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Inverse Modelling of Climatic Change Impacts in the Upper Thames River Basin

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Abstract: Many climate change impact studies have been conducted using a top-down approach. First, outputs from Global Circulation Models (GCMs) are considered which are downscaled in a second step to the river basin scale using either a statistical/empirical or a dynamic approach. The local climatic signal that is obtained is then used as input into a hydrological model to assess the direct consequences in the basin. Problems related to this approach include: a high degree of uncertainty associated with GCM outputs; and an increase in uncertainty due to the downscaling approach. Serious effort is required to validate the GCM outputs and the downscaling techniques. Therefore, the hydrologic system itself, and its general vulnerability, are often not sufficiently studied. An inverse approach is presented here in order to improve the understanding of the processes leading to hydrological hazards, including both flood and drought events. The inverse approach starts with the analysis of existing guidelines and management practices in a river basin with respect to critical hydrological exposures that may lead to failure of the water resources system or parts thereof. At this step, vulnerable components of the river basin are identified together with the risk exposure. In the next step the critical hydrologic exposures are transformed into corresponding critical meteorological conditions. These local weather scenarios are then statistically linked to possible large-scale climate conditions that are available from the GCMs. The results of the analyses are used to provide three sets of recommendations for changing current basin management guidelines: (i) regulatory (review of rules, regulations and operation procedures for existing water management infrastructure); (ii) budgetary (investment in new infrastructure and increase in cost of operating existing facilities); and (iii) engineering (review of current design standards and practices).

1. Introduction

The potential impacts of climate change on water availability and the regime of hydrologic extremes have received considerable attention from hydrologists during the last several years. There is a scientific consensus that the global warming will increase the frequency of extreme atmospheric and hydrologic events. Climate change may also alter the timing of extreme runoff. In many areas where snowfall is currently an important component of the water balance peak streamflow is likely to move from spring to winter. Changes in the frequency and timing of extreme events may be one of the most significant consequences of climate change.

The present tools for modeling the climate change impacts on basin hydrologic processes involve a number of uncertainties. At a global scale, different global circulation models (GCMs) produce different predictions for a given climate change scenario, leading to large divergence in the estimated impacts. At a local scale, physical properties of river basins, and other concurrent basin changes (land use, reservoirs, stream channelling, drainage) also play an important role in the impact variability, generating large regional differences in the basin responses to climate change.

Another important issue in the impact modeling is the identification and separation of natural low-frequency hydro-climatic variability from the systematic change attributed to global climate change. Probability distributions of hydrologic variables exhibit inter-annual, inter-decadal, and longer variations depending on the underlying climate state. Even by the 2050s the effect of climate change on streamflow is often found within the range of natural multi-decadal climate variability.

Incompatibility between temporal scales of GCM outputs and hydrologic models is another limitation in the modeling of climate change impacts on hydrologic processes. Usually short time steps are used to model rainfall-runoff events. However, current GCMs cannot simulate with adequate accuracy short-duration, high-intensity rainfall events. In fact, there is little confidence in the predictions from GCMs for time steps shorter than 1 month. Thus, most impact studies on floods use monthly GCM outputs temporally downscaled into shorter time steps, assuming that the change in mean monthly rainfall is representative of the change in short-duration rainfall. However, some recent studies demonstrated that the extreme rainfall frequency distribution derived from GCM perturbed daily rainfall data is flatter, showing low variability in the extreme rainfall than the distribution of observed daily rainfall data.

The discrepancy between GCM and river basin spatial scales is yet another important source of modeling uncertainty. At present, the spatial resolution of GCM projections is between 3-5° in latitude and 5-10° in longitude. Such resolution is too coarse to capture many important small-scale hydro-climatic processes. As a consequence, GCMs cannot adequately replicate the historic climate of many regions. Some comparative studies based on nine GCM runs evaluated their ability to simulate the magnitude and spatial variability of current temperature and precipitation, and demonstrated considerable variability for the different model simulations.

