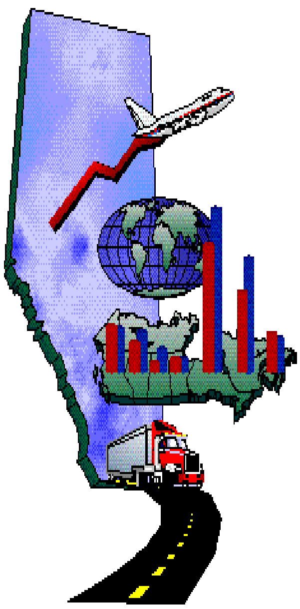
Project Title: Assessment of Virtual Water Flows in Alberta



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10/30/2010, Beijing

Summary

Water scarcity has become more and more serious in Alberta; as a result, water-use conflicts have emerged among agriculture and other water-intensive sectors. Under this background, the study aims at quantifying virtual water flows through food trade in Alberta. Three components is designed as follows: (1) quantifying water footprint of major crops in a spatially explicit way; (2) assessing virtual water flows through the trade of major agricultural products; (3) analyzing the environmental effects of virtual water flows on other countries.

Wheat, barley and canola are the most important crops in Alberta, and they together account for over three fourths of the total crop production. A GIS-based Environmental Policy Integrated Climate (GEPIC) model was used to quantify water footprint of these three crops with spatial resolution of 5 arc-minutes (around 10 km by 10 km nearby equator). Results show relatively low water footprint of individual crops in regions with high precipitation or in the irrigation districts. At the provincial level, barley, wheat and canola had water footprint of 699, 1635 and 2427 m^3/ton, respectively.

The average virtual water exports of crop and livestock products were estimated to be 16.91 Gm^3/yr during 1999-2008. The average virtual water imports were 0.85 Gm^3/yr. This gives the average net virtual water exports of 16.06 Gm^3/yr. On average, each resident in Alberta exported 5083 m^3/cap/yr each year through the net food exports of crop and livestock products. This was almost 2.5 times of the water footprint of Canada. It is obvious that domestic production of crop and livestock products was mainly used for food

exports to other countries. Wheat, beef and canola were the three major products contributing to net virtual water exports, and they combined accounted for over 99% of the total net virtual water export from Alberta.

Japan, Mexico, the US, China, Iran and Indonesia were the top six virtual water importers of Alberta, and they accounted for almost 60% of the total virtual water export. Crop trade between Alberta and these countries resulted in even lower water use efficiency at the global level. For example, the virtual water export from Alberta to Japan was 2.41 Gm^3/yr. However, if Japan produced the traded crops, it would only need 1.06 Gm^3/yr. The reason for this low efficiency is mainly due to the general lower water productivity and higher water footprint of crops from the dominant rainfed agriculture in Alberta.

To conclude, competition of water use among sectors becomes intense in Alberta, but still a large amount of water is used to feed the people outside Canada through food trade. The virtual water exports from Alberta do not help enhance water use efficiency at the global level. Hence, future water and food trade policies have to be carefully formulated in Alberta by considering not only the improvement of water use efficiency among sectors locally, but also the enhancement of water use efficiency at the global level.

1. Introduction

1.1. Climate in Alberta

Alberta (see Fig. 1) has a dry continental climate with warm summers and cold winters. Climate varies considerably with average temperatures in January range from −8 ℃ in the south to −24 ℃ (−11 ℉) in the north, and in July from 24 ℃ (75 ℉) in the south to 16 ℃ (61 ℉) in the north. Annual precipitation ranges from 300 mm/yr in the southeast to 450 mm/yr in the north, except in the foothills of the Rocky Mountains where rainfall can reach 600 mm/yr (see Fig. 2). The northern and western parts of the province experience higher rainfall and lower evaporation rates caused by cooler summer temperatures. The south and east-central portions are prone to drought-like conditions sometimes persisting for several years, although even these areas can receive heavy precipitation.

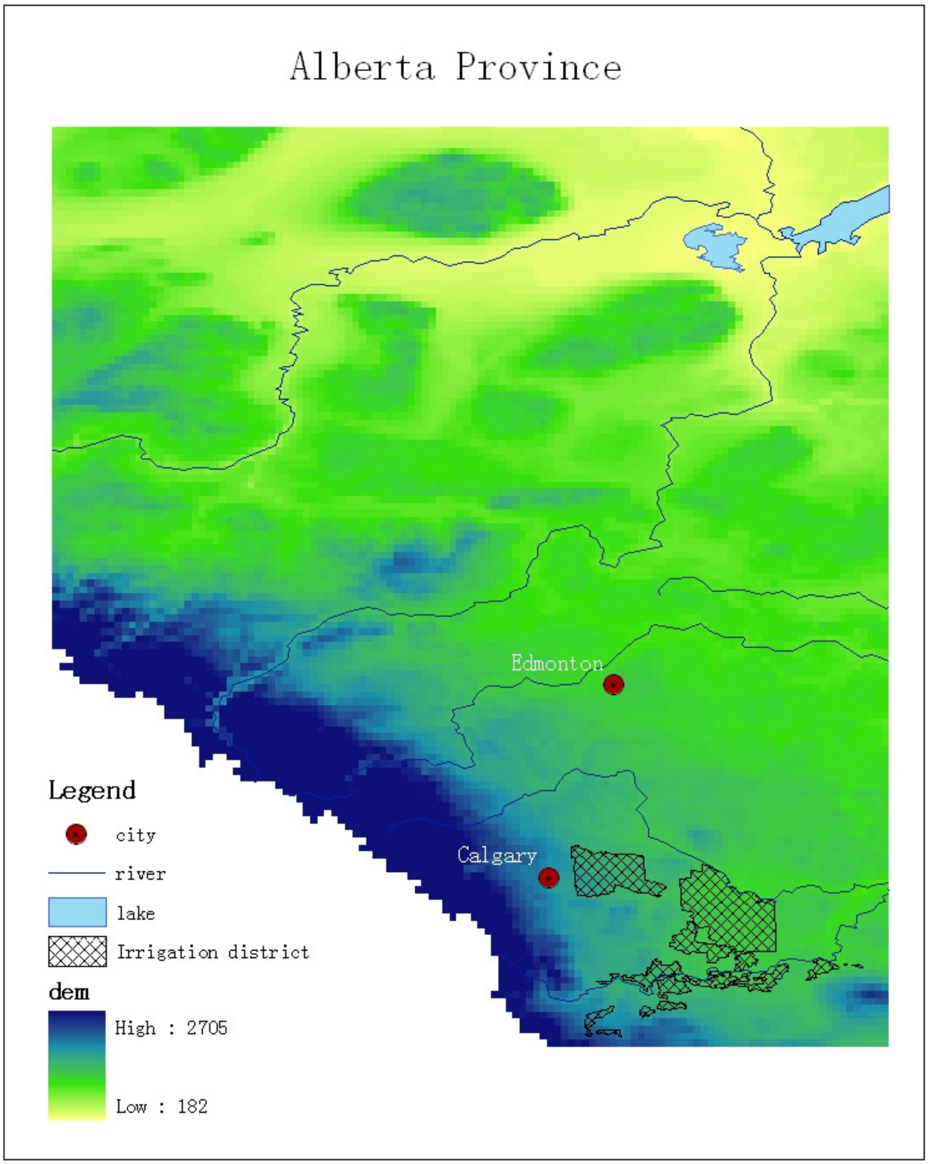

Fig. 1. Basic information of the Alberta province

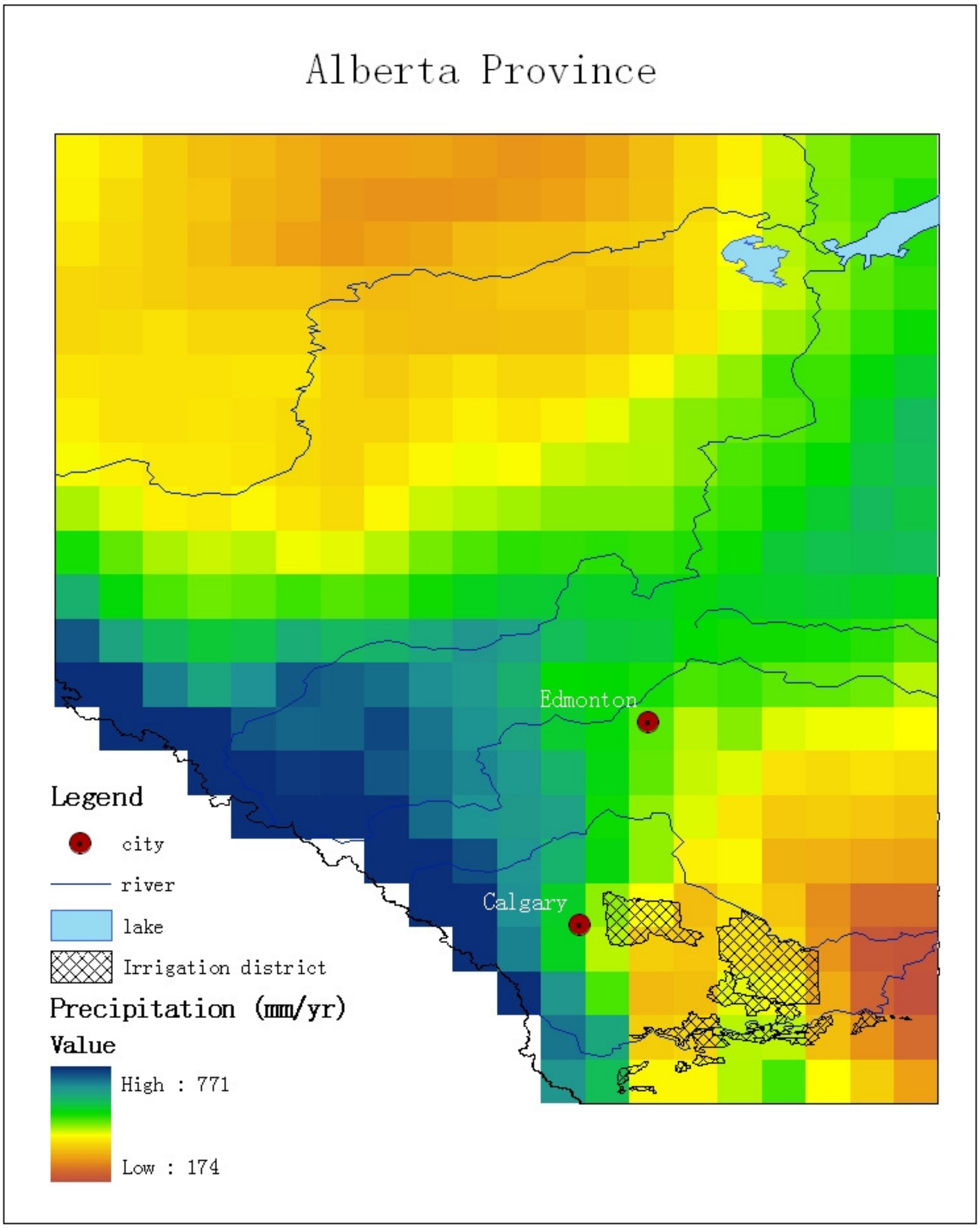

Fig. 2. Precipitation in the Alberta province

1.2. Economy in Alberta

Alberta's economy is one of the strongest in Canada, supported mainly by the petroleum industry and to a lesser extent by agriculture and technology. The total GDP was $291.7 billion in 2008, and the per capita GDP was by far the highest of any province in Canada, over 60% higher than the national average. Energy industry had the largest contribution to GDP in all sectors, and it accounted for over 30% of the total GDP. Alberta is the largest producer of conventional crude oil, synthetic crude, natural gas and gas products in the country. It is the world's 2nd largest exporter of natural gas and the 4th largest producer. The Athabasca Oil Sands have estimated unconventional oil reserves approximately equal to the conventional oil reserves of the rest of the world, estimated to be 1.6 trillion barrels (254 km^3). With the development of new extraction methods such as steam assisted gravity drainage, which was developed in Alberta, bitumen and synthetic crude oil can be produced at costs close to those of conventional crude. Many companies employ both conventional strip mining and non-conventional in situ methods to extract the bitumen from the oil sands. With current technology and at current prices, about 315 billion barrels (50 km^3) of bitumen are recoverable. As of late 2006 there were over $100 billion in oil sands projects under construction or in the planning stages in northeastern Alberta.In both Red Deer and Edmonton, world class polyethylene and vinyl manufacturers produce products are exported to all over the world.

1.3. Agriculture in Alberta

Alberta has one of the world's most productive agricultural economies, and it is Canada's 2nd largest agricultural producer, earning 22% of Canada's farm cash receipts. There are over 70,000 farmers in Alberta. The diversity of landscapes within Alberta (see Fig. 1) allows for the wide variety of products over its 21 million hectares of agricultural land base, accounting for 31.3% of the total farm area in Canada. The agricultural sector is diverse and includes crop production, livestock production and many others. Farming and ranching helped build the economy and attracted early immigrants to Alberta. In 2008, agriculture accounted for around 1.8% of Alberta's GDP.

