An impending water crisis in Canada's western prairie provinces

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Canada is usually considered to be a country with abundant freshwater, but in its western prairie provinces (WPP), an area 1/5 the size of Europe, freshwater is scarce. European settlement of the WPP did not begin until the late 19th and early 20th centuries. Fortuitously, the period since European settlement appears to have been the wettest century of the past two millennia. The frequent, long periods of drought that characterized earlier centuries of the past two millennia were largely absent in the 20th century. Here, we show that climate warming and human modifications to catchments have already significantly reduced the flows of major rivers of the WPP during the summer months, when human demand and in-stream flow needs are greatest. We predict that in the near future climate warming, via its effects on glaciers, snowpacks, and evaporation, will combine with cyclic drought and rapidly increasing human activity in the WPP to cause a crisis in water quantity and quality with far-reaching implications.

climate warming | eutrophication | freshwater supplies

Most global studies rank Canada among the top five countries in terms of per-capita water supplies (1, 2). But these rankings are deceptive, because of the great size of the country, the regional variability in water supply, and the concentration of Canada's population near its southern border. Canada's western prairie provinces (WPP; Fig. 1) have an area of ≈2 million km^2. The WPP lie in the rain shadow of the Rocky Mountains. As a result, they are the driest large area of southern Canada.

Despite the warnings of Captain John Palliser that water was scarce and land was poor (3), the WPP were settled by European immigrants in the late 19th and early 20th centuries. Hardships were severe, particularly in the "dirty 30s," when drought combined with unsuitable land practices to create "dust bowl" conditions throughout western North America (4). From 1998 through 2004, unusually warm temperatures combined with low precipitation and grasshopper plagues to devastate agriculture in the WPP. This recent drought was more severe than in the dirty 30s, when 7.3 million hectares of agricultural land were affected and 250,000 people left the Canadian prairies (5), although improved modern farming practices have greatly reduced the effects on land erosion.

Drylands such as the WPP have been identified by the Millenium Ecosystem Assessment (www.MAweb.org) as "hotspots" for future environmental degradation, because of the combined effects of climate warming and human activity. The WPP are relatively data-rich compared with other dryland areas of the world, and we believe that our analysis provides a case history for what is becoming a much more widespread global problem. Furthermore, Canada is a country with considerable resources available for addressing the problem of protecting freshwater supplies under a changing climate. It should be able to provide leadership and methodology for managing dryland areas in less fortunate parts of the world.

Droughts in Earlier Centuries

Air temperature and precipitation in the WPP have been measured only since the late 19th or early 20th centuries, when European settlers occupied the area. Although residents think of the weather and climate of the 20th century as "normal," recent paleoecological studies suggest otherwise. Climate proxies, including both tree rings (6) and salinity-sensitive diatoms (7), indicate that the climate was unusually stable and moist in the WPP in the 20th century (8). Similar findings have been reported for the western United States (9). In earlier centuries, several droughts per century were common, lasting as long as several decades. According to the same proxy indicators, even the droughts of the 1930s and the past few years are relatively mild when considered in a historical context.

Records from the Hudson's Bay and Northwest companies verify paleoecological conclusions that numerous droughts more severe than any of the 20th century occurred in the 18th and 19th centuries. Problems described include those of declining water supplies and limited transportation, in a time when prairie rivers were critical arteries for travel to central and eastern Canada (6). Even in the moist mid-20th century average annual potential evapotranspiration (PET) exceeded average precipitation in the southern parts of the WPP. Only reliance on rivers and aquifers that originate in the snow and ice fields of the Rocky Mountains (Fig. 1) enabled Europeans to successfully colonize the WPP.

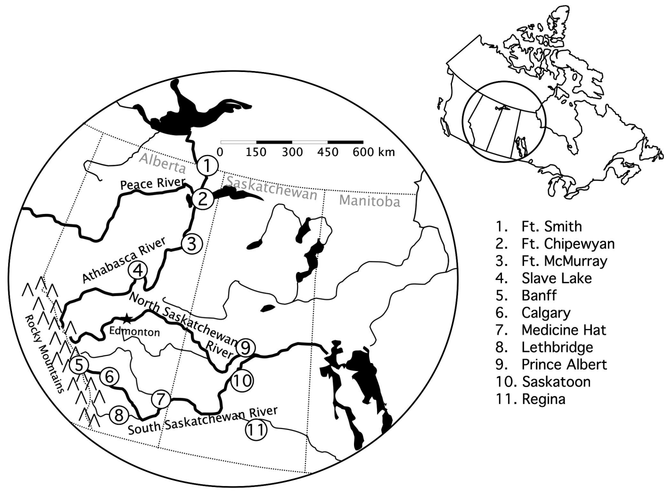

Fig. 1. The WPP and their major rivers. The sites where long-term temperature and precipitation measurements were analyzed are shown.