Finally, GCM simulation is a single realization of many possible climatic futures. Exploring a whole spectrum of alternative climate scenarios would be more useful for effective management of water resource systems. The uncertainty of the GCM outputs can be reduced using an ensemble of simulations, rather than one single experiment result. For now however, GCMs remain to be the principal tools for the detailed modeling of the future climate, and the key challenge to hydrologists is to express the GCM results at a scale more relevant to hydrologic studies.

Climate change impact studies are traditionally conducted using a top-down approach. In the top-down approach, outputs from GCMs are statistically or dynamically downscaled to the river basin scale. The local climatic signal is then used as an input into a hydrologic model to assess the direct consequences in the basin. As the top-down approach moves from the global spatio-temporal scale towards the local scale, the modeling uncertainty increases at each step of the process, reaching its maximum at the end-user level. As a consequence, the end-users (river basin authorities, water resource managers, stakeholders) are often skeptical regarding the possible adverse impacts of climate change.

2. Inverse Modelling of Climate Change Impacts on the Watershed Scale

This paper presents an innovative approach for climate change modelling on the watershed scale developed within the project 'Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions' supported by CFCAS (FIDS, 2003). The inverse impact modeling approach is aimed at assessing the vulnerability of river basin hydrologic processes to climate forcing from a bottom-up perspective. It is illustrated in Figure 1. The approach consists of the following four steps:

(i). Identification of critical hydrologic exposures that may lead to local failures of water resource systems in a particular river basin. Critical exposures are analyzed together with existing guidelines and management practices. The vulnerable components of the river basin are identified together with the risk exposure. The water resource risk is assessed from three different viewpoints: risk and reliability (how often the system fails), resiliency (how quickly the system returns to a satisfactory state once a failure occurred) and vulnerability (how significant the likely consequences of a failure may be). This step is accomplished in collaboration with local water authorities.

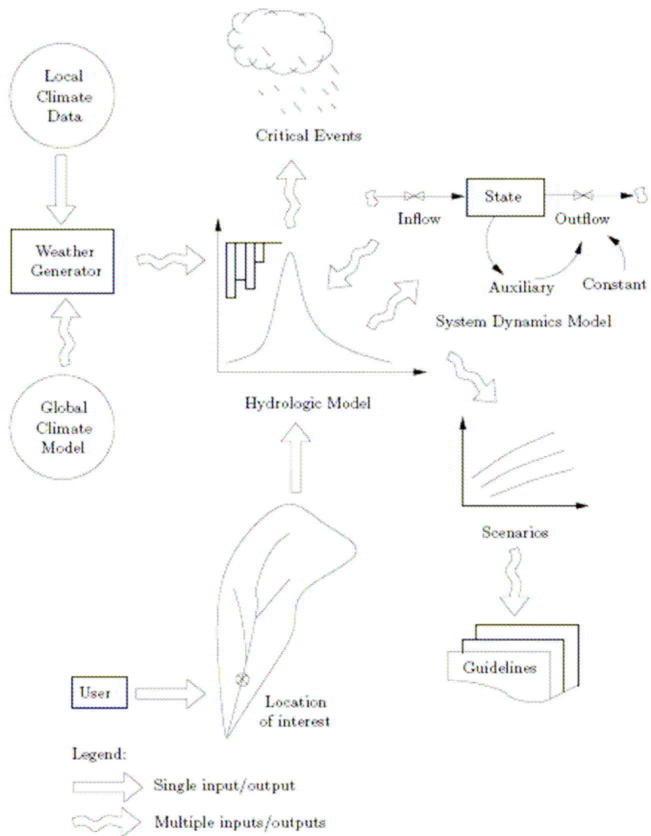

Figure 1. Schematic presentation of the inverse approach

(ii). In the next step, the identified critical hydrologic exposures (such as floods and droughts) are transformed into corresponding critical meteorological conditions (e.g. extreme precipitation events, sudden warming, prolonged dry spells). A hydrologic model (Cunderlik and Simonovic, 2007a) is used to establish the inverse link between hydrologic and meteorological processes. Reservoir operation, flood-plain management and other anthropogenic interventions in the basin are also included in the model.

