PRINCIPAL FACTORS AFFECTING *ESCHERICHIA COLI* AT LAKE WINNIPEG BEACHES, MANITOBA, CANADA

Interim Report

By Dwight Williamson, Wendy Ralley, Alexandra Bourne, Nicole Armstrong, Rollie Fortin, and Colin Hughes

January 29, 2004

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FOREWORD

The following report provides a brief overview of extensive studies undertaken in the summer and fall of 2003 to determine the source of *Escherichia coli* bacteria and the mechanism of transfer to Lake Winnipeg beaches. These studies were undertaken in response to the posting of signs at two Lake Winnipeg beaches for brief periods advising against bathing because of elevated densities of *E. coli*. These findings will be documented in more detail in a technical report and a manuscript will be prepared for submission to a peer-reviewed, scientific journal.

The findings identified in the following report significantly enhance the present understanding of water quality at Lake Winnipeg beaches and the largely natural processes responsible for transferring and dispersing bacteria from the foreshore beach region to bathing water. This phenomenon is likely restricted to large lakes such as Lake Winnipeg due to extensive wave action and daily wind-driven water level fluctuations and likely does not occur to any significant extent on smaller lakes. To the best of the authors' knowledge, the findings identified in the following report have not been previously reported from any other large lake situated at this northern temperate latitude in Canada.

These findings will allow a greater degree of protection to be provided to public health, particularly as intensive work continues to refine the predictive model linking wind-induced water level changes in the south basin of Lake Winnipeg with the transfer of indicator bacteria from the foreshore beach region to bathing water.

Williamson, D.A., W.E. Ralley, A. Bourne, N. Armstrong, R. Fortin, and C.E. Hughes. 2004. Principal factors affecting *Escherichia coli* densities at Lake Winnipeg beaches. Water Quality Management Section. Manitoba Water Stewardship. Manitoba Water Stewardship Report No. 2004-01.

SUMMARY

Beginning in the early 1980s, numerous beaches have been routinely monitoring each summer in Manitoba, including many of the most popular beaches on Lake Winnipeg. Typically, occasional exceedances of Manitoba's recreational water quality objective of 200 *Escherichia coli* / 100 mL have been observed each year on several of the major Lake Winnipeg beaches, but with the exception of only two occasions, densities returned quickly to normal levels that were again within compliance. Three beaches were posted with signs advising against swimming for a brief period in the fall of 1993 and two beaches were posted with advisory signs for brief periods during the summer of 2003.

Lake Winnipeg receives drainage from nearly 1,000,000 km^2, beginning with streams flowing from the eastern slope of the Rocky Mountains in Alberta, much of Saskatchewan, a large portion of northwestern Ontario, and parts of eastern North Dakota and western Minnesota. Within the Manitoba portion of the drainage basin, a population of approximately 650,000 is located in the City of Winnipeg, approximately 65 km upstream of Lake Winnipeg. The south basin of Lake Winnipeg is also surrounded by many small communities and numerous cottages. The Manitoba portion of the basin contains both a large agricultural sector that has shifted production in recent years to greater reliance on livestock, and large populations of natural wildlife.

Considerable work has been undertaken in recent years to identify the source of the occasional occurrences of elevated *E. coli* densities at the Lake Winnipeg beaches. Focus of past studies were directed to the obvious large domestic sewage discharges from the City of Winnipeg, non-point source run-off from livestock operations, and natural wildlife populations throughout the region, but these failed to identify either single or combined sources of bacteria that could account for the infrequent, but relatively high densities observed at several of the Lake Winnipeg beaches.

Following posting of advisory signs at two Lake Winnipeg beaches during the summer of 2003, extensive additional studies were initiated. Multiple techniques were employed to identify the specific origins of *E. coli*, studies were undertaken to determine whether re-growth was potentially occurring in both Lake Winnipeg water and Lake Winnipeg bottom sediments, studies were undertaken to determine die-off rates in both water and sediments, studies were undertaken to again assess the likelihood that the most obvious major sources of bacteria within the basin were responsible for the intermittent elevated bacteria densities, and studies were undertaken to determine whether the source of elevated *E. coli* might originate from foreshore beach regions.