Trends in Air Temperature, Precipitation, and River Flows of the WPP

To determine whether the WPP have warmed significantly, we analyzed annual temperature trends at sites with records pre-

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Abbreviations: WPP, western prairie provinces; PET, potential evapotranspiration.

See accompanying Profile on page 7207.

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Table 1. Historical changes in temperature and precipitation in the WPP, and predictions for increases in temperature, precipitation, and evapotranspiration

		Historical data					Future PET projections		
		Mean annual T, °C		Δ Annual precipitation					
Site	Period	Initial	Change	mm	%	Baseline PET (1961–1990), mm	Δ T CGCM-A2, °C	Δ Annual, precipitation, mm	Δ PET, mm
Fort Smith	1914–2003	−5.0	4.2	-		499.4	4.8	—	133.9
	1970–2003	−2.9	2.0	N/S					
Fort Chipewyan	1885–2003*	−2.6	1.1	−96.6	−24.3	499.1	4.8	31.6	136.2
	1970–2003		N/S	N/S					
Slave Lake	1923–2003	1.4	0.8	N/S		509.0	4.8	64.3	137.9
	1971–2003	−0.2	2.2	−146.5	−26.9				
Banff	1890–2003	2.0	1.0	−130.6	−23.9	483.8	4.8	59.7	134.1
	1970–2003		N/S	N/S					
Calgary	1887–2003	2.5	2.4	N/S		518.4	6.2	22.5	204.5
	1970–2003		N/S	N/S					
Medicine Hat	1885–2003	4.5	2.3	N/S		587.1	6.5	10.5	237.0
	1970–2003	4.5	1.7	N/S					
Lethbridge	1909–2003	4.6	2.0	−67.0	−18.2	555.9	6.2	22.7	234.9
	1970–2003	5.0	1.4†	N/S					
Prince Albert	1891–2003	−0.6	3.1	N/S		521.6	5.5	22.4	162.8
	1970–2003	−0.5	2.2	N/S					
Saskatoon	1909–2003	0.3	3.6	−50.9	−14.0	546.6	5.5	19.2	173.0
	1970–2003	1.0	1.7	−79.2†	−21.5				
Regina	1884–2003	−0.5	4.0	N/S		547.5	8.4	14.9	303.5
	1970–2003	1.6	0.9	N/S					

Sites with > 80 years of record and negligible effects of urbanization on warning were selected (Environment Canada's Canadian Daily Climate Data database). Temperature and precipitation changes are predicted from multiple global climate models. PET is calculated from a basic temperature-precipitation model (16). NS, not significant.

*1902–2003 for precipitation.

†$0.05 < P < 0.07$.

dating 1925. We chose sites where urban "heat island" effects are unlikely to have contributed to the observed warming, such as airports well outside of urban areas. Most of these sites have undergone a warming of 1–4°C in the past 80–118 years, with much of the increase since 1970 (Table 1). Almost half of the sites analyzed currently receive 14–24% less total annual precipitation than at the beginning of the period of record (Table 1), and none has experienced increases in precipitation. Several studies have determined long-term trends in annual river flows (10–12) but such analyses do not reflect trends during the seasons of peak water demand. In the WPP, peak demands for water occur in the summer months (May–August), when irrigation and municipal use are maximum. In-stream flow needs are also greatest during this period, as a result of warm waters, low oxygen, and coldwater fish fauna that inhabit the rivers and spawn in either spring or fall.