(iii). A weather generator (WG) is used to simulate the critical meteorological conditions under present and future climatic scenarios (Sharif et al., 2007). The weather generator produces synthetic weather data that are statistically similar to the observed data. Since the focus is mainly on extreme hydrologic events, the generator reflects not only the mean conditions, but also the statistical properties of extreme meteorological events.

(iv). In the final stage, the parameters of WG are linked with GCMs and an ensemble of simulations reflecting different future climatic conditions is generated. The frequency of critical meteorological events causing specific water resources risks is then assessed from the WG outputs (Prodanovic and Simonovic, 2007a).

The presented approach can be used for the development of hazard risk management strategies under present and future climatic conditions for any water resource system. The main advantages of the inverse approach over the traditional top-down approach are: (a) focus on specific existing water and potential water resource problems; (b) direct link with the end-user; and (c) easy updating, when new and improved GCM outputs become available.

3. Modelling Climate Change Impacts in the Upper Thames River Basin

3.1 Description of the Upper Thames River Basin

The majority of the Upper Thames River basin (located in south-western Ontario) consists of agricultural lands (80%), while forest cover and urban uses take about 10% each. Basin's land area is approximately 3,500 km^2. The population of the basin is about 450,000, of which approximately 350,000 are residents of the City of London, the largest urban center in the basin (Figure 2). Other urban centers are those of Mitchell, St. Marys, Stratford, Ingersoll and Woodstock. The region is divided into three counties: Perth to the north, Oxford to the east, and Middlesex to the west.

