water content.

RESULTS The CATHY model was calibrated against daily streamflow measured close to the outlet of the catchment (gauge 1 in Figure 1) for a 1-year simulation period (Oct 2001–Oct 2002). The model was then verified for different simulation periods between Oct 2002 and Jan 2006 against daily streamflow measured at the outlet and at three internal stations (gauges 2, 3, and 4 in Figure 1), as well as against daily groundwater level data at the six monitoring wells shown in Figure 1. Once calibrated and tested, the model was run on the 30-year past and future atmospheric datasets.

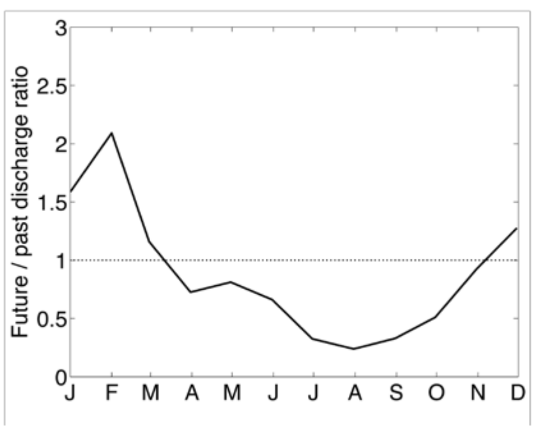

Figure 2. Ratio of mean monthly discharge simulated under future climate conditions to mean monthly discharge simulated under the past climate.

Climate change impacts In Figure 2 the ratio of the mean monthly discharge (mmd) at the outlet for the 2041-70 period to the mmd for the 1961-90 period is plotted. Climate change impacts are more significant during the peak winter (Jan-Feb) and summer (Jul-Aug) months, with a strong increase in future discharge in winter and a strong decrease in summer. The winter effect is due to the combination of more precipitation and higher temperatures, which increases the proportion of rainfall to snowfall. Higher temperatures also lead to a reduction in snow cover, resulting in a shift in spring freshet from April to March and a decrease in streamflow during the spring season. In the summer, the strong decrease in river discharge is the result of a slight decrease in total precipitation combined with a marked increase in evaporation due to higher temperatures.

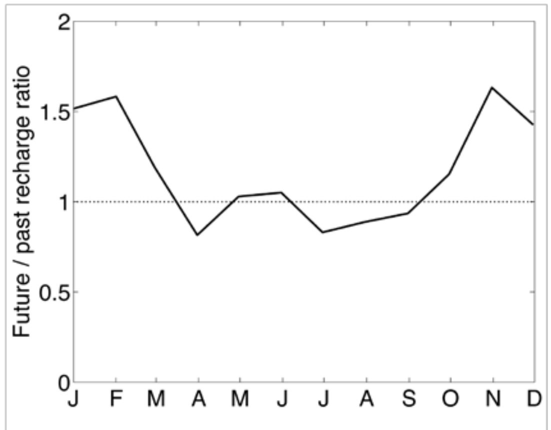

Figure 3. Ratio of mean monthly total recharge simulated under future climate conditions to mean monthly total recharge simulated under the past climate.

In Figure 3 the future/past ratio of mean monthly total recharge is plotted. The aquifer of the des Anglais basin receives most of its recharge in the spring and fall through snowmelt and heavier rainfall, respectively. Projected climate change results in a significant increase in winter season recharge due to a higher rain/snow ratio caused by higher temperatures, less recharge in the spring due to an earlier and less intense snowmelt, a general decrease over the summer due to increased evaporation, and an increase in the fall due to increased precipitation.