Total production of major crops was estimated to be 19.1 million ton in 2008 (Statistics Canada 2009b), or around 5500 kg/cap/yr. Wheat remained the largest crop, with production estimated at around 9 million tones, followed by barley and canola in 2009. Wheat, barley and canola together accounted for over three fourths of the total crop production. The spatial distribution of these three crops is shown in the following graph (Fig. 3-5). The annual crop production is shown in Fig. 6.

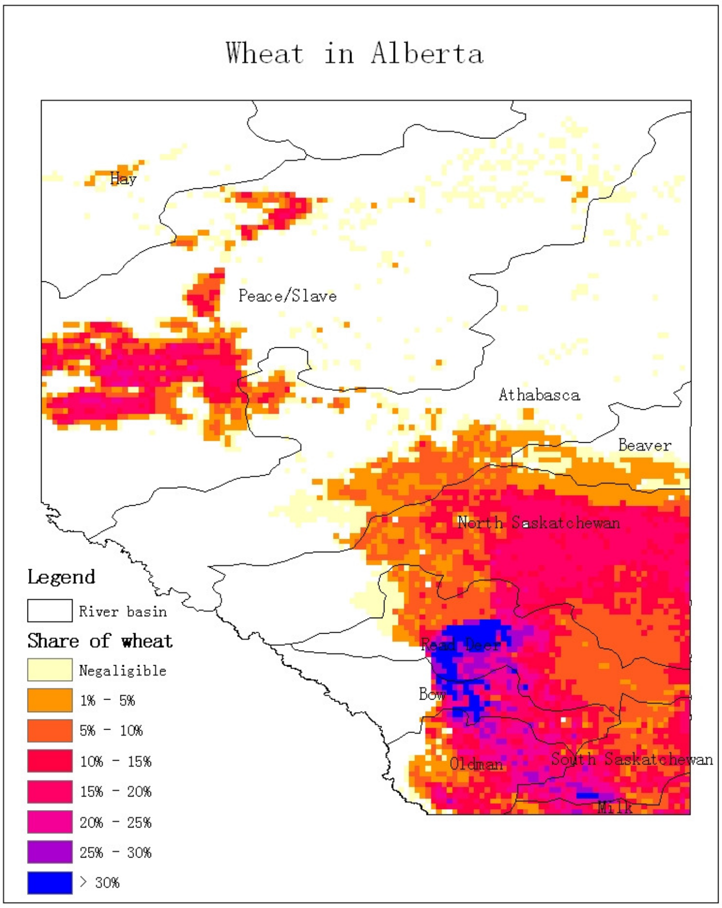

Fig.3. Spatial distribution of wheat in Alberta

Data Source: Ramankutty et al. (2008)

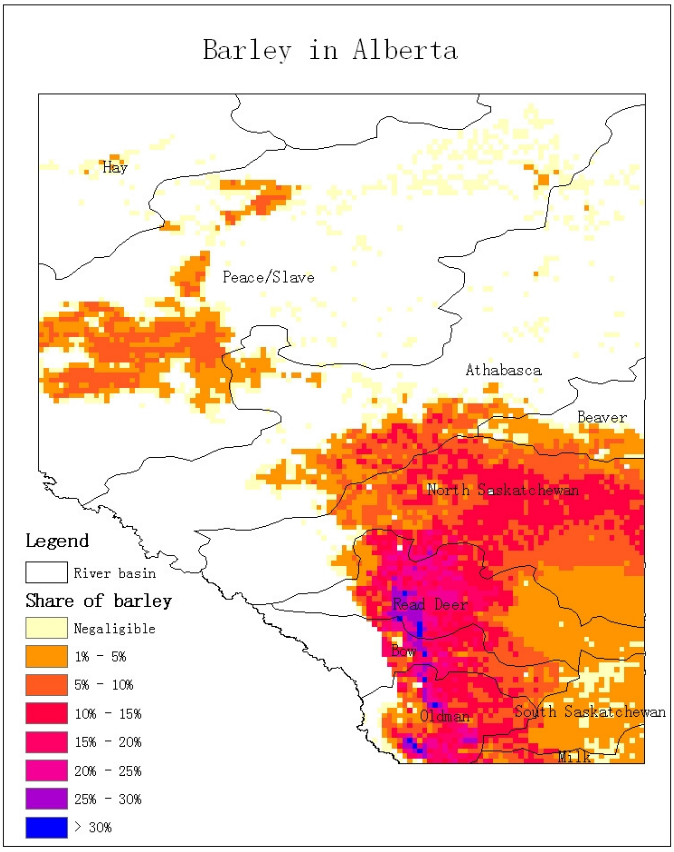

Fig.4. Spatial distribution of barley in Alberta

Data Source: Ramankutty et al. (2008)

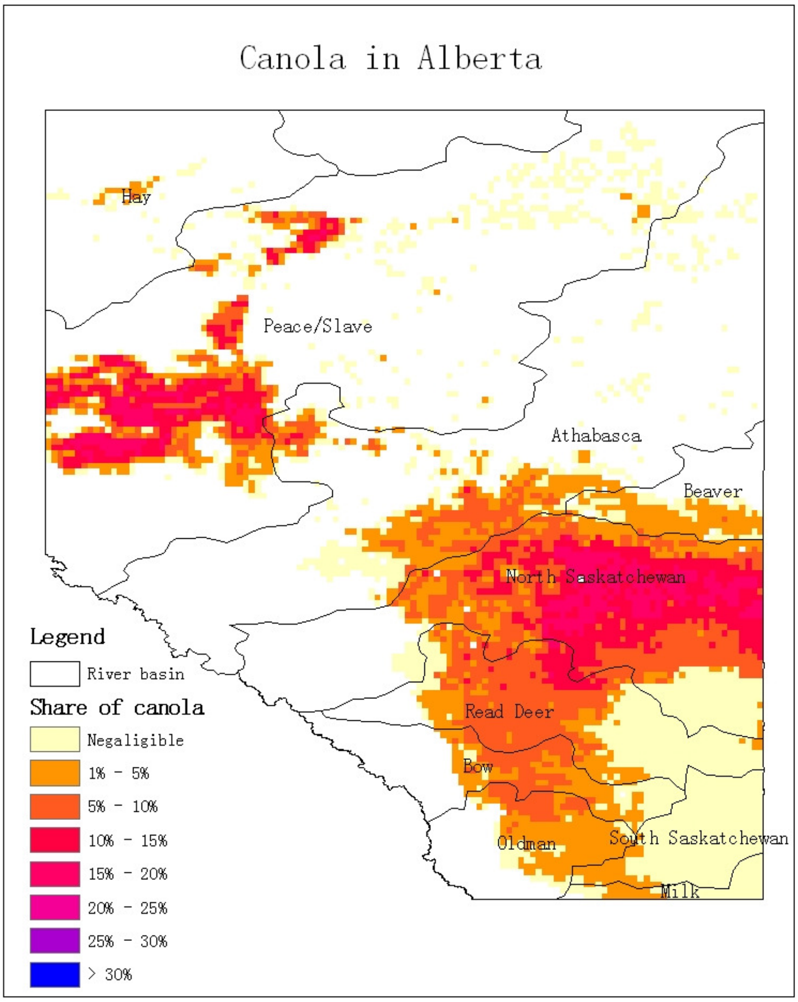

Fig.5. Spatial distribution of canola in Alberta

Data Source: Ramankutty et al. (2008)

Alberta leads Canada in cattle and calf, with 5.9 million head as of 2006, or 40% of the Canadian total. Beef cattle production is Alberta's largest agricultural sector providing C$2.9 billion in farm cash receipts annually or 34% of Alberta farm production income. Of Alberta's estimated 2009 beef production, 16% is sold within the province, 45% to other provinces, 31% to the US and 8% to other countries. Beef is Alberta's number one agri-food export. Annual exports of Alberta beef and cattle are valued at approximately

C$ 1.4 billion in 2009. For other livestock, Alberta has 14% of Canada's total hog receipts. In 2004, provincial support totaling C$6.6 million was made available to sheep, goat, deer, elk, reindeer and bison producers to help maintain their heads.

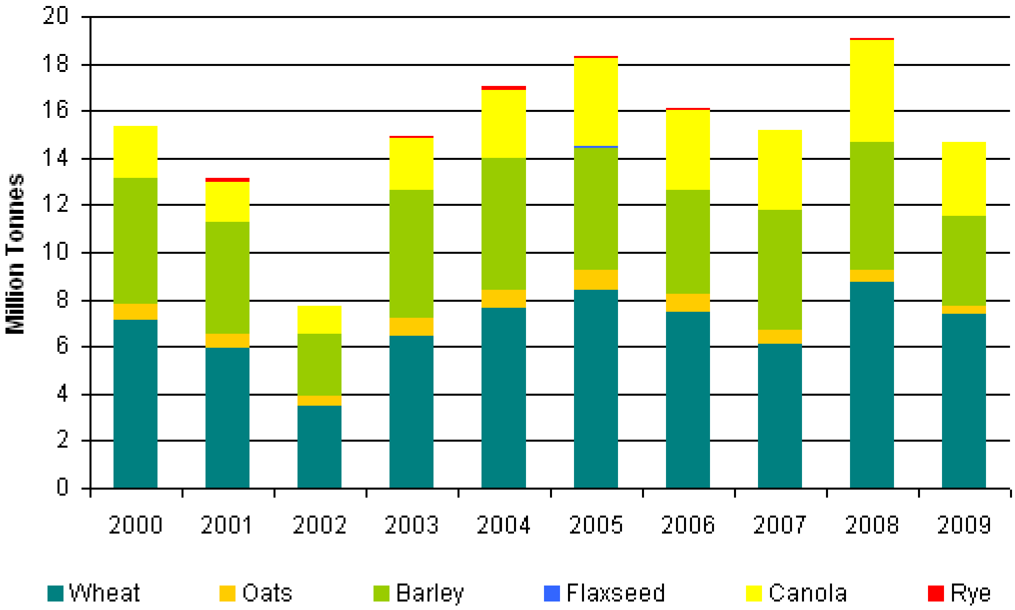

Fig.6. Major crop production in Alberta, 2000-2009.

Data Source: Statistics Canada (2009).

1.4. Exports in Alberta

Alberta was the second largest provincial exporter in Canada, behind Ontario, accounting for 24.0% of Canada's total exports in 2008 (Statistics Canada 2009a). Alberta exported $109.0 billion worth of goods in 2008, 33.2% higher than 2007. The higher energy prices were a major reason for the increasing exports. Energy exports rose to $79.3 billion in 2008 from $56.3 billion in 2007. Non-energy exports also increased significantly, by 16.4% to $29.8 billion, largely due to the increase in higher prices of grains.

Alberta's international exports of primary and processed agricultural and food products reached a record of $8.1 billion in 2008, and were 25.6% higher than in 2007 (Statistics Canada 2009a). Substantial increases in exports of grains and oilseeds, mainly due to the high prices, contributed to the growth of the exports. The top five Agri-Food exports were wheat, canola seed, beef, live cattle and pork (Fig. 7). These five products together accounted for around 69.5% of the province's total agri-food exports. The four largest export market of Alberta were the United States, Japan, China and Mexico, ranking in a decreasing way.