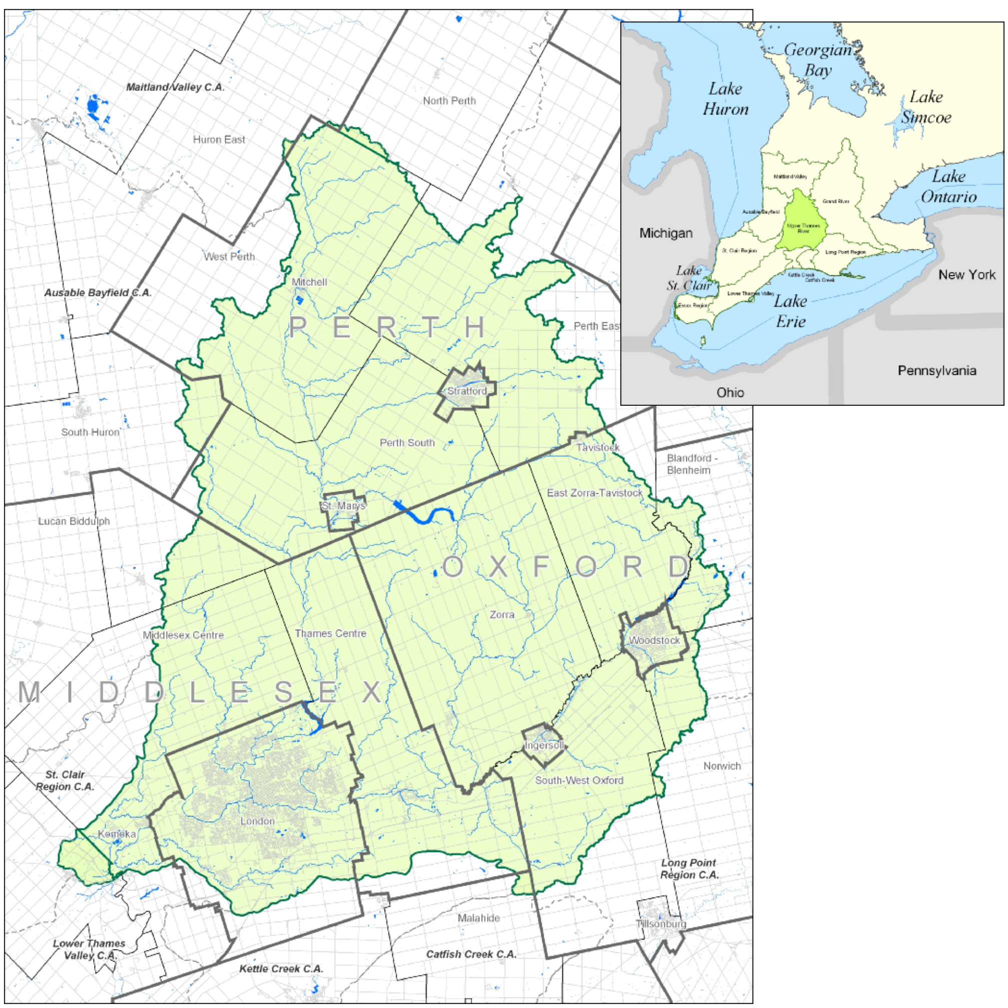

Figure 2. The Upper Thames River Basin

The Upper Thames River basin consists of two major tributaries of the river Thames: the North Thames River, flowing southward through Mitchell, St. Marys, and eventually into London, and the Thames River (South Branch), flowing through Woodstock, Ingersoll, and east London. The two branches meet in London near the centre of the city, referred to as the Forks. The Thames then flows westwards and exits the basin near Delaware (15 km west of London), eventually draining into Lake St. Clair. The length of the Thames River (from Tavistock to its mouth at Lake St. Clair) is approximately 273 km, while its annual discharge (measured at the Byron stream gauge) is about 41 m^3/s. The Upper Thames River basin receives about 1,000 mm of annual precipitation, 60% of which is lost through evaporation and/or evapotranspiration, stored in ponds and wetlands, or recharged as groundwater. The slope of the Thames River is about 1.9 m/km for most of its upper reaches, while its lower reaches are much flatter with a slope of less than 0.2 m/km.

The Upper Thames River basin includes three major water management reservoirs: Wildwood (completed in 1965), Pittock (completed in 1967) and Fanshawe (completed in 1952) near St. Marys, Woodstock and London, respectively. The three reservoirs were constructed primarily for flood control purposes, with Wildwood and Pittock also designed and used for low flow augmentation. Since their construction, the purposes of all three reservoirs have expanded to include recreational uses. Other major flood management infrastructure in the Upper Thames River basin includes extensive dyking systems in the cities of St. Marys and London, as well as a diversion channels in the towns of Ingersoll, Stratford and Mitchell.

Floods represent major hydrologic hazards in the Upper Thames River basin. On average, 25% of all floods occur during March, while more than 50% of all floods happen between February and April (Cunderlik and Simonovic, 2007b). Early springs therefore see basin wide floods resulting from sudden warming and snowmelt on a yearly basis. Times between December and April may also see severe floods resulting from a combination effect of snowmelt and intensive precipitation. Summer frontal storms are also known to produce severe flooding in and around the basin, but such storms are less frequent—even though their magnitude can (sometimes significantly) exceed springtime flooding. In fact, some of the highest observed floods have occurred during the summer months.

Drought conditions in the Upper Thames River basin are possible at any time of the year, although they are most frequent between the months of June and September. In the summer months the mean monthly flows are in the order of 25 to 30% of long term annual mean flow. As a reference, mean monthly flows in spring time are as large as 300% of the mean annual value (Cunderlik and Simonovic, 2005). During the summer months a large percentage of baseflow in area rivers (located in the vicinity of sewage treatment plants) consists of treated effluent. As the Thames River is defined by Ontario's Ministry of Environment as a watercourse with total phosphorous concentration below the minimum provincial standard, water quality during the course of low flow often becomes a problem.