Reliable summer (May–August) flow records exist for 90–100 years for most major rivers in the WPP. Although there is considerable regional and temporal variability, total annual stream flows have generally demonstrated moderate declines in Canada during the 20th century (5, 10, 11, 13), unlike the increases observed for rivers of Eurasia (14). However, in contrast to annual flows, summer flows in major rivers of the WPP have declined rapidly during the 20th century. Current summer flows in the WPP are 20–84% lower than they were in the early 20th century (Fig. 2). A comparison of rivers suggests that damming, human water withdrawals, and increased warming via its effects on evaporation, evapotranspiration, and winter snowpack have contributed to the declines in flow. The Athabasca River, the only major river in the WPP without dams or large water withdrawals, has summer flows in its lower reaches that have declined by 30% since 1970, and 20% for the period or record (Fig. 2*a*), despite increased flows from glacial sources in its headwaters caused by a 2°C increase in average annual air temperatures. In other major rivers of the WPP, where impoundments and large-scale water extractions have radically altered annual flow patterns (e.g., the Peace and Oldman rivers), summer flows are now 40–60% below historical values (Fig. 2*b*). Similar effects of impoundment and flow regulation on seasonal flows have been noted by others (15).

Worst affected is the South Saskatchewan River, where summer flows have been reduced by 84% since the early 20th century (Fig. 2*c*). The river's major tributaries (the Oldman, Bow, and Red Deer rivers) all have been subjected to multiple impoundments and large withdrawals for irrigation, municipal, and industrial uses. All of the tributaries also flow through semiarid and subhumid ecozones, where average annual evapotranspiration exceeds average annual precipitation.

More than 70% of licensed surface water withdrawals in Alberta are for irrigation in its dry southern regions drained by the South Saskatchewan and its tributaries. Each year, >2.5 km^3 of water are used to irrigate ≈400,000 hectares (≈1 million acres) of land (Statistics Canada, Ottawa, www.statcan.ca), comprising 70% of irrigated agriculture in Canada. This extensive irrigation system has relied heavily on reservoirs that trap spring snowmelt runoff from the eastern Rocky Mountains. Of water removed, only ≈20% is returned to the river.

Declining Glaciers and Snowpacks of the Rocky Mountains

Most climate models project an additional warming of several degrees for the area by the latter part of the 21st century (Canadian Institute for Climate Studies Project, University of Victoria, Victoria, BC, Canada, www.cics.uvic.ca/scenarios, Fig. 3). Regional general circulation models coupled with a standard method of calculation (16) indicate that the predicted warming could increase evaporation by up to 55% in some regions of the