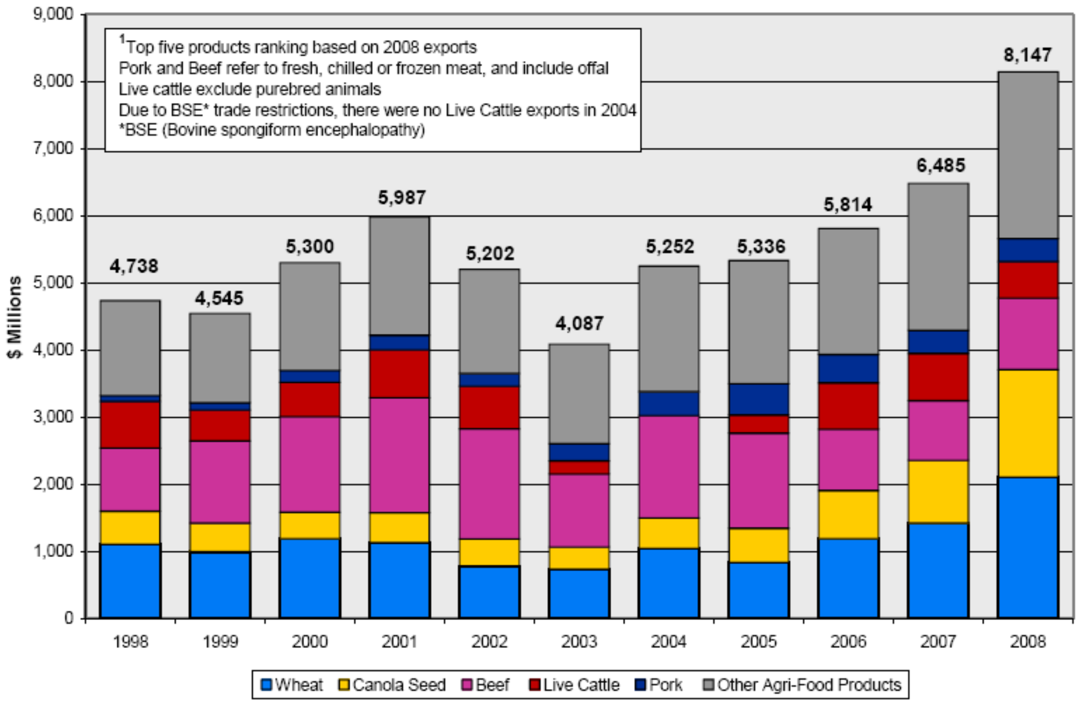

Fig.7. Alberta Top Five International Agri-Food Exports, 1998-2009

Data Source: Statistics Canada (2009a)

1.5. Water Resources and Water Use in Alberta

Canada is one of the world's largest countries in terms of water resources; however, its water supplies are unevenly distributed. The southern parts of the Prairie Provinces are still dry and water scarcity is emerging in province e.g. Alberta. With the fast-growing population and economy, water demand for industrial, urban, and environmental water use has increased significantly. There are rising concerns for the sustainable water uses by various sectors of Alberta's economy, particularly agricultural and oil sectors.

Alberta is home to 65% of all irrigation in Canada (Statistics Canada 2007). Irrigation area has increased from 19,223 hectares in 1911 to 495,786 hectares in 2008, with the sharpest increase coming after 1970 (Ministry of Agriculture and Rural Development 2009a). The distribution of the irrigation area in Alberta primarily involves the 13 irrigation districts in southern Alberta (see Fig. 8 and Table 1), representing the largest amount of water allocated for a specific purpose in Alberta at over 3.5 billion m^3. The four largest districts (e.g. Eastern, St. Mary River, Western, and Bow River Irrigation Districts) account for 83% of total diversions, with two more accounting for an additional 12% (Ministry of Agriculture and Rural Development 2009b). Seven remaining small districts account for the other 5%. Irrigation plays an important role in Alberta's agricultural production. On less than 6% of the cultivated land base in the province, irrigation contributes more than 19% of the gross primary agricultural production.

According to a report of Alberta Environment, as of December 2005, the total water allocation in Alberta was 9.56 Gm^3 ($1Gm^3=10^9$ m^3) of water for various purposes (AMEC Earth & Environmental 2007). Of this, 9.25 Gm^3 was for surface water and 0.31 million Gm^3 was for ground water. The irrigation sector accounts for 43% of the total water allocation. The industrial sector accounts for 28% followed by the municipal (11%), and petroleum (8%). All other sectors combined accounts for 10%.

Agriculture and oil sectors are the two mainstays of the Alberta economy and two large water users. Water is essential for both the growth of agricultural products and the production of the oil sector. Several years of drought have exacerbated a dilemma faced by the province of Alberta for the choices that must be made between conflicting uses of the limited water resources by these two sectors (Gaudet et al. 2006).

Table.1. Irrigation districts in Alberta. Source: Ministry of Agriculture and Rural Development (2009a)

Irrigation Districts	Length of Distribution System (km)	Land under Irrigation (Ha)
Aetna	27	781
Bow River	1058	80209
Eastern	1784	111267
Leavitt	56	1862
Lethbridge Northern	650	49526
Magrath	106	4528
Mountain View	35	426
Raymond	247	13055
Ross Creek	20	427
St. Mary River	1719	138712
Taber	364	31110
United	227	6992
Western	1077	27375

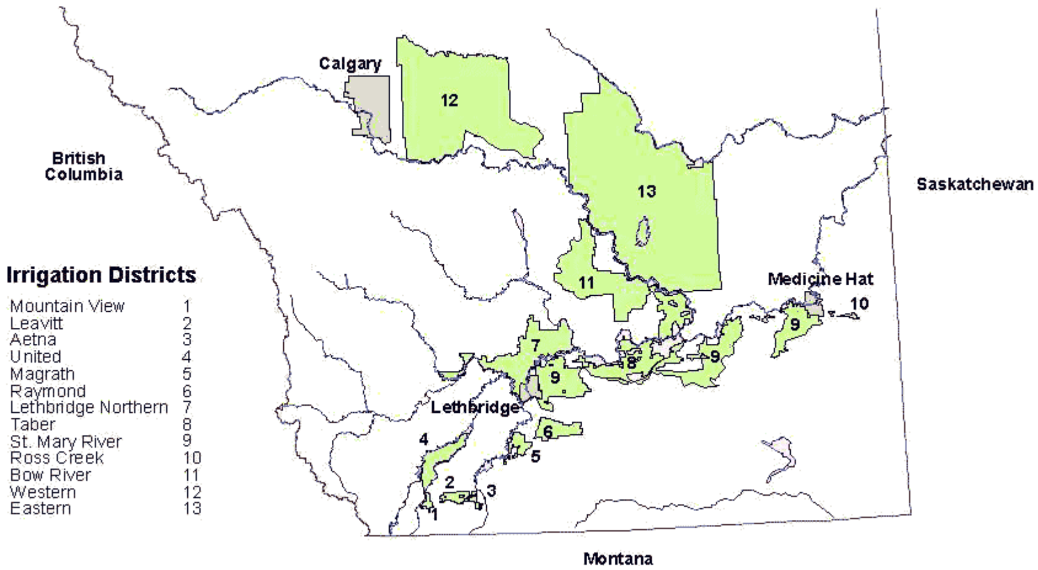

Fig.8. Irrigation districts in Alberta

Source: Online at

http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/irr4475/$FILE/irrbase.gif

1.6. Objectives and Contents of the Study

Water scarcity has become more and more serious in Alberta; as a result, water-use conflicts have emerged among agricultural sector and other water-intensive sectors. Agriculture is by far the largest water user in Alberta. A large amount of water is used to irrigate crops and support livestock production. Such agricultural production is partly used to meet the food consumption in Canada, while a large share of it also supports Alberta's international food exports. Since agricultural production is very water intensive, food trade virtually indicates a kind of water trade, or termed as virtual water trade by scholars (Allan 1993) (J. Liu et al. 2007a).

This projects aims at quantifying virtual water flows through food trade in Alberta. Three components is designed as follows: (1) quantifying water footprint of major crops in a spatially explicit way; (2) assessing virtual water flows through the trade of major agricultural products; (3) analyzing the environmental effects of virtual water flows on other countries.

2. Method

2.1. Calculation of water footprint with GEPIC

A GIS-based Environmental Policy Integrated Climate (GEPIC) model (Junguo Liu et al. 2007b; Junguo Liu 2009) is selected to quantify water footprint (WF) of major crops in a spatially explicit way. The GEPIC model is developed by Beijing Forestry University (BFU) and the Swiss Federal Institute of Aquatic Science and Technology (Eawag). It is designed to simulate the spatial and temporal dynamics of the major processes of the soil-crop-atmosphere-management system. GEPIC integrates a geographical information system (GIS) with a widely-used EPIC model (version EPIC0509) (Williams et al. 1989), which explicitly considers key processes in ecosystems such as weather, hydrology, vegetation growth, nutrient and carbon cycling, soil erosion, tillage, and plant environmental control. The integration allows GEPIC to use all the functions of the EPIC model to simulate the above processes on a daily time step for more than 100 vegetations including crops, grass, and trees (Junguo Liu 2009). Climate data, soil parameters, crop distribution, terrain properties (elevation and slope) and crop management are needed for the calculation of consumptive water use. Details of the GEPIC and EPIC models are described in Liu et al. (2007b) and (Williams et al. 1989), respectively.

In GEPIC, potential crop yield is simulated based on the interception of solar radiation, crop parameters, leaf area index (LAI) and harvest index (HI). The daily potential growth is decreased by stresses caused by water, nitrogen and phosphorus deficiencies, extreme temperatures, and poor soil aeration. GEPIC uses radiation-use efficiency in calculating photosynthetic production of biomass. Intercepted photosynthetic active radiation is estimated with a Beer's law equation (Monsi and Saeki 1953). Potential increase in biomass for a day is estimated using Monteith's approach (Monteith 1977). Simulated potential biomass is adjusted daily for stress from five factors (water, temperature, nitrogen, phosphorus and aeration) in proportion to the extent of the most severe stress during that day. Crop yield is defined as the marketable part of the total above ground biomass produced. It is estimated by multiplying the above-ground biomass at maturity by a water stress adjusted harvest index for the particular crop. In our study, a fresh yield is calculated using a moisture content of 14% in wheat seeds as suggested by Bessembinder et al. (2005). The fresh yield is estimated by dividing the dry yield by 0.86.

The GEPIC model offers five methods for estimating potential evapotranspiration: Hargreaves (Hargreaves and Samani 1985), Penman (Penman 1948), Priestley–Taylor (Priestley and Taylor 1972), Penman–Monteith (Monteith 1965), and Baier–Robertson (Baier and Robertson 1965). When wind speed, relative humidity, and solar radiation data are not available, the Hargreaves or Priestley–Taylor methods provide options that give realistic results in most cases. In this study, the Hargreaves method was chosen to estimate potential evapotranspiration. The Hargreaves method estimates potential evapotranspiration as a function of extraterrestrial radiation and air temperature. The actual ET is the sum of transpiration and evaporation. The GEPIC model computes evaporation from soil and transpiration from plants separately by an approach similar to that of Ritchie (1972).

The GEPIC model comprises of components of hydrology and crop growth modules. The hydrological module enables the quantification of the consumptive water use of different crops, while the crop growth module enables the quantification of crop biomass and crop yield. Water footprint (WF) is defined as the consumptive water use for per unit weight of crop production. The water footprint *f* of crop *c* in grid cell *i* is expressed as

$$f_i^c = \frac{10 \times ET_i^c}{Y_i^c} \quad \text{(Eq. 1)}$$

Where *ET* is evapotranspiration in mm/yr, and *Y* is crop yield in ton/yr.

CWU comprises of two components: green consumptive water use (GCWU) and blue consumptive water use (BCWU). Here green water refers to the water that comes from precipitation, is stored in the soil, and subsequently fed back to the atmosphere (Falkenmark 1995; Savenije 2000), while blue water is the water in rivers, lakes, reservoirs, ponds and aquifers. Traditional water resources assessment generally emphasizes surface water and groundwater, or blue water defined here. However, green water is a very important component of water resources and it accounts for about 60% of the total water resources (Schiermeier 2008). The concepts of green and blue water enriched the implication of water resources; in addition, these concepts associate the water cycle processes with ecological processes.

For rainfed agriculture, irrigation is not applied; hence, CWU is equal to GCWU. For irrigated agriculture, CWU is partly from green water and partly from blue water. In order to estimate the proportion of green and blue water uses, two different soil water balances are performed according to FAO (2005):

(1) Soil water balance *I* is carried out by assuming that the soil does not receive any irrigation water. Seasonal evapotranspiration computed using this soil water balance is referred to as *SET1*.

(2) Soil water balance *II* is carried out by assuming the soil receives sufficient irrigation water. Seasonal evapotranspiration computed using this soil water balance is referred to as *SET2*.

For a specific crop under irrigated conditions, according to FAO (2005), green water use is equal to *SET1*, while blue water use is equal to the difference between *SET2* and *SET1*, or SET2 – SET1 in crop growing periods. Hence, for a specific crop under irrigated conditions, the proportion of blue water in crop growing periods is calculated as:

$b = (SET2 - SET1)/SET2$ (Eq. 2)

$g = SET1/SET2$ (Eq. 3)

where *b* and *g* are the blue and green water proportions under irrigated conditions.

It needs to be pointed out that *SET1* is not exactly the "green" part of seasonal evapotranspiration in the irrigated systems. Particularly in semi-arid and arid regions, crops in rainfed systems generally grow slower than those under irrigated systems, partly due to the lack of water and fertilizer. Smaller crops in rainfed systems often abstract less rain water from unsaturated soil; hence, *SET1* may underestimate the green water proportion.

2.2. Quantification of water footprint (WF) with high spatial resolution

WF of a crop is calculated with the GEPIC model with spatial resolution of 5 arc-minutes (around 10 km by 10 km nearby equator). This resolution is selected mainly because it is so far the highest resolution for cropland data (e.g. the data from Ramankutty et al. (2008)). Besides the land use data, the other main input data for the GEPIC model include location information (e.g. DEM and slope), climate data, soil physical parameters, plant parameters, and management data, such as irrigation and fertilizer application. The data sources are described in later section, and listed also in Appendix 1. In this study, water footprint was only assessed for wheat, barley and canola with a high spatial resolution. These crops are the most important exporting crops and they combined accounted for 99% of the virtual water exports in Alberta (see the Results section).