3.2 Critical Hydrologic Exposures

The first step in the application of the inverse approach involves identification of the critical flood exposures within the area under consideration. In consultation with the Upper Thames River Conservation Authority the information in Table 1 has been assembled. Similar information has also been obtained for other locations in the basin, but are not presented here (Prodanovic and Simonovic, 2007b; 2007c). The entries have been taken from a local flood time operations manual, and show either exposures, or required course of action government (and other) officials need to take. One of the objectives of this analysis is to show how the frequency of occurrence of such exposures might shift with a changing climatic signal.

In consultation with the Upper Thames River Conservation Authority, as well as meeting with various stakeholders in the basin, it was established that critical drought exposures (although acknowledged as real and possibly threatening) do not play a major role in current water resources management practice. One of the reasons for this is that impacts from severe droughts have not been felt in this area for quite some time; studies of agricultural and other drought related damage for this area is virtually non-existent. Drought damage is further masked by widespread use and availability of water for agricultural, industrial, commercial, and residential purposes, especially in the County of Oxford where water use is highest in the region.

In Ontario, in 1999, a program - Ontario Low Water Response (OLWR) - was established to respond to low water conditions in watersheds across the province. The program outlines specific definitions on how droughts are defined in the province, and how different severity of low water conditions are addressed (OLWR, 2003). Based on these drought definitions, information in Table 2 is presented, and serves to identify drought related hydrologic exposures as they relate to less than normal streamflow conditions.

Table 1. Critical flood exposures at the Byron stream gauge (after Prodanovic and Simonovic, 2007b)

Peak Flow (m^3/s)	Flood Exposure
285	Boating restrictions on the Thames
350	Flooding of grazing areas at Dellaware Flats
460	Water over-tops banks at the forks
565	City commences patrolling river banks
600	Greenway park near Lombardo Bridge begins to flood at shallow depths
840	Top of dyke—Old Bridge Road, Byron
970	Greenway park near sewer treatment plant flooded
990	Top of London's dykes
1080	Flooding of homes at end of Evergreen and Riverside Avenues near Wharncliffe Bridge
1260	Pumping station near Springbank park flooded
1300	Flooding of Wonderland Gardens and adjacent property
1420	Riverside Drive / Wonderland Road intersection inundated
1640	Sewer treatment plant building floods
1700	Property flooding on east side of Wonderland Road north of Riverside Drive

Table 2. Critical drought exposures in the Upper Thames River Basin (after OLWR, 2003)

Monthly Streamflow	Level†	Drought Exposure
Less than 70 % of lowest average summer month	I	Potential water supply problems; Request volontary conservation; Ask for 10 % reduction in water use; Inform media of drought conditions.
Less than 50 % of lowest average summer month	II	Minor supply problems, but potential for major problems; Request volontary conservation of additional 10% and impose restrictions; Contact major water users; Limit new water use permits; Monitor and enforce complience with existing permits; Modify reservoir operations.
Less than 30 % of lowest average summer month	III	Supply fails to meet usual demand; Social and economic impacts; Impose maximum conservation, restriction, and regulation; Reduce water permit levels; Set and institute water use priorities; Enforce water use; Consider hauling water.

3.3 Weather Generator

The weather generator model (Sharif et al., 2007) used in this study takes daily historical climate information for a number of weather stations as input, and generates an arbitrary long period of record statistically similar to the historic data—referred to as the historic climate. Other climates are generated by various perturbation mechanisms that force the weather generator to produce climatic information based on outputs from latest global circulation models as well as locally observed climatic data. Three different climates are developed for use in the Upper Thames River basin. They include the historic climate, obtained by perturbing and shuffling locally observed data for years 1964-2001. Other climates (dry and wet) are based on IPCC scenarios: (a) a world with rapid *global* change towards service and information based economies, utilizing reductions of material intensity and use, together with the introduction of clean resource-efficient technologies; and (b) *local* solutions to economic, social and environmental well being with diverse technological change towards environmental protection and social equity at regional levels.