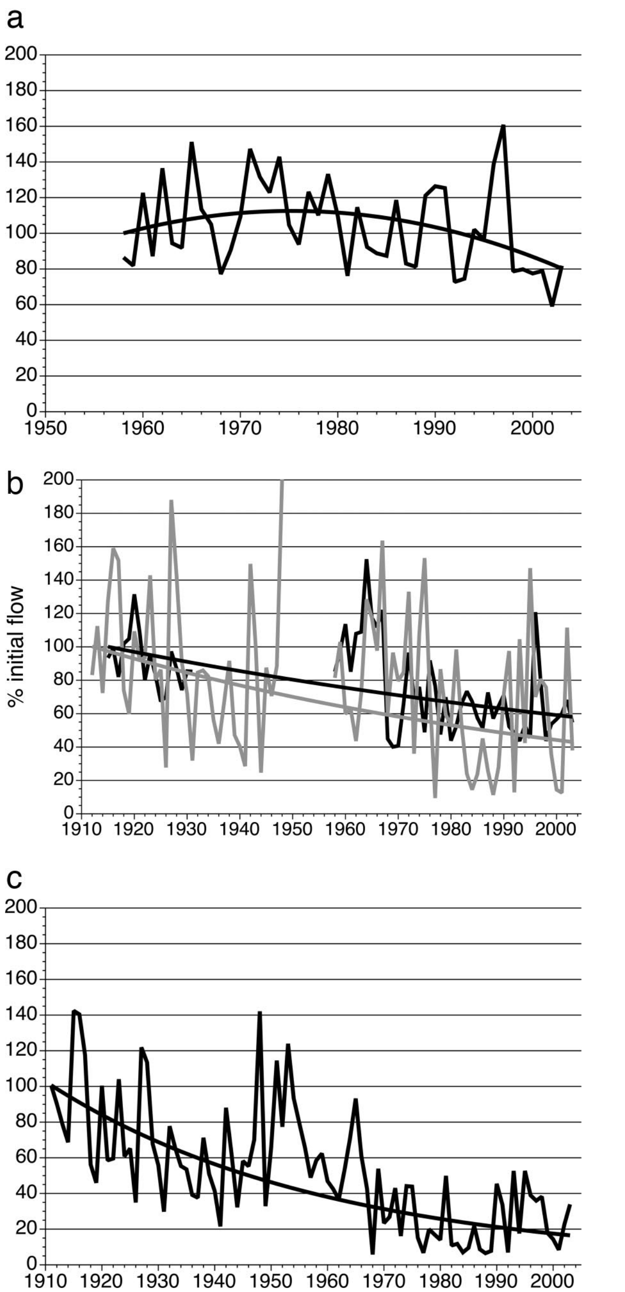

Fig. 2. Long-term relative change in summer flow (May–August) in major rivers of the WPP. (*a*) The Athabasca River downstream of Fort McMurray, Alberta (−19.8% from 1958–2003; −33.3% since 1970; $P < 0.05$). (*b*) Represented by the black line is the Peace River at the town of Peace River, Alberta (−42.1% from 1915–2003; $P < 0.0001$), and represented by the gray line is the Oldman River at Lethbridge, Alberta (−57.1% from 1912–2003; $P < 0.0005$). (*c*) The South Saskatchewan River at Saskatoon, Saskatchewan (−83.6% from 1912–2003; $P < 0.0001$). The smooth lines are regressions representing the best fit to the data for the entire period. The percentage reduction in flow is the change in regressed flow during the period of record.

WPP in the 21st century (Table 1). Most climate models also predict slight increases in precipitation in the WPP (Table 1), but the projected increases are much lower than the expected increases in evapotranspiration. Increases also would be in contrast to historical trends of either declining or relatively stable precipitation in the region. Whether precipitation decreases or increases, the WPP is likely to be much drier in the years ahead.

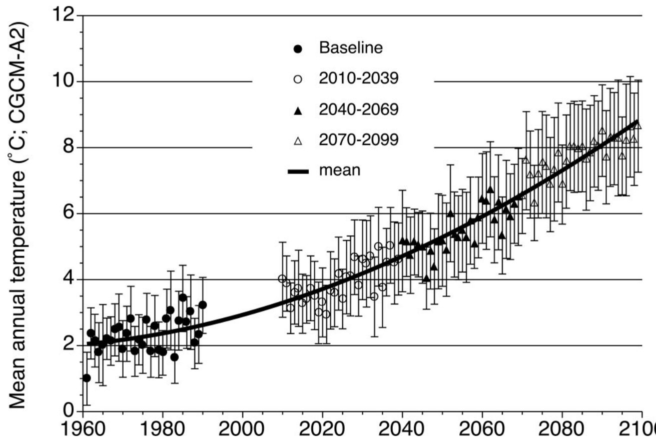

Fig. 3. Temperature increases (°C) predicted by 10 regional general circulation models (mean $\Delta T = +6.5$°C increase from 1961–1990 average; CGCM-2A, Canadian Institute for Climate Studies Project, University of Victoria). The heavy line is a regression of all model data. Points and vertical lines are means and standard deviations among all 10 WPP regional centroids.

All of the major rivers crossing the WPP originate in the Rocky Mountains, where deep snowpacks and melting glaciers maintain river and groundwater supplies. There are signs that these mountain water supplies are diminishing. Glaciers have receded rapidly in the 20th century. Glacial wasting in the eastern Rocky Mountains, which historically contributed 13–56% of summer flows in the Bow River at Banff (17), has advanced enough that glacial melt is now declining (18).

Most large glaciers in the headwaters of the Bow, Saskatchewan, and Athabasca rivers have shrunk by ≈25% in the last century (19). In the Hector Lake basin at the headwaters of the Bow River, the areal extent of 21 glaciers declined by 26.6% between 1951 and 1993, from 23.00 to 16.88 km^2. After the late 1960s, glacial mass balances were predominantly negative (20). The termini of the Bow, Saskatchewan, and Athabasca glaciers are now 1.5 km or more upslope of their position in the early 20th century (State of the Canadian Cryosphere, www.socc.uwaterloo.ca/glaciers/glaciers_hist_e.cfm; Fig. 4), and their masses are shrinking rapidly. Eventually glacial sources of water to these rivers will cease to exist (17), although there have been no predictions of when this might occur. In nearby Glacier National Park, Montana, the U.S. Geological Survey predicts that glaciers will be gone by 2030 (21). The glaciers of the Canadian Rockies are much larger, and their likelihood of disappearing will depend on measures taken to control global greenhouse gas emissions.