2.3. Quantification of water footprint at the provincial level

WF of a crop at the provincial level is calculated as

$$F = \frac{\sum_i (f_i^I \times P_i^I + f_i^R \times P_i^R)}{\sum_i (P_i^I + P_i^R)}$$

Where F is the water footprint at the provincial level, f is the water footprint at the grid cell level, i is the grid cell code within the province, I indicates irrigated agriculture, R indicates rainfed agriculture, and P is the crop production. P is calculated by multiplying crop yield with harvested area. Crop yield is simulated with the GEPIC model while the harvested area is obtained from available cropland distribution maps.

2.4. Quantification of virtual water trade

Alberta is a net exporting province. Hence, we here calculate net virtual water export (NVWE), which is the difference between virtual water export (VWE) and virtual water import (VWI).

$$NVWE^c = VWE^c - VWI^c = F^c \times EXP^c - F^c \times IMP^c$$

Where c indicates crop code, and EXP and IMP are volume of export and import in ton/yr, respectively.

WF of wheat, barley and canola was calculated with the GEPIC model as explained above. WF of other crops was not calculated here. Instead, the WF of beans and potato were obtained from Liu et al.(2009a), who estimated these values with a spatial resolution of 30 arc-minutes. The WF of alfalfa, hay and timothy were from Hoekstra et al. (2007), who calculated these values for Canada as a whole. Due to the dominant role of wheat, barley and canola in shaping virtual water exports, uncertainties in WF of other crops will not significantly affect the simulation results. WF values of livestock products are from Hoekstra et al. (2007), who calculated these values for Canada as a whole.

2.5. Data source

The DEM data are obtained from the 1-km resolution digital elevation model GTOPO30 of the United States Geological Survey (USGS) (EROS Data Center 1998). Terrain slopes are from the 1-km resolution (3000) HYDRO1K digital raster slope map, which defines the maximum change in the elevations between each cell and its eight neighbors (USGS 2000). Both the DEM and slope maps are transformed into 5-minitue maps, in which the value of each grid is equal to the averages in the corresponding higher resolution maps.

Historical monthly data on maximum temperature, minimum temperature, precipitation and number of wet days between 1998 and 2002 are obtained with a spatial resolution of 30 arc min from the Climate Research Unit of the University of East Anglia (CRU TS2.1) (Mitchell and Jones 2005). A monthly to daily weather converter (MODAWEC) model is used to generate the daily weather data (Junguo Liu et al. 2009b). A grid cell with a spatial resolution of 30 arc-min contains 36 small grid cells with a spatial resolution of 5 arc-minutes. Since 5-min climate data are not available, it is assumed that climatic parameters in all the 36 small grid cells are the same as those in the large grid cell for the 30-min resolution.

Soil parameters of soil depth, percent sand and silt, bulk density, pH, organic carbon content are taken from Batjes (2006). Soil parameters are available for 5 soil layers (0–20, 20–40, 40–60, 60–80, 80–100 cm). The soil data are available with spatial resolution of 5 arc-minutes.

Crop parameters of the wheat, barley and canola are obtained from the default crop parameter file in EPIC. It is assumed that in the irrigation districts, all crops are planted under irrigated conditions. Outside of the 13 irrigation districts, it is assumed that all crops are grown under rainfed conditions.

Food trade data (import/export) are obtained from the *Economics and Competitiveness Division* of the *Alberta Agriculture and Rural Development*. The trade data cover a period from 1999 to 2008 for eight crop types: alfalfa, barley, canola, dried beans, wheat, hay, timothy and potato. These crops accounted for 96.9% of the total crop export in terms of values. In the statistics, the trade data not only include trade for crops and crop products but also for products of manufacture.

3. Virtual Water Flows

3.1. Spatial distribution of water footprint of wheat, barley and canola

The water footprint of various crops is simulated with the GEPIC model. Fig. 9-11 show the spatial distribution of water footprint of wheat, barley and canola. For wheat, there is a general trend that regions with high precipitation have lower water footprint. This can be seen from the relatively low water footprint in the Peace/Slave, Athabasca, and Beaver river basins and also in the northern part of the North Saskatchewan river basin, and the relatively high water footprint in many river basins in the southern part of Alberta. It is also noticed that in the dry regions in the south, water footprint is relatively lower in the irrigation districts. This is because irrigation is applied when insufficient rainfall is available. In this case, irrigated wheat can achieve high crop yield as well as low water footprint. The lowest water footprint of wheat occurs in the Western irrigation district in Alberta. In general, the rules hold also for barley and canola: low water footprint occurs normally in regions with high precipitation or in the irrigation districts. When comparing the three crops, it seems that in general barley has the lowest WF, canola has the highest WF, and wheat has a WF between barley and canola.