The emphasis in flood studies has been on basin response to short-duration high intensity precipitation, for which the hourly version of the generated weather was used. In the study of drought and low flows, daily version of the weather generator model is employed with precipitation and temperature as input.

3.4 Hydrologic Modeling

Two hydrologic models are developed for the implementation of the inverse approach (Cunderlik and Simonovic, 2007a). The event hydrologic model consists of thirty two spatial units (also called subbasins or subcatchments), twenty one river reaches, and three reservoirs. The basin representation of the model consists of three components (or methods) describing loss, transform and baseflow components. Since detailed evapotranspiration need not be made in event models, the loss components were modelled using the initial and constant method. The transform component is modelled using Clark's unit hydrograph, and the baseflow is represented using the baseflow recession method. River and reservoir routing is computed using the modified pulls method and storage-discharge curves provided by the Upper Thames River Conservation Authority.

The continuous hydrologic model is a semi-distributed rainfall-runoff model based on the computational engine of HEC-HMS (USAGE, 2000) using the soil moisture accounting algorithm to represent losses. The long term moisture characteristics of the Upper Thames River basin are captured by conceptually representing a region with a number of reservoirs, with water flowing between them. The following reservoirs are used: canopy, surface, soil, and various ground water storage reservoirs. The flows of water from and to the reservoirs include: precipitation (snow and/or rain), evapotranspiration, soil infiltration, percolation, ground water flow (interflow and baseflow), as well as ground water recharge.

3.5 Frequency Analyses

The precipitation and temperature data produced by the daily weather generator (for historic, wet and dry climates) is used as an input into the hydrologic model (Cunderlik and Simonovic, 2007). The output of the hydrologic model includes daily flow hydrographs for a number of stations in the study area (for historic, wet and dry climates), for which frequency analyses are performed. Gumbel and the Log Pearson III statistical distributions are employed to fit the hydrologic output data and produce frequency plots.

4. Climate Change Impacts in the Upper Thames River Basin

4.1 Main Impacts

Results of the analyses are illustrated in Figures 3 and 4. Figure 3 presents the results for one hydrologic exposure – the event that causes the dykes in London to over-top. From Table 1 we see that the corresponding flow is 990 m^3/s. After the implementation of the inverse approach we can observe that the recurrence intervals for this critical hydrologic exposure is 33 years under the historic climate, 17 years under conditions of wet climate, and 65 years under the dry climate.

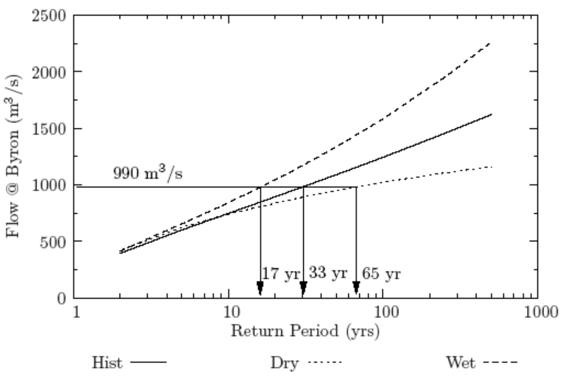

Figure 3. Climate change impact on flooding

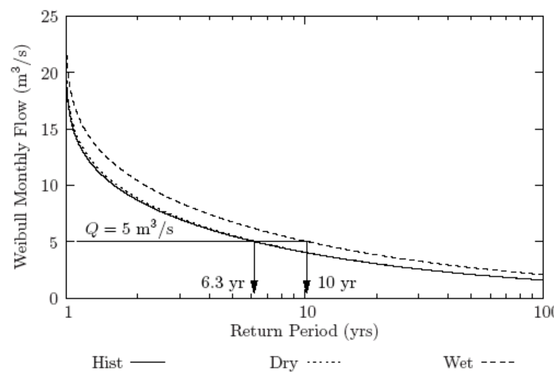

Figure 4. Climate change impact on drought

Figure 4 presents the results of drought and low flow analyses in the Upper Thames River basin. For one critical drought exposure – frequency of occurrence of level II drought (see Table 2) in the vicinity of the Greenway Pollution Control Plant in Byron we found the lowest average summer month flow to be 9.5 m^3/s. In order for level II drought to occur, the lowest average summer flow must drop to 50% of its average to approximately 5 m^3/s. After the implementation of the inverse approach we can observe that the recurrence intervals for this critical hydrologic exposure is 6.3 years under the historic climate, 10 years under conditions of wet climate, and 6.3 years under the dry climate.