The number of days that winter snow has remained on the ground and the maximum depths of the snowpacks have declined significantly in much of the WPP since the mid-20th century (Table 2). Winter precipitation that normally falls as snow is expected to increasingly fall as rain as climate warms. Winter snowpacks also will be subjected to increasing periodic melts during warmer winter conditions. As a result, the snowpacks that have yielded high river flows in May and June will diminish, supplying little more than half of the water they currently do (22). The primary spring melt also will occur earlier in the year, which will exacerbate the effects of drought. These conditions will become more prevalent at higher latitudes and altitudes as climate warms (23), contributing further to critical water supply problems. At present, monitoring of snow cover in Canada is seriously deficient (24), despite warnings that decreases in snow cover could have critical social and economic consequences (25).

The Cumulative Effects of Drought, Climate Warming, Increasing Human Demand, and Catchment Modifications

As the result of increased industrial development, Alberta, the westernmost province of the WPP, has experienced rapid pop-

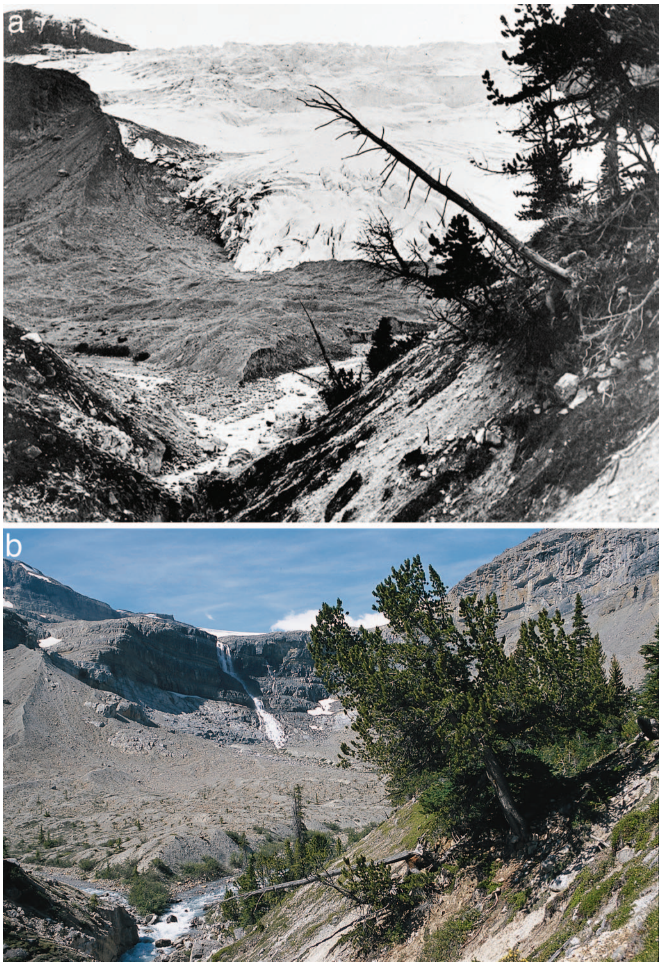

Fig. 4. Historical (*a*, 1897) and recent (*b*, 2002) photographs of the Bow Glacier, one of the major sources of the Bow River. The photograph in *a* was taken by John Norman Collie, Professor of Chemistry at University College London (London). [Reproduced with permission from the Whyte Museum of the Canadian Rockies, Banff, AB, Canada, where its call number is V14/AC-OP/772 (Copyright 1999, Whyte Museum of the Canadian Rockies.] The photograph in *b* is by Graeme Pole. [Reproduced with permission from Mountain Vision Publishing, Banff, AB, Canada (Copyright 2003, Mountain Vision Publishing).]

ulation increase. This increase has been largely fuelled by rapid expansion in Alberta's oil sands-based petroleum industry, because of increasing global recognition of the size of the reserve and Canada's political stability. Some communities have grown by 15–40% in the period 1996–2001 (Statistics Canada, Ottawa, www.statcan.ca). Calgary and Edmonton, with their surrounding suburbs, now have >1 million people each. Continued development has caused rapid immigration from other parts of Canada and abroad and even more rapid increases in freshwater use. Unfortunately, this rapid growth, which is expected to continue, has rendered Alberta the most vulnerable of the WPP to water shortages.