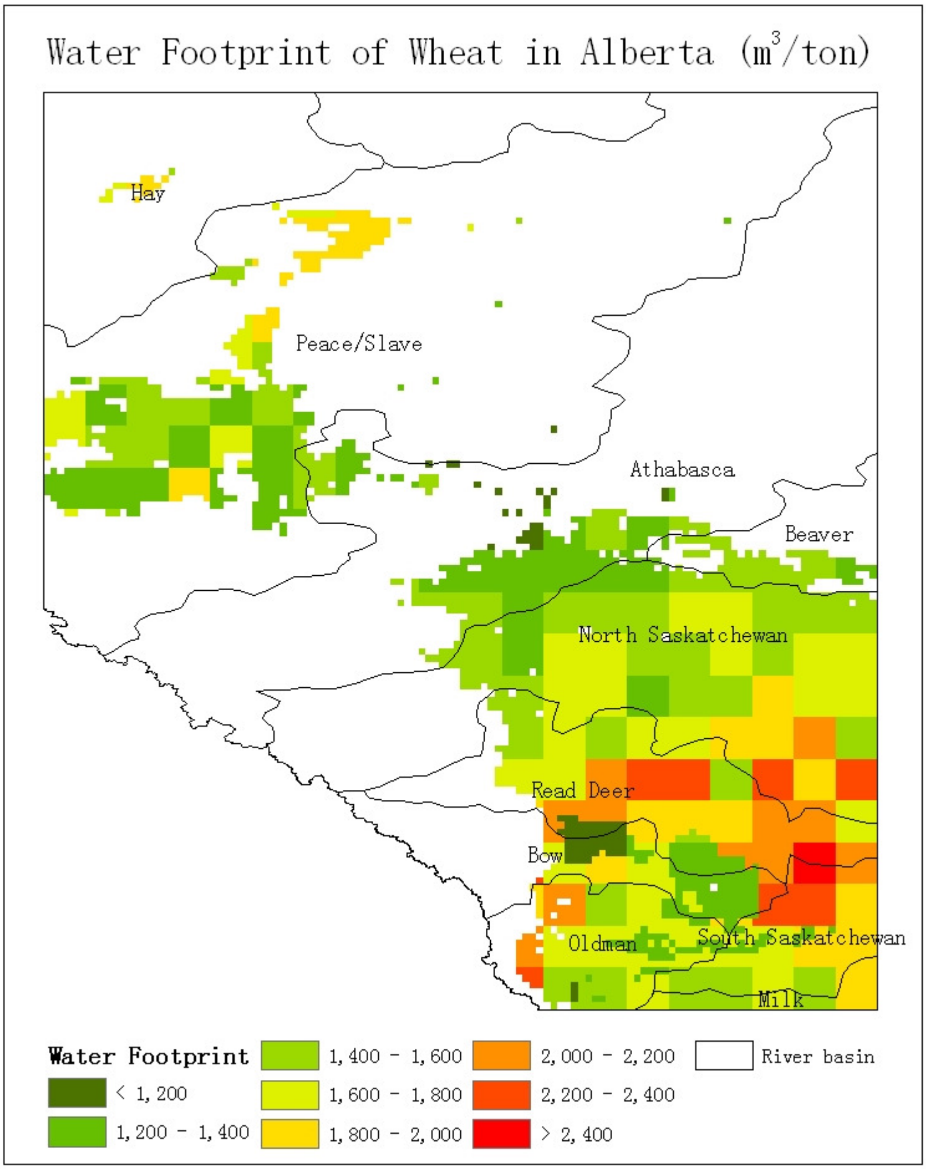

Fig.9. Water footprint of wheat in Alberta

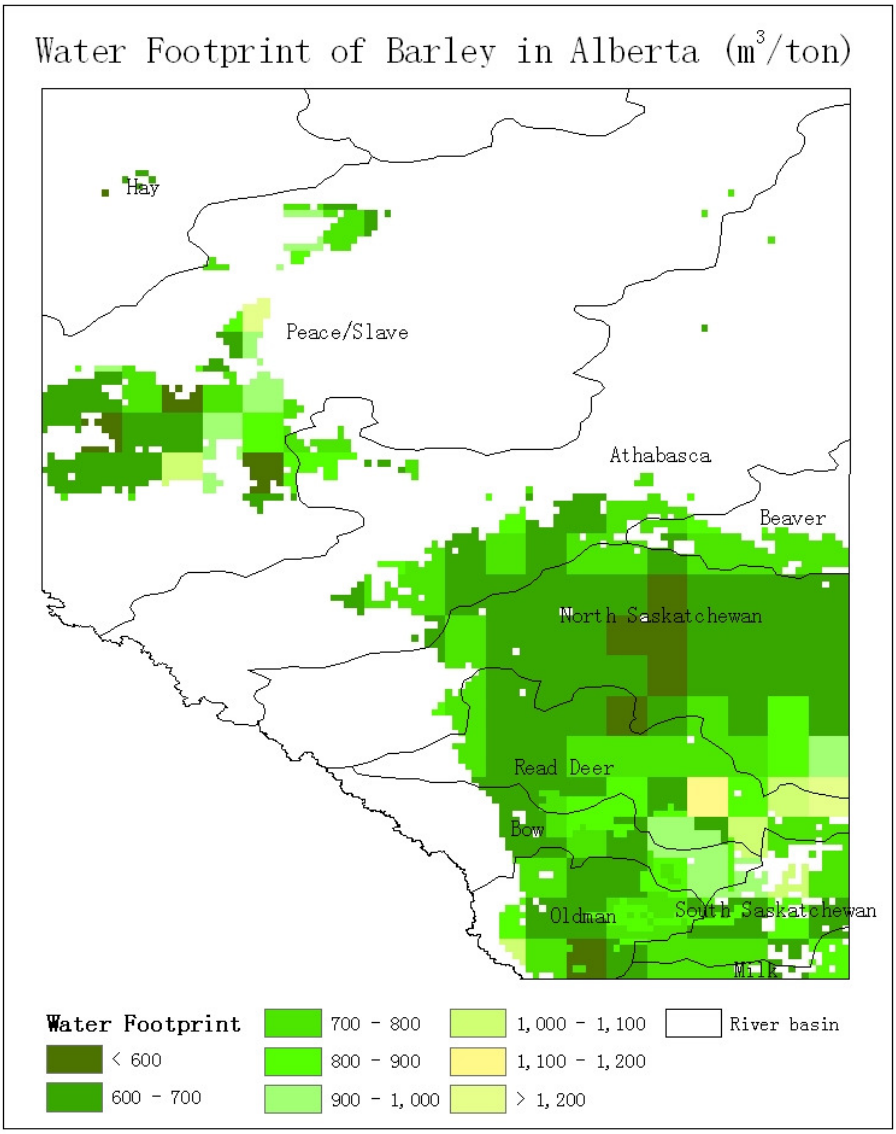

Fig.10. Water footprint of barley in Alberta

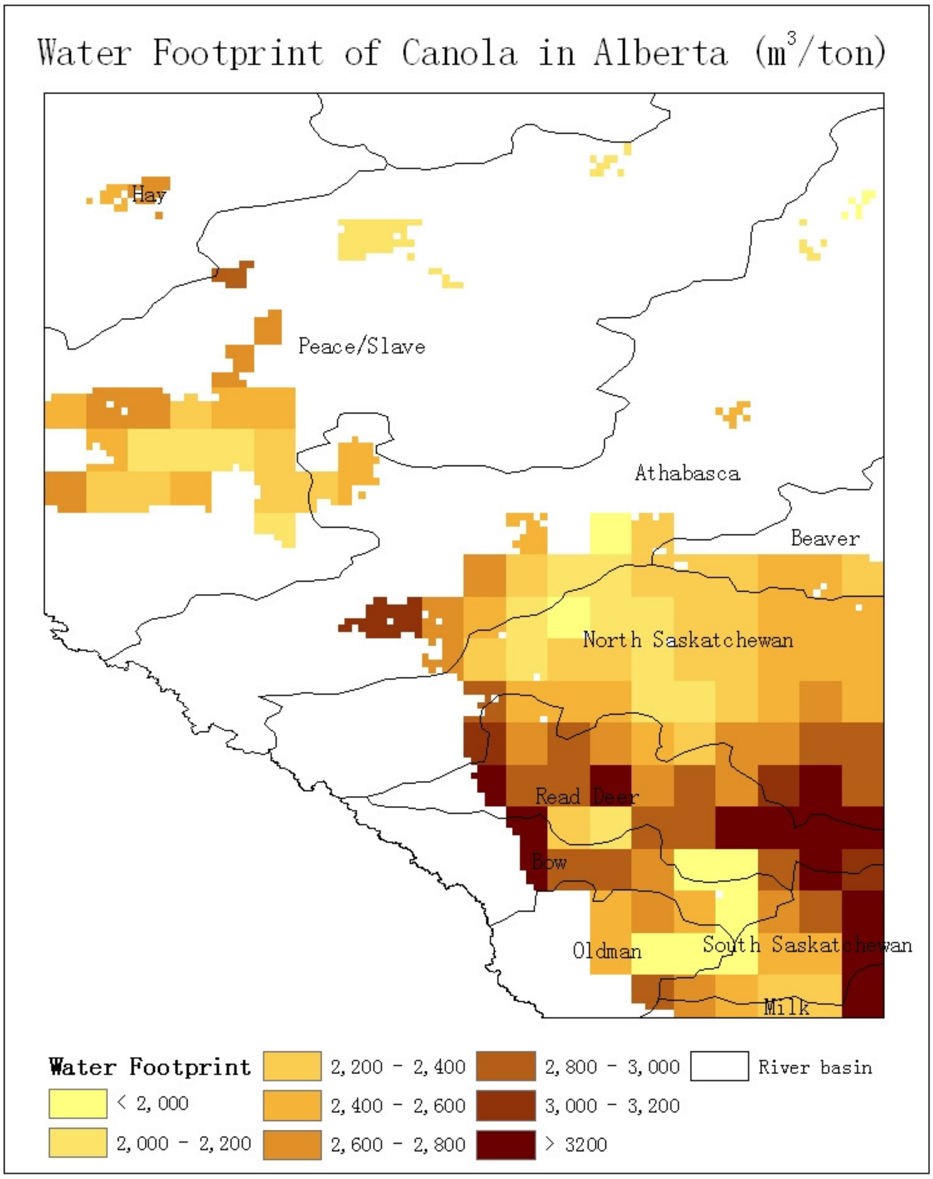

Fig.11. Water footprint of canola in Alberta

3.2. Average water footprint at provincial level

At the provincial level, barley, wheat and canola have WF of 699, 1635 and 2427 m^3/ton (Fig. 12). For both wheat and canola, WF in irrigation districts is lower than that outside of the irrigation districts. This means that irrigation is very effective to increase crop water productivity of both the crops. For barley, it seems the WF is even higher in the irrigation districts. This is probably because the barley is a drought tolerant crop, and in general barley can achieve a good yield in dry conditions. Irrigation may not increase crop yield significant; hence it is not an effective way to enhance crop water productivity.

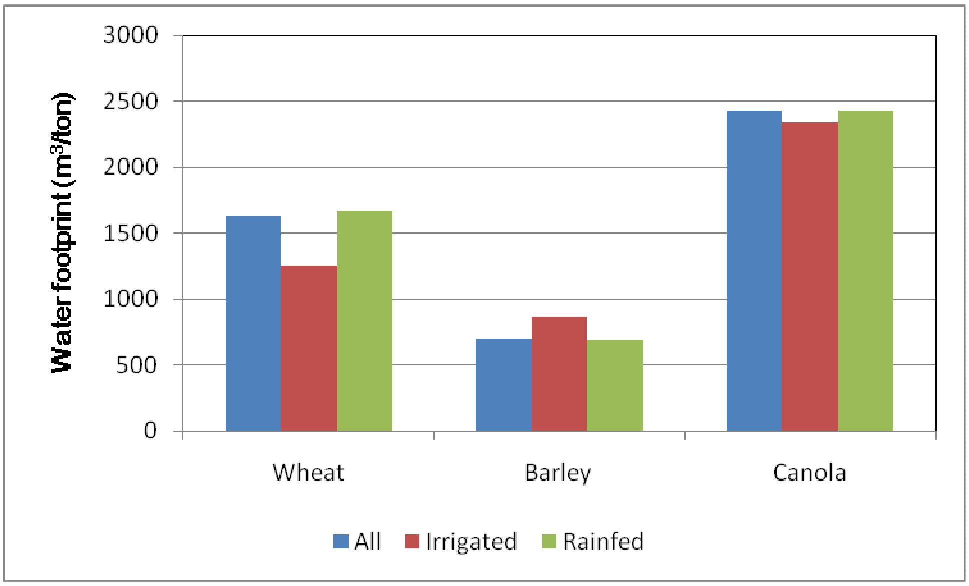

Fig. 12. Water footprint of wheat, barley and canola under different conditions

All means the combination of irrigated and rainfed conditions

Irrigated means irrigated conditions

Rainfed means rainfed conditions

The green water proportions of wheat, barley and canola are all high (96.2% for wheat, 95.9% for barley and 99.1% for canola) at the provincial level (Fig. 13). This is mainly caused by the dominant rainfed cropland. When irrigated cropland is considered, wheat, barley and canola have green water proportions of 41.4%, 54.0% and 57.5% respectively. For wheat, almost 60% of the total consumptive water use is from blue water. For barley and canola, the dependency ratio of blue water is lower than 50%.

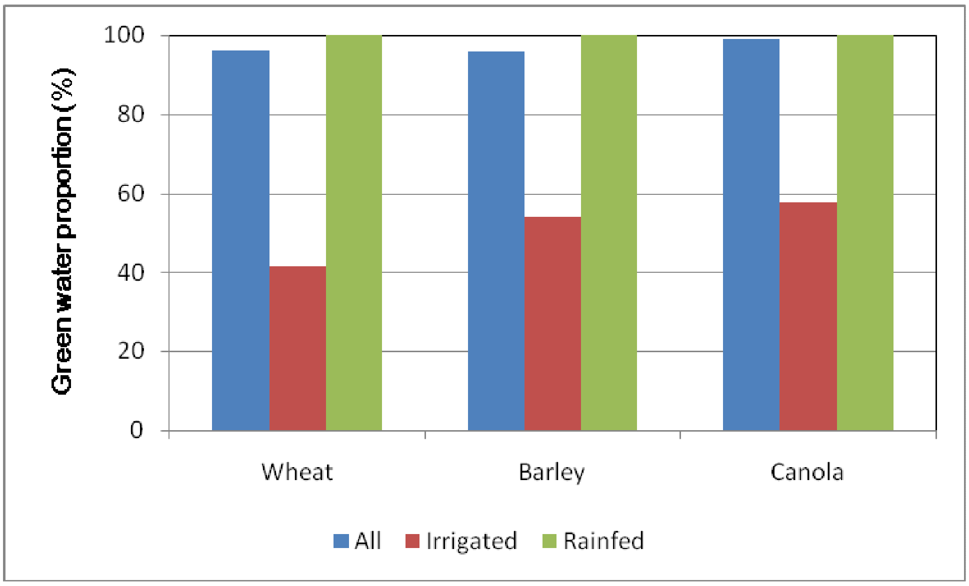

Fig. 13. Green water proportion of wheat, barley and canola under different conditions

All means the combination of irrigated and rainfed conditions

Irrigated means irrigated conditions

Rainfed means rainfed conditions

3.3. Assessment of virtual water flows for crops

The average annual virtual water export was 12.10 Gm^3/yr during 1999-2008 (Fig. 14). Wheat was the largest virtual water exporter and it accounted for 65% of the total virtual water export of crops. Next to wheat, canola and barley also contributed greatly. These three crops combined contributed to 99% of the total virtual water exports of crop products. The dominance of virtual water exports of wheat, canola and barley can also be seen from the annual virtual water exports in Fig. 14 and 15.

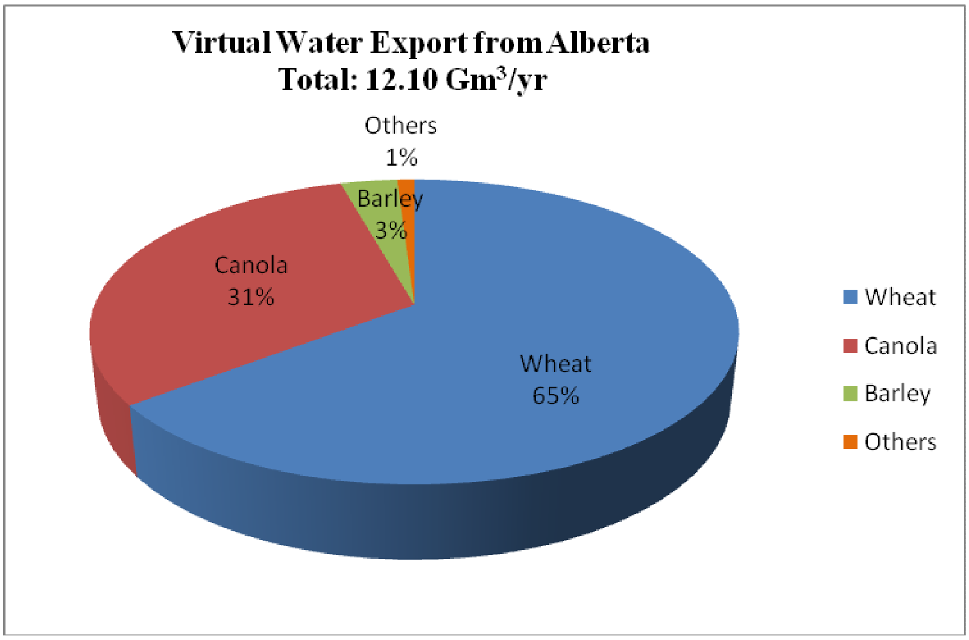

Fig. 14. Virtual water export of crop products from Alberta (average 1999-2008)

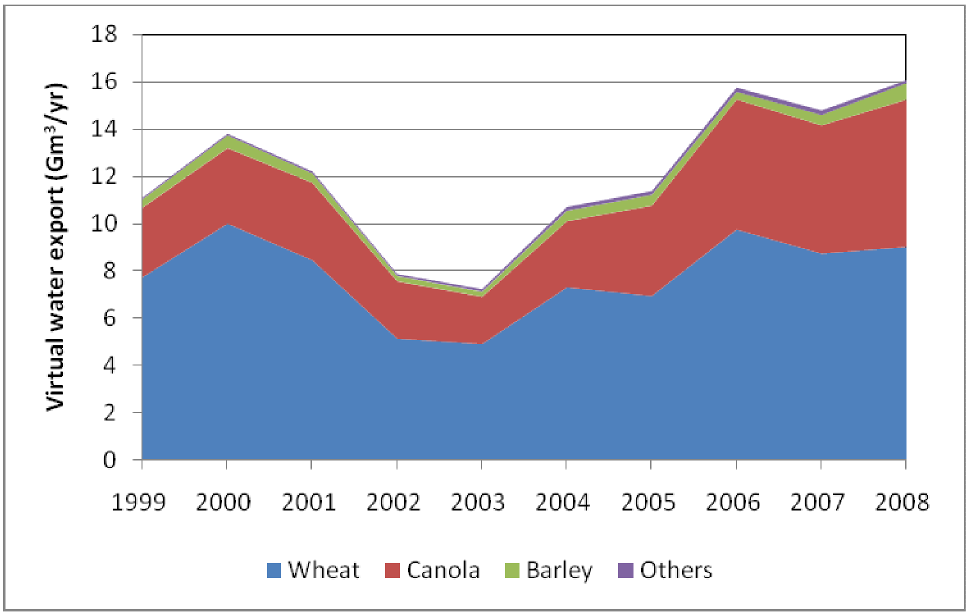

Fig. 15. Annual virtual water export of crop products from Alberta (1999-2008)

Virtual water imports were marginal compared to virtual water exports. The average annual virtual water imports were about 0.727 Gm3, which is equivalent to 6% of the total virtual water exports. Cereal crops accounted for over 93% of the total virtual water imports of crop products (Fig. 16-17).