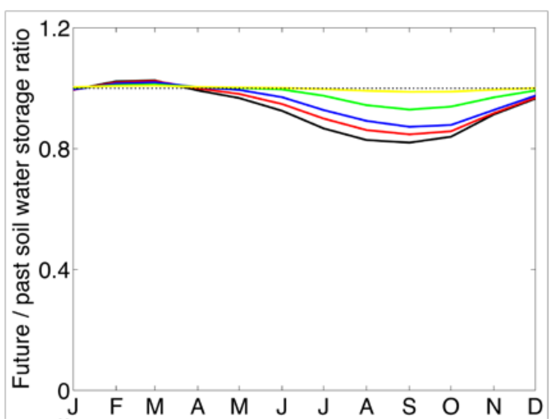

Figure 4. Ratio of mean monthly soil water storage simulated under future climate conditions to mean monthly soil water storage simulated under the past climate: 0.05 m depth (black line); 0.15 m depth (red line); 0.45 m depth (blue line), 0.90 m depth (green line), 2.0 m depth (yellow line).

In Figure 4 the future/past ratio of mean monthly soil water storage is plotted at 5 different soil depths. Compared to water fluxes across a point or boundary (discharge at a catchment outlet in Figure 2 and recharge across the water table in Figure 3), water storage volumes seem to be less sensitive to climate change. The impacts are most strongly felt nearest to the surface, which is directly exposed to variations in precipitation and evapotranspiration, and are progressively dampened as soil depth increases. In terms of intra-annual dynamics, the patterns are nonetheless similar to those observed for recharge and discharge, with all soil depths displaying a decrease in subsurface storage during the summer period and an increase (albeit very slight) over the peak winter and early spring months.

Comparison of CATHY and CLASS models The CRCM model, with CLASS internally coupled to its atmospheric part, was used to provide predictions of runoff and soil water storage for the past and future climate simulations at the CRCM grid scale (the 4 grid points shown in Figure 1). With appropriate averaging to ensure consistency, these outputs were compared to results produced by the CATHY model over the des Anglais river basin and at its outlet.

Mean monthly runoff for the past and future periods is shown in Figure 5. CLASS produces higher estimates of surface and subsurface runoff throughout the annual cycle for both past and future simulations, with the greatest difference occurring at peak flow during snowmelt. Monthly soil water storage within each of the three CLASS layers is shown in Figure 6. CLASS and CATHY are in general agreement in terms of the intra-annual variability of moisture content in the first two soil layers, particularly for the top layer where water variations are most directly affected by rainfall events and diurnal temperature changes. The largest differences between the two models occur in the third layer, with CATHY predicting wetter soil conditions over the entire simulation period and moisture fluctuations of much smaller amplitude.

Further analysis A more detailed report on the results presented here, together with additional analyses, can be found in Sulis et al. (2010).

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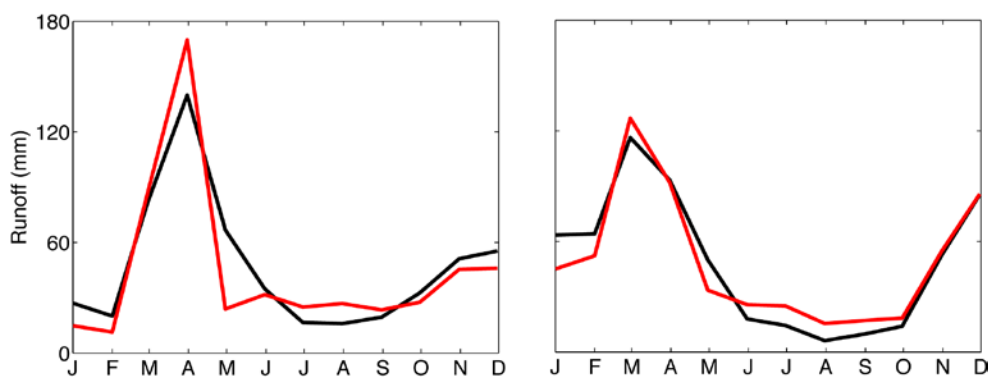

Figure 5. Mean monthly runoff for the past (left graph) and future (right graph) climate change projections: CLASS surface and subsurface runoff (red line); CATHY catchment outlet discharge (black line).