Agriculture also has expanded rapidly. In addition to irrigated agriculture, intensive livestock operations are important to economic development in the southern part of the WPP. Alberta now stocks 6.4 million cattle and 1.8 million hogs (Statistics Canada, Ottawa, www.statcan.ca), demanding large supplies of freshwater. Much of their feed is grown on land irrigated from the already oversubscribed Oldman and Bow rivers. Studies have proposed that livestock numbers could be doubled in the next decade (26).

Municipalities, pulp mills, and other industries also use considerable water, although much of it is returned to rivers after use. The petroleum industry injects freshwater or steam into subsurface oil deposits to facilitate gas and heavy oil recovery. Currently, amounts of water used for deep well injection are <1% of licensed water withdrawals in Alberta, but the water is permanently removed from the water cycle. Also, water for deep-well injection currently comprises 25% of licensed groundwater withdrawals, approximately equal to water licensed for municipal use (27).

The Athabasca River supplies the water for oil-sands development in northeastern Alberta. Currently, the oil sands consume three to six barrels of water per barrel of oil produced. Unless future water use is curtailed, oil-sands development will require ≈45 $m^3 \cdot s^{-1}$ of water supply by 2020, based on recent estimates (27, 28). This is the equivalent of nearly half of the Athabasca River's low winter flow during eight of the years since 1980 and in every year since 1999. The Athabasca and Peace rivers are critical for ecological sustenance of the Peace-Athabasca Delta World Heritage Site at the rivers' confluence, which is home to several thousand aboriginal people. The vast Delta wetlands are already exhibiting negative effects of declining water supply from climate change and the Bennett Dam on the Peace, but large industrial oil-sands projects in the Athabasca drainage and reservoirs on the Peace River continue to be proposed and approved.

Wetlands are known to be important features of the hydrological landscape, regulating flows and removing chemicals and silt (29). Roughly 70% of the wetlands of the southern WPP have already been drained or destroyed, and surveys indicate that wetland losses are still occurring (Ducks Unlimited Canada, Stonewall, MB, Canada; www.ducks.ca). Agriculture is the biggest destroyer of wetlands, but expansion of urban areas and transportation corridors are increasingly important.

Peatlands cover 365,160 km^2 in Alberta, Saskatchewan, and Manitoba, or 21% of the land base (30). Declining water supplies and warming temperatures may impair carbon fixation in these peatlands and increase decomposition rates (30). Increasing forest fires cause underlying peat to become oxidized, releasing carbon dioxide and methane to the atmosphere (31). The total area to be stripped by oil-sands mining in northern Alberta will be ≈2,000 km^2 by 2020 (27, 32). An estimated 22–60% of this area is peatlands that will be destroyed by strip mining, and reclamation of peatlands has so far proven impossible. Peat stripping for horticultural purposes also decreases wetland areas and releases significant stores of carbon (31).

In the dry centuries before European settlement, only nomadic aboriginal bands inhabited the WPP. Even in the dirty 30s, human and livestock populations were far lower than at present and there was little industry, muting the potential societal effects of severe drought. The extreme droughts in the 19th and earlier centuries also occurred under cooler climates than at present or than expected later in this century.

There are also signs that changes in ocean temperatures caused by greenhouse gas forcing are beginning to contribute to widespread midlatitude drying that affects both North America and Eurasia (33). If the trends described above continue, the combination of climate warming, increases in human populations and industry, and historic drought is likely to cause an unprecedented water crisis in the WPP. The resulting decrease in water quantity will contribute to declining water quality, as described below. This decline will exacerbate the water crisis in the WPP.