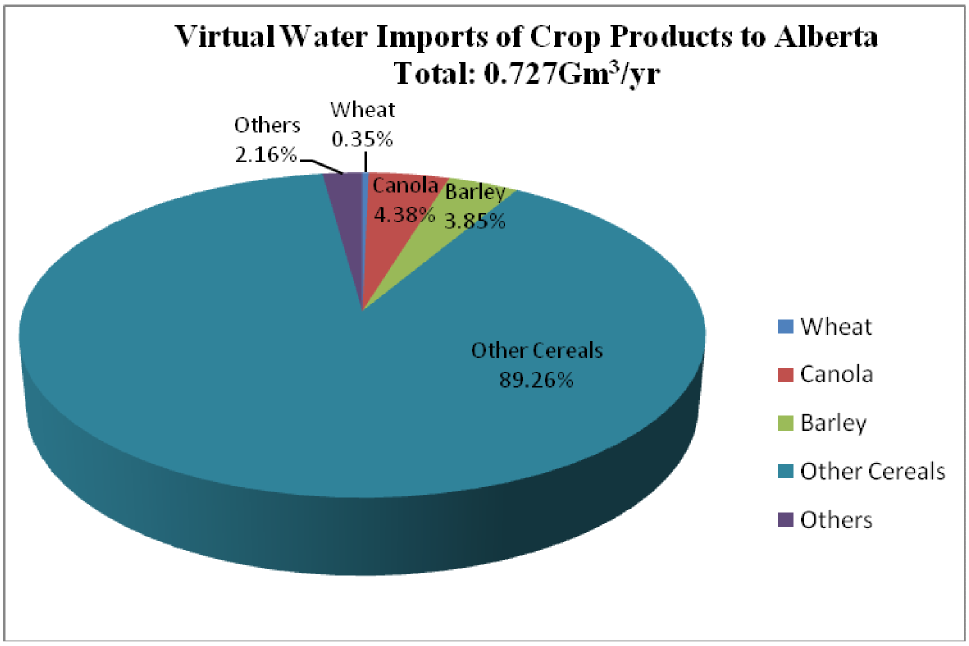

Fig. 16. Virtual water imports of crop products to Alberta (average 1999-20008)

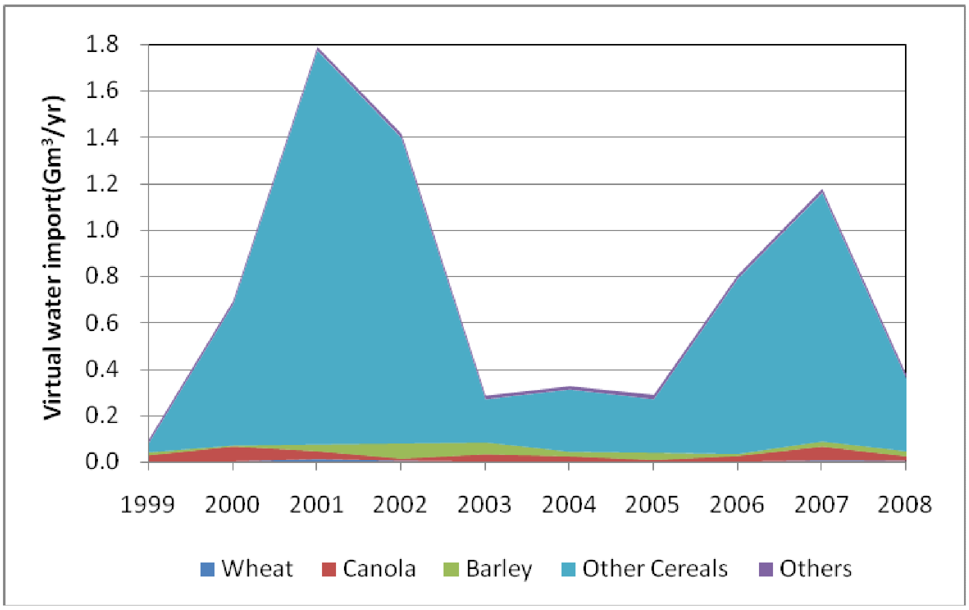

Fig. 17. Annual virtual water imports of crop products to Alberta (1999-20008)

The average annual net virtual water exports were 11.372 Gm^3 during 1999-2008 (Fig. 18). On a per capita basis, the average annual net virtual water exports were 3600 m^3/cap/yr during this period.

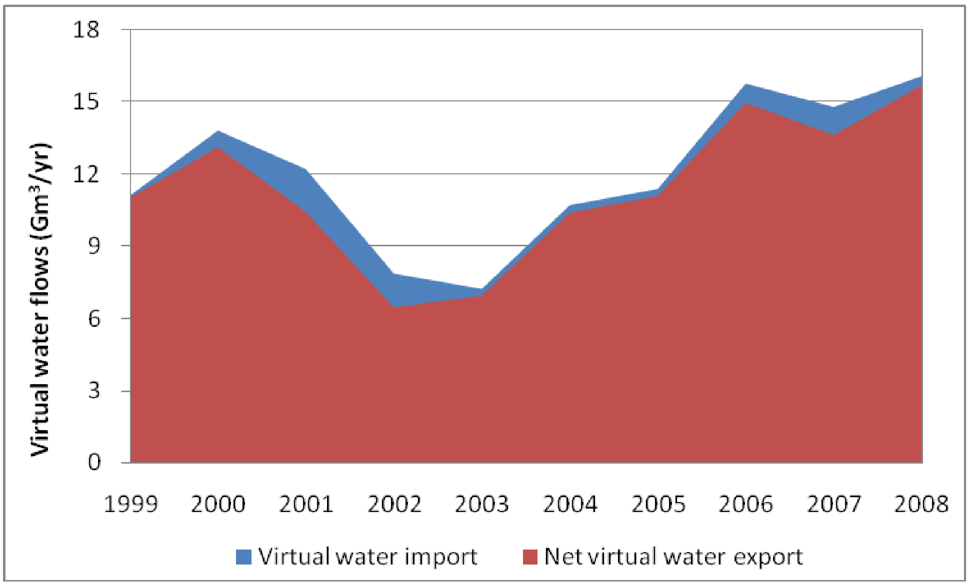

Fig. 18. Annual net virtual water export of crop products to Alberta (1999-2008)

3.4. Assessment of virtual water flows for livestock products

Here beef, pork, horse meat, other meat, processed meats, dairy produce and eggs were taken into accounts for the calculation of virtual water flows. Both exports and imports of horse meat and eggs are very tiny and almost marginal compared to other products. Hence, in the graphs, the virtual water imports/exports of these two categories are not included.

The total virtual water exports of livestock products were 4.81 Gm3/yr during 1999-2008. Beef and pork were two major livestock products shaping the virtual water exports (Fig. 19). Particularly, beef accounted for over 93%. Pork accounted for around 6%. All other accounted for about 1%. Beef and pork were dominant in virtual water exports in all years during 1999-2008 (Fig. 20).

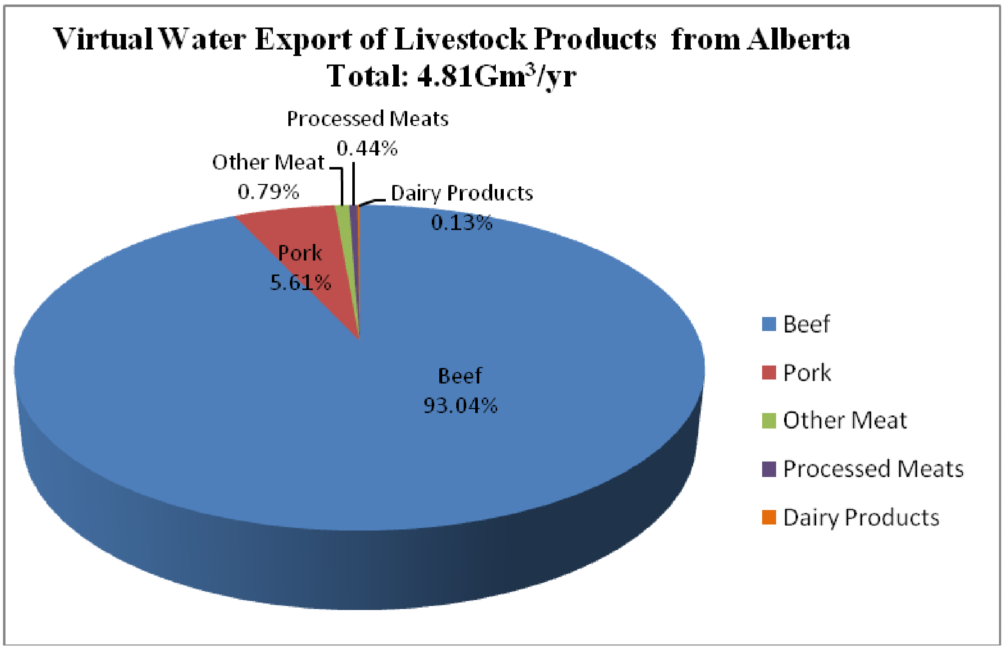

Fig. 19. Average virtual water export of livestock products from Alberta (average 1999-2008)

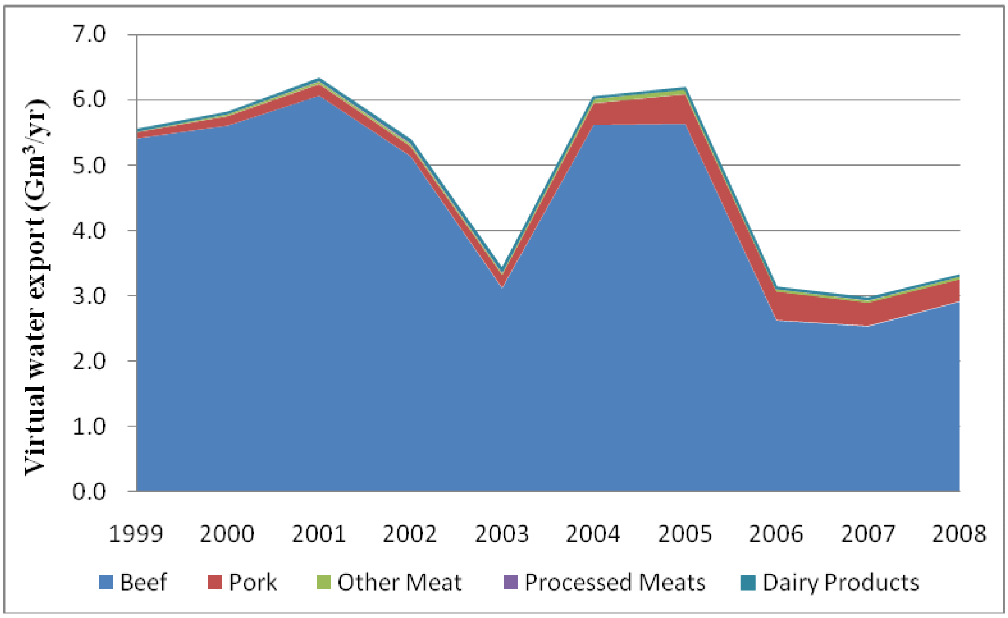

Fig. 20. Annual virtual water export of livestock products from Alberta (1999-2008)

Virtual water imports of livestock products were marginal compared to virtual water exports. The average virtual water imports were 0.12 Gm3/yr during 1999-2008 (Fig. 21), which was 2.5% of the average virtual water exports. Beef accounted for over 50% of the total virtual water imports. The annual virtual water imports are shown in Fig. 22.