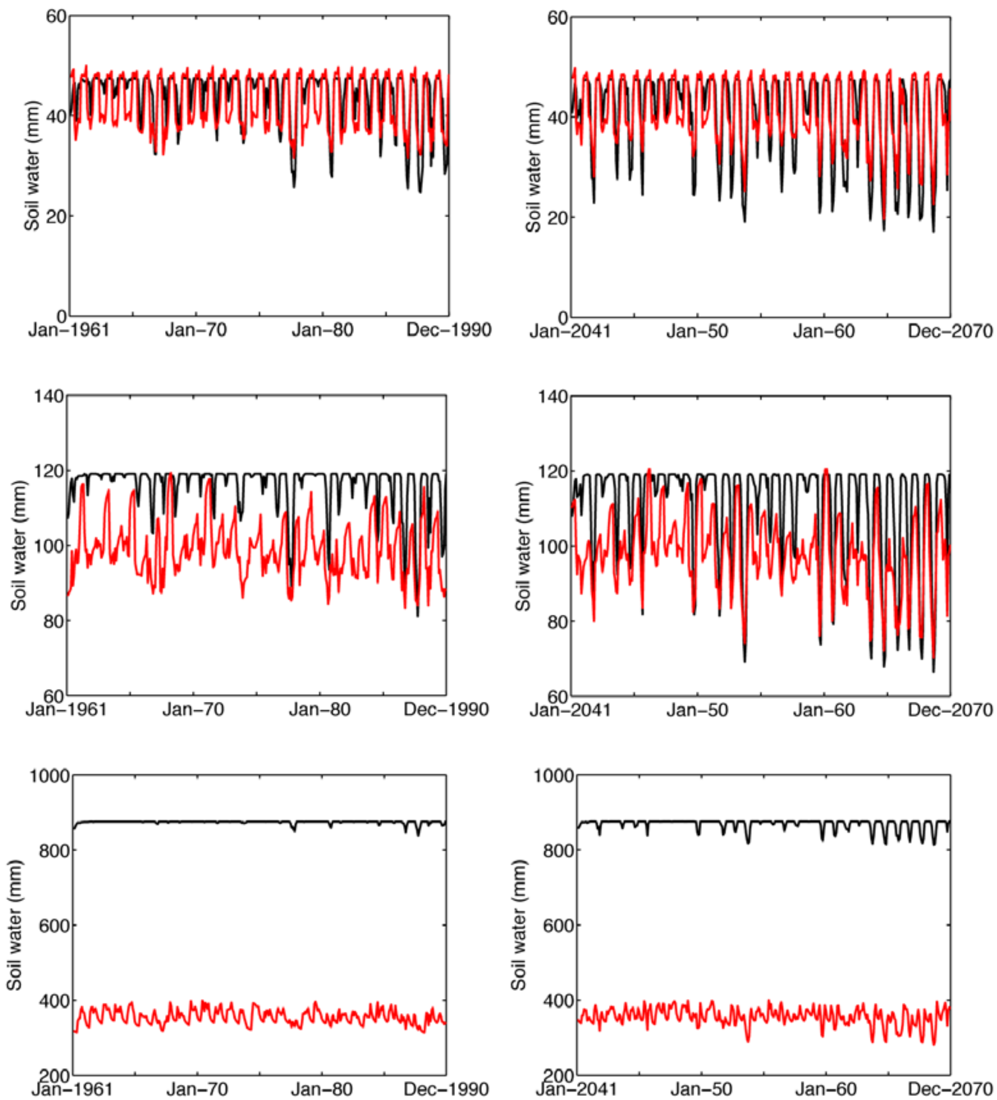

Figure 6. Monthly soil water content in the 0–0.10 m (top graphs), 0.10–0.35 m (middle graphs), and 0.35–4.10 m (bottom graphs) CLASS layers for the past (left graphs) and future (right graphs) climate change projections: CLASS (red line), CATHY (black line).

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