Eutrophication of WPP Lakes and Rivers

Rapid land-use changes, destruction of wetlands and riparian areas, increased discharges of manure and human wastes, and increased fertilizer use all will contribute to increased inputs of

Table 2. Historical changes in yearly persistence and maximum depth of snowpacks in the WPP (Environment Canada's Canadian Daily Climate Data database)

		Days with snowpack, yr^{-1}		Maximum snowpack	
Site	Period	Absolute change	% Change	Absolute change, cm	% Change
Fort Smith	1956–2003	−7.7	−3.6	N/S	
Fort Chipewyan	1963–1993	N/S		N/S	
Slave Lake	1971–2003	−39.0	−24.7	−26.8	−54.1
Banff	1956–2003	N/S		−32.3	−61.3
Calgary	1956–2003	6.3	4.4	N/S	
Medicine Hat	1956–2003	−25.3	−23.1	−9.9	−38.1
Lethbridge	1962–2003	N/S		−18.3	−63.5
Prince Albert	1956–2003	−16.2	−9.4	−29.8	−52.4
Saskatoon	1956–2003	−23.3	−14.3	−10.4	−31.1
Regina	1956–2003	−24.0	−15.0	−32.4	−54.7

N/S, not significant.

nutrients to waters of the WPP. Lower water flows as described above cause increased water retention times in lakes, resulting in higher nutrient retention and larger algal blooms, i.e., accelerated eutrophication (34–36). There will also be an increasing risk from waterborne pathogens. Warmer waters, longer ice-free seasons, and declining sport fisheries will exacerbate the eutrophication problem (37).

Although Cyanobacteria blooms occurred in many lakes even before humans modified the landscape, paleoecological studies show that inputs of phosphorus and nitrogen have increased slowly over the past century, beginning at approximately the time of human settlement (38, 39). The increase in phosphorus typically exceeds that of nitrogen, causing N/P ratios to decline (37, 38). Lower N/P ratios favor nitrogen-fixing Cyanobacteria, which can supplement dissolved nitrogen sources with atmospheric N_2 (40, 41). The eutrophication is accompanied by an increased problem with waterborne pathogens. For example, a recent study revealed that agriculture in the catchment of the North Saskatchewan River was a major source of *Giardia lamblia* and *Cryptosporidium spp.* to Edmonton's water supply (42). These protozoans are resistant to normal drinking-water chlorination and demand installation of advanced technologies to ensure their removal. In areas of the WPP with moderate to heavy agriculture, rapid increases in animal populations have rendered many streams noncompliant with water protection guidelines for pathogens and nutrients (43).

Clearing of forested land at least doubles the nutrient losses from land until forests are re-established (44, 45). Even greater increases in nutrient losses occur if the land is converted to pastures, feedlots, croplands, and urban areas (45). Increasing recreational demand by expanding human populations, poor fisheries management, and nonexistent enforcement of laws protecting fisheries habitat have lead to the widespread declines and collapses of fisheries for piscivorous species in Alberta (46, 47). Similar declines in piscivorous fish have been observed in other regions (48). The resulting "trophic cascade" can result in high populations of zooplanktivorous fish, stimulating a change from a low-algal to a high-algal phase in lakes (49, 50). The precipitous decline in piscivorous predatory fishes has likely contributed to the increase in algal abundance in many Alberta lakes. Without protection of fisheries habitat and implementation of compensatory fisheries management practices, this problem will worsen.

Problems and Solutions

The cumulative effects of climate warming, drought, and human activity have seldom, if ever, been considered by land managers and policy makers (37). There is little integrated catchment planning in the WPP, and science is poorly represented in the planning process. Generally, decisions to expand cities, clear forested land, fill in wetlands, place and construct feedlots, approve major industrial projects and expansions, apply fertilizer, apportion water supplies, and expand cottage developments are made on a project-specific basis by communities, committees, or even individuals. Ecological instream flow needs and lake levels are often ignored or underestimated. This lack of integrated planning has resulted in the allocation of >100% of at least one river's water, leading to conflict between licensed users. When communities resist development because of concerns over environmental impacts, decision-making powers are often removed to provincial political levels. In addition, governmental agencies charged with environmental monitoring and applying and enforcing laws protecting freshwater resources have suffered extreme funding cuts, primarily for short-sighted budgetary reasons. As a consequence, historical weather, snowpack, and water quality and quantity data are often incomplete or nonexistent. Unfortunately, this host of problems is not unique to the WPP, but is shared by many regions of the world (51). As problems arise, reactionary solutions are derived piecemeal, usually by different departments and levels of government, and too late for easy, inexpensive, or timely remediation. Major societies in the past have faced extended water shortages, often with dire consequences. Catchment-scale planning for management and conservation of freshwaters in the WPP and other rapidly developing dryland areas is urgently needed to maximize efficient use of increasingly scarce freshwaters in a time of warming climate and rapidly increasing human activity.