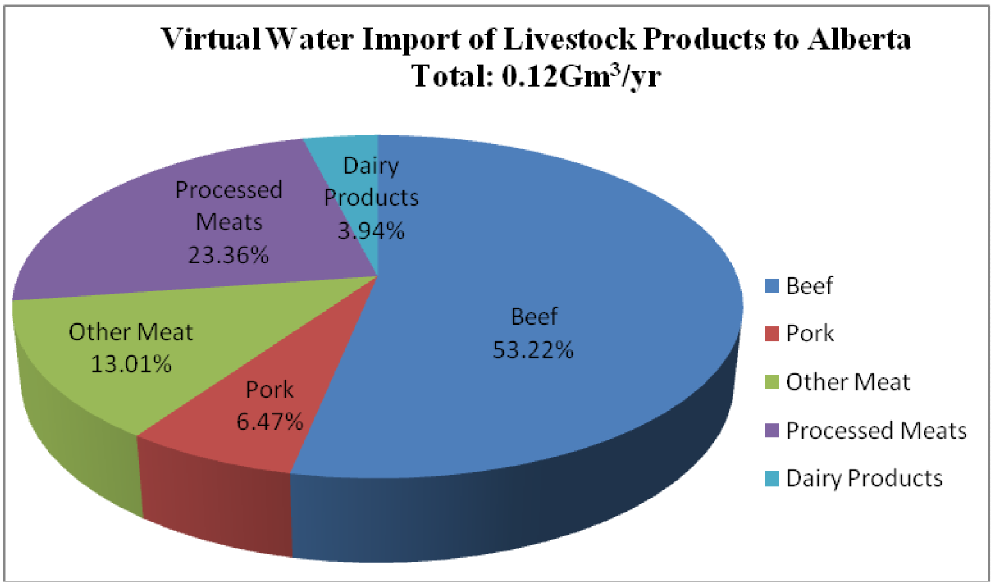

Fig. 21. Average virtual water import of livestock products to Alberta (average 1999-2008)

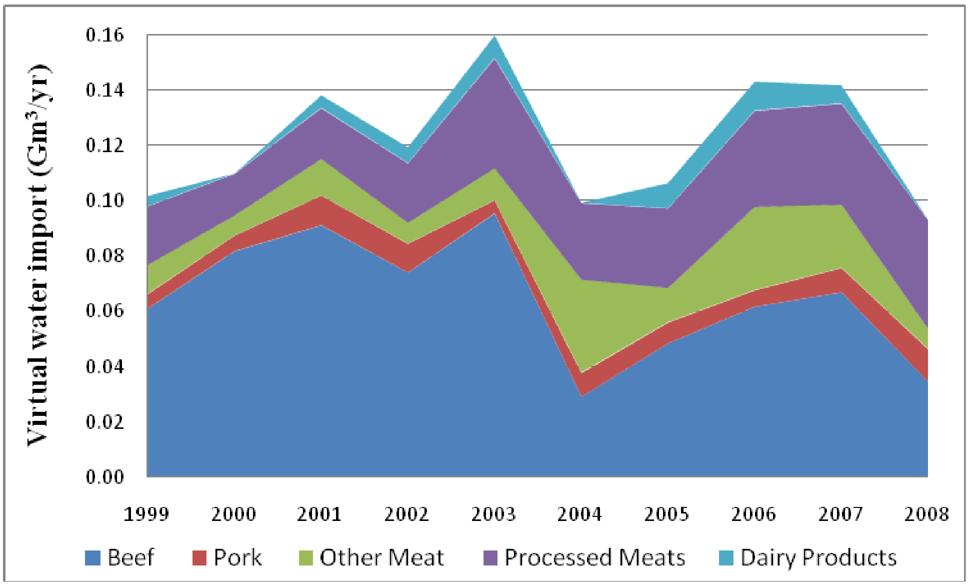

Fig. 22. Annual virtual water import of livestock products to Alberta (1999-2008)

The average annual net virtual water imports of livestock products were

4.69 Gm^3/yr. It is very clear that virtual water exports played an important role in shaping virtual water trade of livestock products in Alberta (Fig. 23). On a per capita basis, the average annual net virtual water imports were 1485 m^3/cap/yr.

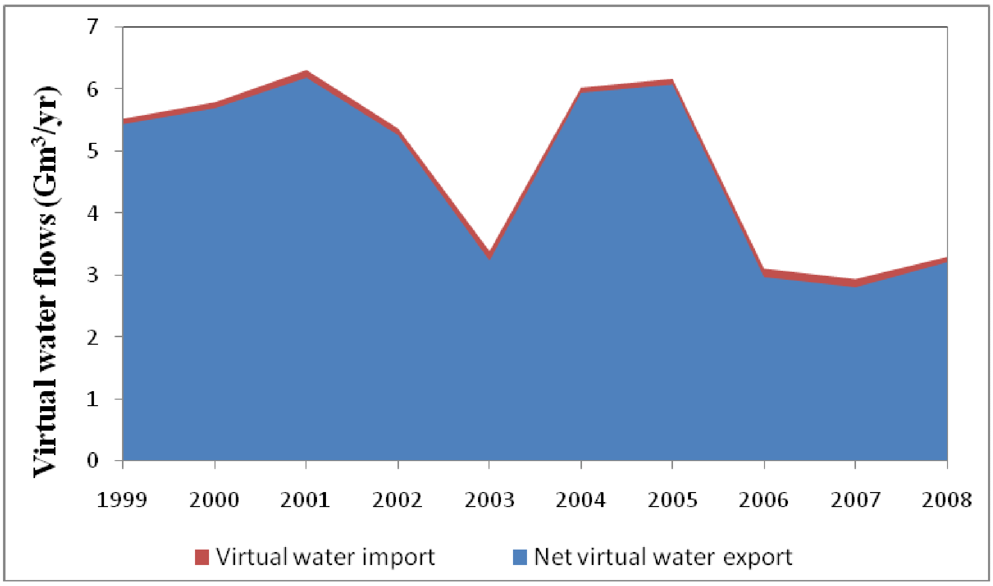

Fig. 23. Annual net virtual water export of livestock products from Alberta (1999-2008)

3.5. Virtual water trade of Alberta

The average virtual water exports of crop and livestock products were 16.91 Gm^3/yr. The average virtual water imports of crop and livestock products were 0.85 Gm^3/yr. This gives the average net virtual water exports of 16.06 Gm^3/yr. On the per capita basis, the average net virtual water exports were 5083 m^3/cap/yr. This means that, on average, each resident in Alberta exported 5083 m^3/cap/yr each year. According to Hoekstra and Chapagain (2007), the water footprint of Canada was 2049 m^3/cap/yr during 1997-2001. The average net virtual water exports from Alberta were almost 2.5 times of the water footprint of Canada. It is obvious that domestic production of crop and livestock products was mainly used for food exports to other countries. The annual virtual water flows are shown in Fig. 24.

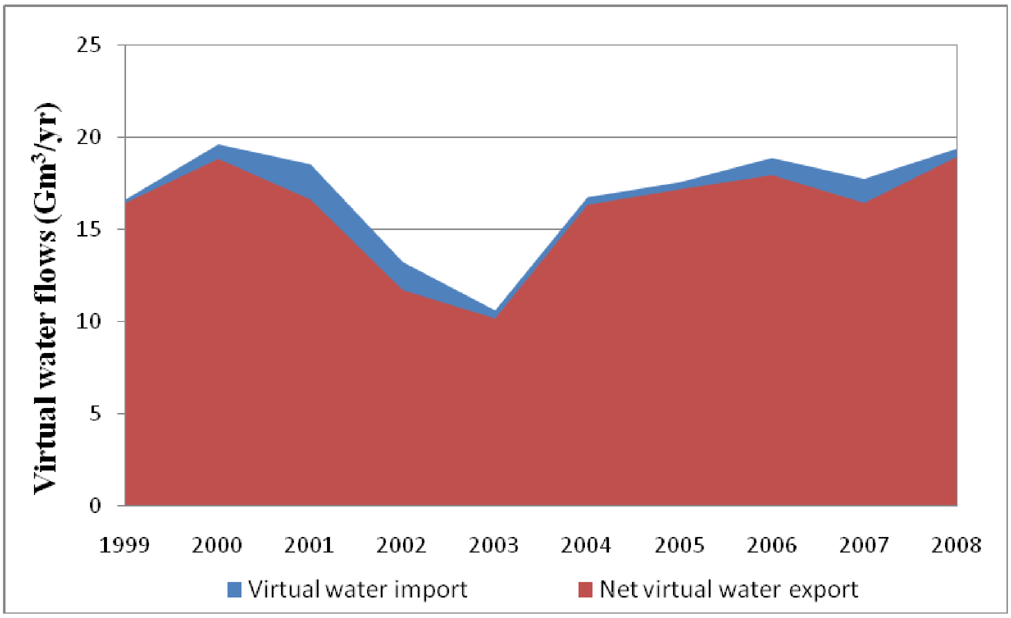

Fig. 24. Annual virtual water flows of Alberta (1999-2008)

The breakdown indicates that wheat, beef and canola were the three major products for net virtual water exports (Fig. 25). They combined accounted for over 99% of the total net virtual water export from Alberta. Particularly for wheat, it accounted for almost half of the total net virtual water export.

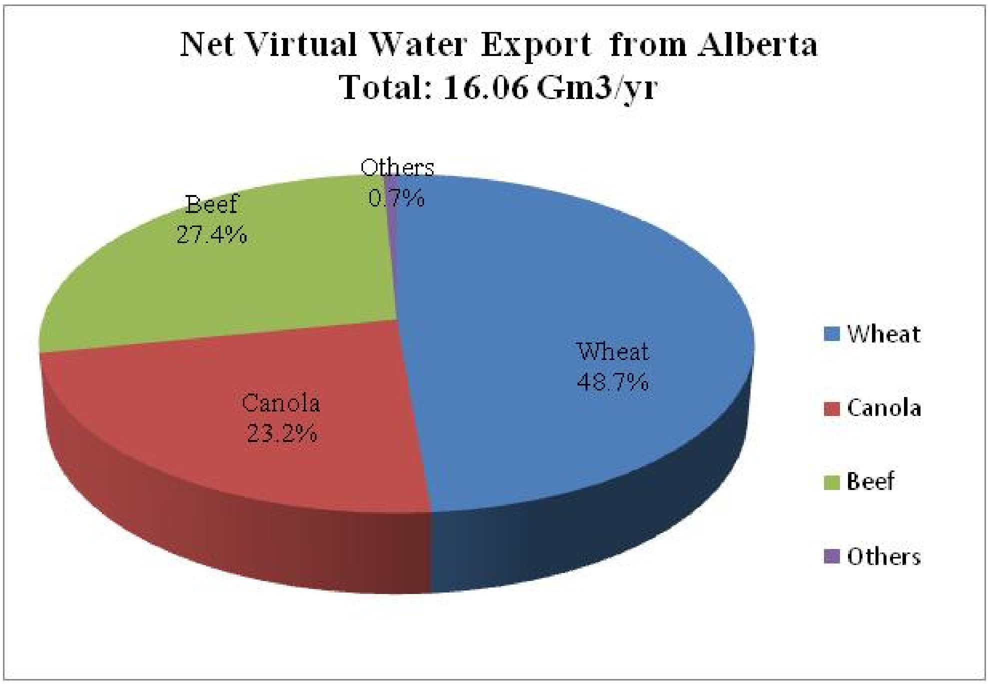

Fig. 25. Breakdown of net virtual water export from Alberta (average of 1999-2008)

4. Impacts of virtual water flows

The destinations of imports and exports have been collected for crop products. Detailed information of destinations of imports and exports of livestock products was not obtained. Hence, in this section, only the virtual water exports of crop products from Alberta were reported. The average annual virtual water export was 12.10 Gm^3/yr during 1999-2008. The largest virtual water importers were Japan, Mexico, the US, China, Iran and Indonesia (in a decreasing order), and those countries accounted for 57% of the total virtual water exports from Alberta (Fig. 26). It is clear that Alberta had virtual water exports to almost all countries in the world, particularly those in East and South and Southeast Asia, Middle East and North Africa, and many countries in South America (Fig. 27). The average annual virtual water export was 0.73 Gm^3/yr during 1999-2008, and the US alone accounted for over 96% of the total virtual water imports to Alberta (Fig. 26).

Virtual water losses were calculated as the difference between virtual water export from Alberta and virtual water import in the importing counries. Virtual water import was estimated by multiplying the import volumes by the WF of importing commodities of the importing countries (in other worlds, for this estimation, it was assumed that the importing commodities were produced domestically in the importing countries). In the calculation, wheat was not planted in Indonesia. In this case, the global average water footprint of wheat was used.

For the top six virtual water importers of Alberta, virtual water losses occurred in all countries except Iran (Table 2). This means that, at the global level, crop trade of Alberta did not help improve water use efficiency. On the contrary, crop trade resulted in even lower water use efficiency. For example, the virtual water export from Alberta to Japan was 2.41 Gm^3/yr. However, if Japan produced the traded crops, it would only need 1.06 Gm^3/yr. This resulted in a virtual water loss of 1.35 Gm^3/yr. In other words, water use efficiency was 230% lower due to the crop trade between Japan and Alberta. The reason for this low efficiency is due to the higher water productivity in importing countries than Alberta. For example, the WF of wheat in Alberta was 1635 m^3/ton, but it was only 734 m^3/ton in Japan. The general high WF in Alberta is mainly due to two reasons: first, rainfed agriculture was dominant in Alberta; second, precipitation was low. Due to the low precipitation and dominant rainfed agriculture, crop yield of crops was generally low and water use efficiency was low, leading to high water footprint. Iran was the only country with virtual water gain from the trade. Iran had a generally higherWF than Alberta, or lower water use efficiency.