In conclusion (a) the most critical simulation in the study of flooding (using the wet climate) indicates significant increases in frequency and magnitude of future flood events. Such changes lower the level of protection offered by current flood management infrastructure (dams, dykes, etc.), and are seen as a starting point towards formulation of new (and/or improved) flood management guidelines basin wide; and (b) the drier climate conditions obtained by the weather generator (and simulated with a continuous hydrologic model) do not show a tendency towards more extreme drought conditions. Despite this however, severe droughts are possible in the basin (with a return period of 10 years or less) and are not adequately addressed in the current management practice.

4.2 Practical Implications

Climate change impacts in the Upper Thames River Basin assessed through the implementation of the inverse approach indicate that some of the current guidelines and management practises may need revision. Flooding in the basin will occur more frequently causing higher potential property damage, and more frequent inconvenience flooding, such as roads overtopping. This is an impact of serious concern for flood damage centers across the watershed, including St. Marys, Mitchell, Ingersoll, and London. The changing climatic conditions are expected to increase flood damage in the future. The City of London has a number of flood management works, namely the Fanshawe Reservoir and an elaborate dyking system along the Thames River. These flood management works have been originally designed to provide safety to the city from damaging floods. As a result of climatic change, this infrastructure may in the future provide a lower level of safety than it has been originally designed for. For example the Fanshawe dam is designed to reduce downstream flooding, and the existing 1:100 year inflow of 941 m^3/s will be drastically reduced to 1:50 years as a result of the changing climate. Therefore, appropriate government officials may need to consider retrofitting or upgrading this and other existing flood management works in the basin, which will result in increased budgets for flood management operations. A further consequence of potentially changed climate is that current design standards for bridges, roads, sewers, drains, storm water facilities and other municipal infrastructure should be reviewed, in order to assess their ability to cope with the changing hydro-climatic conditions. The following presents a summary of issues regarding possible changes of flood management guidelines as a result of climatic change in the Upper Thames River Basin:

(a) *Regulatory.* Changing hydro-climatic characteristics imply that rules and regulations currently employed by the Upper Thames River Conservation Authority may need revision. This recommendation is supported by the analysis showing that floods of all magnitudes will increase in frequency of occurrence. Possible revisions of existing regulation include those pertaining to: (i) use of river and its adjacent park land for recreation (including boating, camping, swimming, fishing, jogging, etc.); (ii) removal of pumping stations near area rivers during the course of a flood (see Table 1); (iii) patrolling of river banks during periods of high water levels and monitoring performance of critical infrastructure (such as roads, bridges, culverts, drains, sewer systems); (iv) issuing of permits for the construction of such infrastructure for floodplain development (including construction of roads, buildings, bridges, culverts, drains, sewer systems, etc); (v) revision of reservoir operating procedures (including smaller dams, weirs, outflows, etc.).

(b) *Budgetary.* This set of guidelines look at possible changes in allocation of budgets for safe operation of existing flood management infrastructure, as well as budgetary constraints to be imposed by investment needed for future infrastructure still in the planning stages. Since floods will occur more frequently, so will the maintenance, retrofitting and upgrading of existing flood management infrastructure. An evaluation of current structural and non-structural measures used to reduce flood damage (such as reservoirs, dykes, floodwalls or implementation of land use zoning practises, flood warning systems, waterproofing, etc.) will need to take place. Next to changed maintenance budgets for existing infrastructure, a need will arise for investment in additional infrastructure to bring the flood protection to regulatory levels and meet the needs of the population.