In response to increasing evidence for water shortages and the need for integrated watershed management, several new programs are attempting to provide direction. The North Saskatchewan Watershed Alliance (Edmonton, AB, Canada, www.nswa.ab.ca) is attempting an assessment of the state of the North Saskatchewan River, with the intention of providing background for strategic watershed planning. The Alberta Water for Life program (Edmonton, AB, Canada, www.waterforlife.gov.ab.ca) has formed committees to study sustainable water strategies for the major river watersheds of Alberta. Both of these processes are in their early stages, and no comprehensive measures have yet been recommended. Although little can be done to halt the disappearance of snowpacks and ice fields, much can be done to protect the integrity of the watersheds of the WPP, by retaining or restoring wetlands and riparian zones. Agricultural developments and industries can be chosen that do not require extensive water supplies, at least during the water-scarce summer months. Controlling greenhouse gas emissions soon can reduce the amount of warming, and hence evaporation and glacial wastage, expected in the latter years of this century. Finally, it may prove wise to keep human populations in the dry WPP relatively low, to avoid the water scarcity that has already become a major problem in the southwestern United States and many other populous dryland areas of the world (ref. 1 and Millennium Ecosystem Assessment, www.MAweb.org).

Methods

Sites with >80 years of record and negligible effects of urbanization on warming were selected for analyses of historical daily temperature, precipitation, and snowpack data (e.g., small towns or airports outside of major urban centers; Environment Canada's Canadian Daily Climate Data database; www.climate.weatheroffice.ec.gc.ca). Daily stream-flow data were used to determine long-term changes in total summer river flow (May–August; Water Survey of Canada HYDAT database, www.wsc.ec.gc.ca). In many instances, winter flow data are incomplete. For this reason and because of the ecological and economic importance of summer stream flow in high-latitude ecosystems, we analyzed only summer stream flow.

Climate Warming Scenarios. Climate warming scenarios for the WPP were generated by the Canadian Institute for Climate Studies Project's CGCM-2A model (University of Victoria, Victoria, BC, Canada). Data from 10 regional models, covering Alberta, central and southern Saskatchewan, and southern Manitoba, were used to determine the anticipated Canadian general circulation model-based projections for future temperature and precipitation changes for this part of Canada.

PET Calculations. Calculation of monthly PET was done according to Thornthwaite (16). Long-term climate records generally only include temperature and precipitation data. Hence, we are limited in our ability to back-cast PET to the use of simple models. Values for annual heat index are calculated from monthly temperatures

$$I = \sum_{j=1}^{12} (T_j/5)^{1.514},$$

where I = annual heat index, T = monthly mean temperature (°C), and j = number of month (e.g., January = 1). Monthly PET is then calculated from mean monthly temperature, annual heat indices, and standardized mean monthly daylight hours

$$PET_j = 16 \cdot L_d (10^T/I)^a,$$

where PET_j = monthly PET (mm), L_d = standardized daylight hours (i.e., mean monthly hours of daylight/12), $a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 0.01792\, I + 0.49239$, $a = 0.16\, I + 0.5$, and

$$PET = \sum_{j=1}^{12} PET_j,$$

where PET = annual PET (mm).

Absolute values, trends, and percentages of change for all variables were calculated from best-fit lines (ANOVA) for long-term trends in summer stream flow and climatic variables by using SPSS 6.1.1 for Macintosh. Significance in trends or differences was attributed where $P \leq 0.05$.

CGCM-A2 climate scenario projections are courtesy of the Canadian Institute for Climate Studies Project at the University of Victoria. Historical climate data are from Environment Canada's Canadian Daily Climate Data database, and river flow data are from Environment Canada's Hydrometric Database (HYDAT) database (water survey). Reviews by V. St. Louis, S. R. Carpenter, and B. J. Peterson helped to improve an earlier draft of the manuscript. This study was funded by Freshwater Research Ltd., the Walter and Duncan Gordon Foundation, and a Natural Sciences and Engineering Research Council Discovery Grant (to D.W.S.).

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