Table 2. Virtual water loss due to crop exports from Alberta

Importers	**VWE from Alberta**	**VWI**	**Virtual water loss**
	Gm^3/yr	Gm^3/yr	Gm^3/yr
Japan	2.41	1.06	1.35
Mexico	1.25	1.12	0.13
US	1.21	0.63	0.58
China	1.07	0.69	0.38
Iran	0.49	0.91	-0.42
Indonesia	0.47	0.39	0.08

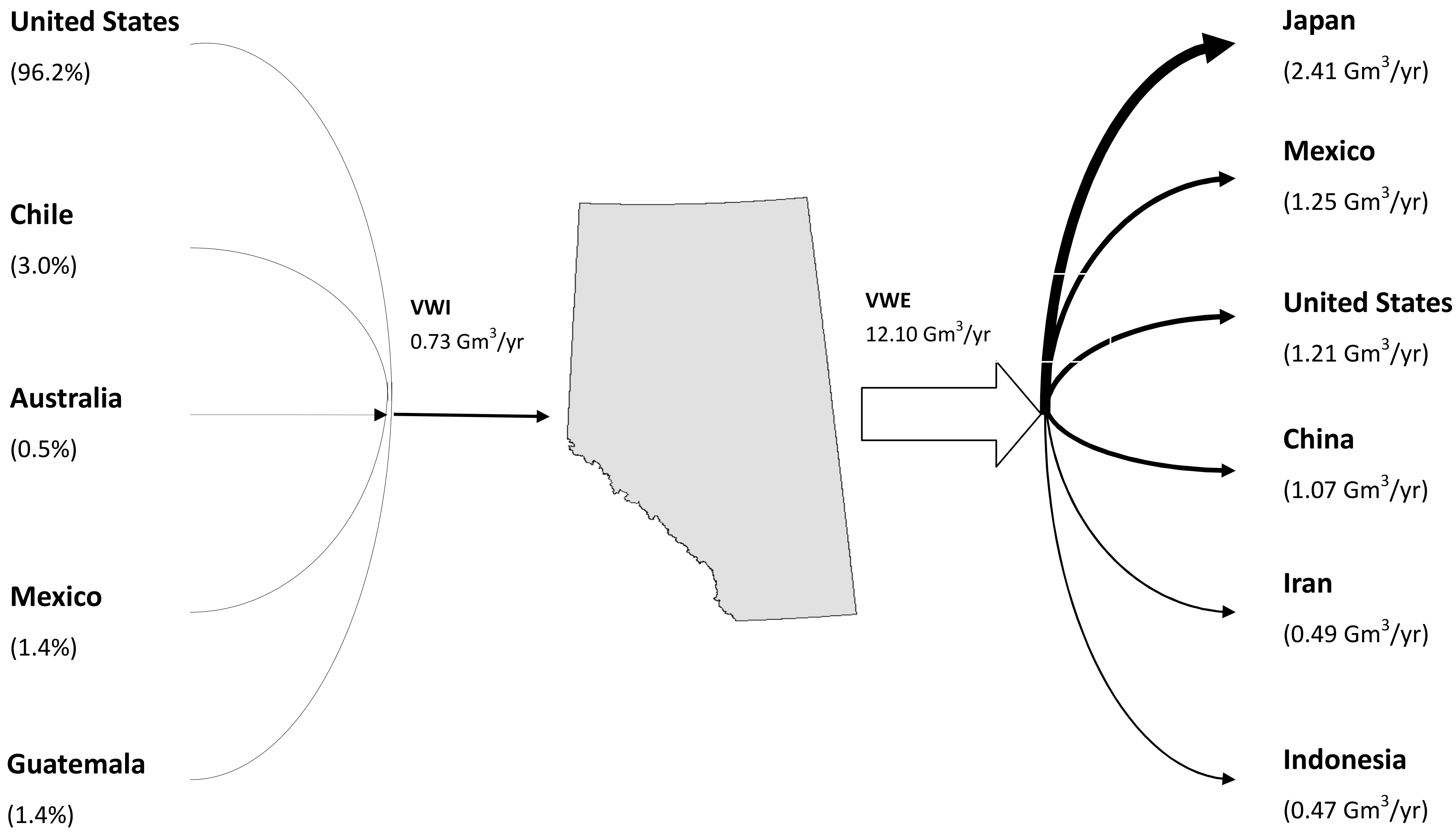

Fig. 26. Sources and destinations of virtual water trade of crop products in Alberta

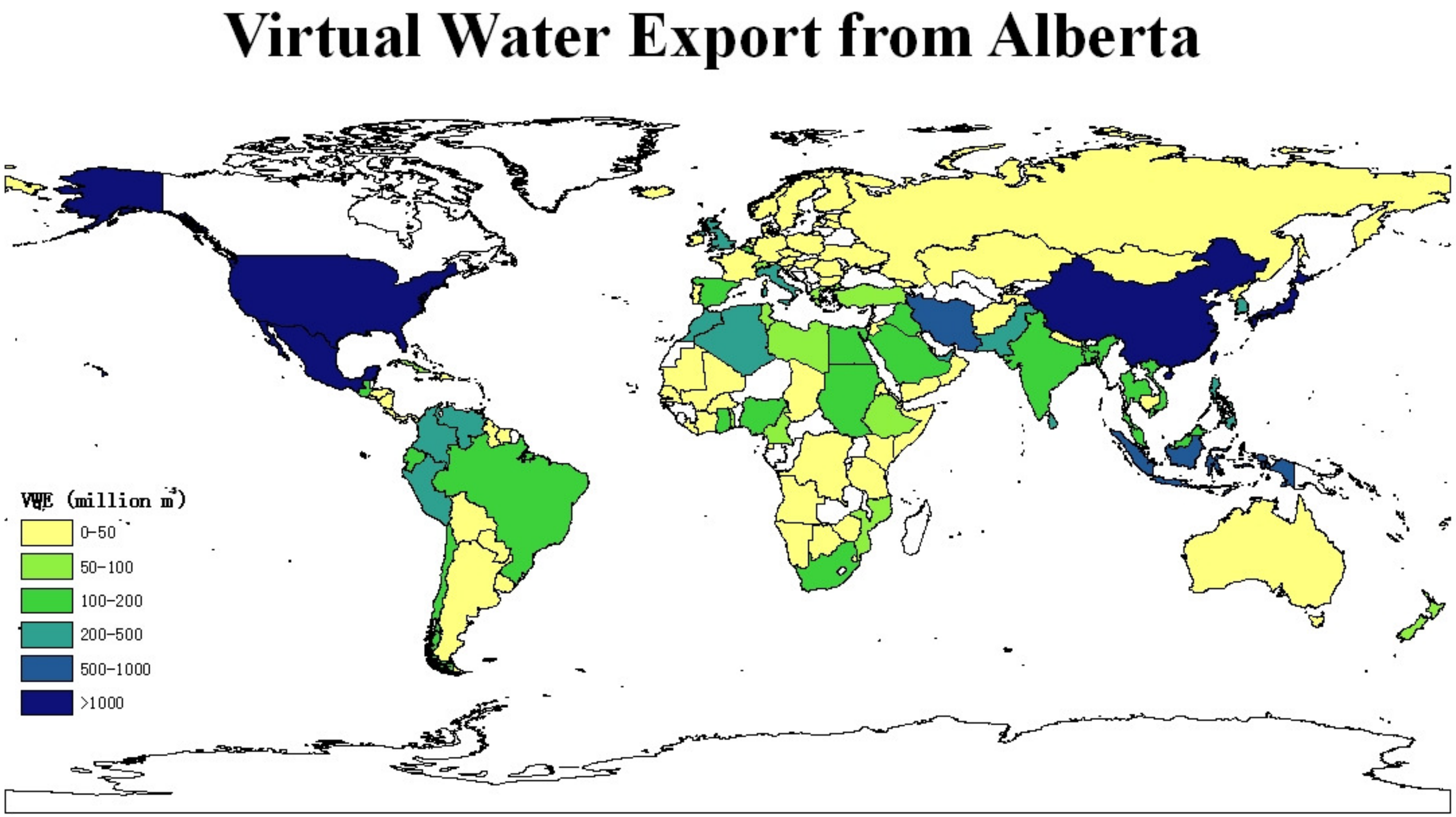

Fig. 27. Distribution of virtual water exports of crop products from Alberta

5. Relevance of the obtained results for Alberta and its water policy

Competition of water use among agriculture, thermal power, municipality, industry, and water injection becomes intense in Alberta. Regional water scarcity is a major constraint for future sustainable development. Our results show a large amount of water is not consumed by the local people; on the contrary, it is used by people outside Canada through food trade. Equivalently, each person in Alberta exports 5083 m^3 of water in terms of net virtual water exports. Our estimation also shows that virtual water exports from Alberta did not help enhance water use efficiency at the global level. Top virtual water importers such as Japan, Mexico, US and China generally had higher water productivity and lower water footprint of crop products than Alberta. Crop trade between Alberta and other countries leads to virtual water losses on the global scale. Hence, future water and food trade policies have to be carefully formulated by considering not only the improvement of water use efficiency among sectors in Alberta, but also the enhancement of water use efficiency at the global level.

6. Limitation of this study

This study is so far, to our best understanding, the first comprehensive one for the virtual water assessment of Alberta. Giving the current absence of such assessments, we consider the results from this report encouraging and reasonable as an early approximation. Nonetheless, a number of limitations in our study still remain. First, the water footprint of wheat, barley and canola may be largely influenced by the lack of locally available climate, soil and management data. It is very difficult to obtain these data from the local agencies or the Internet. Many efforts have been made but the difficulties lead to the application of such data from global database, e.g. climate data from the Climate Research Unit of the University of East Anglia in UK. Access of local data is a key for the more accurate estimation. Second, the lack of locally available information associated with the limited time does not allow estimation of water footprint of livestock products. Instead, the average water footprint of Canada was used for the calculation. Third, virtual water flows were only assessed for crop and livestock products but not for energy carriers. Energy sector is important for Alberta and virtual water flows through energy trade is interesting. A comprehensive assessment requires a good knowledge of water use in the supply chain of energy production. Last but not least, virtual water flows between Alberta and destination countries were only assessed for crop products mainly due to the unavailability of data for livestock products. To conclude, the data issue was more serious than expected when the research was conducted. Availability of local data will no doubt improve the accuracy of the study, but a lot of efforts are still needed to further the sharing of data.

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Appendix 1. Input data list for this project

Data name	Required information	Spatial Resolution	Data Source
DEM map	- Elevation	5 arc-min	GTOPO30http://www1.gsi.go.jp/geowww/globalmap-gsi/gtopo30/gtopo30.html
Crop distribution map	-Harvest area of wheat, barley, canola in each grid cell	5 arc-min	SAGE and local statistics http://www.sage.wisc.edu/
Soil map	(1) Number of soil layers; (2) Soil Hydrologic group; (3) Maximum rooting depth (mm); (4) Soil depth of each layer ; (5) Bulk density (g/cm^3); (6) Saturated hydraulic conductivity (mm/hr); (7) Organic carbon content; (8) Clay content; (9) Silt content; (10) Sand content; (11) Rock fragment content; (12) Soil albedo	5 arc-min	ISRIC http://www.isric.org/UK/About+ISRIC/Projects/Track+Record/WISE.htm
Climate station data	Monthly data on (1) precipitation; (2) max temperature; (3) Min temperature; (4) number of wet days	30 arc-min	CRU http://www.cru.uea.ac.uk/
Management data	Irrigation districts	-	Local statistics
Food trade data	-Exports/Import of wheat, canola, beef, barley, pork and other agricultural products in Alberta for different periods, destination of exports	At Alberta provincial level	Local statistics

Appendix 2. Important events and distinctions

October 19 to 22, 2009: Training course on modeling and simulating the food-water nexus with GEPIC. This course was organized in Edmonton, Alberta, and Prof. Junguo Liu gave lectures to 12 participants from universities, research institutes and governmental organizations.

February 24 2010: Teleconference with WWF-Canada. Tony Maas (director of freshwater Program) and Eric Mysak (Freshwater Research Assistant) from WWF-Canada joined the teleconference with Prof. Junguo Liu. Both of them would like to collaborate for the assessment of water footprint in Canada.

September 7 2010: Meeting on Water Footprinting and Accounting in Stockholm, Sweden. This meeting was organized by UNEP in Stockholm, and Prof. Junguo Liu was invited to give a talk on *Water Footprint Assessment: from global to local*. The virtual water assessment of Alberta was talked as a case study.

September 9 2010: Water Footprint Network Partner Forum in Stockholm, Sweden. This forum was organized in the World Water Week in Stockholm. During this forum, Prof. Junguo Liu was invited to give a talk on the activities of Beijing Forestry University on water footprint network. The case study of virtual water assessment of Alberta was presented.

September 12-30 2010: Meeting between Prof. Junguo Liu and Dr. Karim Abbaspour of Eawag in Beijing, China. Prof. Liu invited Dr. Abbaspour to visit Beijing Forestry University and they shared information of the project progress.

October 26-28 2010: Water Footprint Training Course in China. Beijing Forestry University organized the 1st training course on water footprint in China. Twenty-three participants from mainland China, Hong Kong, India and UK were invited to the course. Prof. Junguo Liu and Prof. Arjen Hoekstra gave lectures on water footprint and virtual water during the course. Virtual water assessment of Alberta was talked as a case study to the participants.

November 25-26 2010: Strategic Workshop "Accounting for water scarcity and pollution in the rule of international trade" in Amsterdam, the Netherlands. This workshop was organized by the Water Footprint Network and co-sponsored by the European Science Foundation and the United Nations Environment Programme. During this workshop, Prof. Junguo Liu was invited to give a talk on virtual water assessment in China and Alberta.