(c) *Engineering.* Changes in this set of regulations aim to look at possible changes in design standards for municipal infrastructure (such as roads, buildings, bridges, culverts, drains, sewer systems, treatment plants, etc.). Changes are going to be necessary as climate change is expected to bring about changes in hydro-climatic conditions. Since current hydro-climatic conditions have been used to formulate today's design standards, it only follows that under changing conditions different standards should be set, or at least old ones comprehensively reviewed.

Four categories of recommendations are made regarding drought conditions in the Upper Thames River Basin:

(a) *Drought impact assessment.* Local and/or regional drought impact assessment are non-existent in the Upper Thames River Basin, in spite of the fact that severe droughts can occur with a probability of 1 in 10 and sometimes less for any given year. The first recommendation is that a drought impact assessment study be commissioned to assess drought impacts on: (i) agriculture; (ii) tourism and recreation; (iii) wetlands; (iv) reservoir operations; (v) ground water withdrawal; and (vi) streamflow water quality.

(b) *Local drought triggers.* Drought is a spatially variable phenomena, and therefore drought thresholds and/or triggers need to be locally defined and set on a sub-watershed scale. Emphasis should be placed on drought triggers of urban and rural areas, as urban residents (especially those receiving water from the Great Lakes) are often unaware of drought conditions. Furthermore, as physical and socio-economic conditions change in the basin (such as land development, population growth, water use patters, etc) so could the drought triggers. Careful long-term monitoring of such conditions is necessary as changes in drought triggers over time are possible. A flexible regulatory framework should be set to allow changes in definitions, should they be deemed necessary.

(c) *Water quality management.* Drought conditions contribute to lower water quality. As the Upper Thames River basin watercourses systematically experience water quality problems (particularly with total phosphorous loading) new regulations should be placed to monitor water quality. A review of all existing water quality guidelines should also take place and include a review of: (i) agricultural fertilizer use; (ii) storm water management techniques for current and future land development; (iii) combined sewer discharges; (iv) pollution control plant effluent strategies; and (v) landfill use practices, including solid waste management.

(d) *Education programs.* Increasing awareness of drought conditions and their potentially devastating impacts on people, plant and animal life is seen as paramount to the sustainability of the natural environment. Novel educational programs (targeting water resources managers and practitioners, municipal and other government officials, farmers, as well as the general public) are urgently needed. The following set of initiatives are suggested to achieve greater awareness of droughts and its adverse impacts: (i) enhance communication of current drought conditions (including specific goals and targets, and practical means to achieve them); (ii) introduce smart water use techniques (using new technology and modifying long held beliefs that water is a limitless resource); and (iii) enhance interactions between socio-economic and physical domains (emphasizing a systemic approach where a realization that structure of socio-economic systems has just as much to do with drought as current climatic and/or physical conditions).

5. Conclusions

Original inverse approach to assessment of climate change impacts on watershed scale has been presented and implemented in the Upper Thames River Basin in south-western Ontario. The approach identifies critical hydrologic exposures that may lead to local failures of existing water resource systems. The critical exposures, such as floods and droughts, are then inversely transformed into corresponding meteorological conditions by means of hydrologic models. The hydrologic models are linked with future climate scenarios generated by a weather generating algorithm coupled with outputs from global circulation models. The results of the assessment showed that under the dry scenario the critical rainfall events may occur with approximately the same frequency and under the wet scenario more frequently than they occur under the present conditions. According to the evaluated scenarios, climate change may have beneficial impacts on the distribution of hydrologic extremes in the study area. The future regime of maximum flows in the basin can be characterized as less extreme in terms of magnitude, and more variable in terms of both occurrence and magnitude. Low flows may become less extreme, less variable in terms of magnitude, and more irregular in terms of occurrence. Conclusions of the climate change impact assessment are converted into a set of suggestions for possible modification of water management guidelines in the basin.

6. Acknowledgments

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