It was concluded that elevated densities of *E. coli* were present in the surficial water underlying sand in the foreshore beach region at many Lake Winnipeg beaches, that these bacteria populations were being transferred periodically to bathing water with wind-induced water level changes, and that the majority of *E. coli* originated from animal sources rather than humans with gulls and terns being the largest single animal contributors. There was strong presumptive evidence to indicate that the *E. coli* population in both the foreshore beach region and bathing water resulted from bacterial re-growth and that this re-growth likely occurred in the wet sand underlying the foreshore beach region. Densities of *E. coli* bacteria were correlated with wind-induced water level changes in the south basin of Lake Winnipeg, with short-term water level changes accounting for approximately 40 % of the observed variability in bacteria densities at Gimli and West Grand beaches. This identified mechanism of transport from the foreshore beach region to bathing water is likely an important mechanism only in large lakes such as Lake Winnipeg because of the absence of significant wave action and associated daily water level fluctuations in smaller recreational lakes.

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INTRODUCTION

Water quality at many of Manitoba's most popular bathing beaches has been monitored each year since the early 1980s for recreational water quality indicator bacteria. A number of these beaches are located in the south basin of Lake Winnipeg (Figure 1). Indicator bacteria are those organisms that may not be necessarily pathogenic themselves, but when densities become elevated, so do densities of other pathogenic organisms. Studies conducted elsewhere and described by Williamson (1985, 1988a, 1988b, 1988c) have linked increased densities of indicator organisms to increased illness rates among bathers. The most common indicator organism used by most jurisdictions in North America at the present time is the bacteria *Escherichia coli*.

There are two general types of illnesses most commonly contracted by bathers. First, infections of the eyes, ears, nose, and throat can be caused by bacteria such as *Pseudomonas aeruginosa* and *Staphylococcus aureus*. These infections are most frequently transferred from one bather to another in crowded swimming areas. Second, stomach upset or gastroenteritis is typically caused by *Salmonella* bacteria or enteric viruses. Bathers have been found to contract slightly increased rates of gastroenteritis when *Escherichia coli* or fecal coliform bacteria densities become elevated. Symptoms of gastroenteritis include mild fever, vomiting, diarrhea and stomach cramps.

Manitoba has established a water quality objective to protect public health at recreational beaches that was derived directly from guidance provided by a committee of federal, provincial, and territorial health officials (Health and Welfare Canada 1992). Manitoba's water quality objective is 200 *E. coli* / 100 mL (Williamson 2002). Occasionally, *E. coli* densities exceed the water quality objective at Lake Winnipeg beaches, but these periodic elevated densities normally return to low levels quickly.

A protocol was developed jointly by environment and health officials in 1994 to guide beach posting decisions in Manitoba. When monitoring evidence indicates that densities are persisting above the recreational water quality objective, the Medical Officer of Health can post signs advising against swimming. Lake Winnipeg beaches have been posted with warning signs on only two occasions in the past. Three beaches located on the west-side of Lake Winnipeg were briefly posted with advisory signs in the early fall of 1993. West Grand and Gimli beaches were briefly posted with advisory signs in the summer of 2003.

Studies have been underway for a number of years to identify the source of bacteria contributing to the occasional elevated bacteria densities observed at Lake Winnipeg beaches. Similar to many beach water quality studies conducted elsewhere, focus was placed on linking contributions from single large or multiple external sources such as municipal wastewater, livestock, or wildlife populations. However, direct linkages could not be successfully established. Recently, advanced analytical techniques have become commercially available to discriminate between animal and human sources of *E. coli* bacteria and when animal sources dominate, to identify the contributing species (Parveen *et al.* 1999, Wiggins *et al.* 1999, Carson *et al.* 2001, Scott *et al.* 2002). Following posting of advisory signs in the summer of 2003,

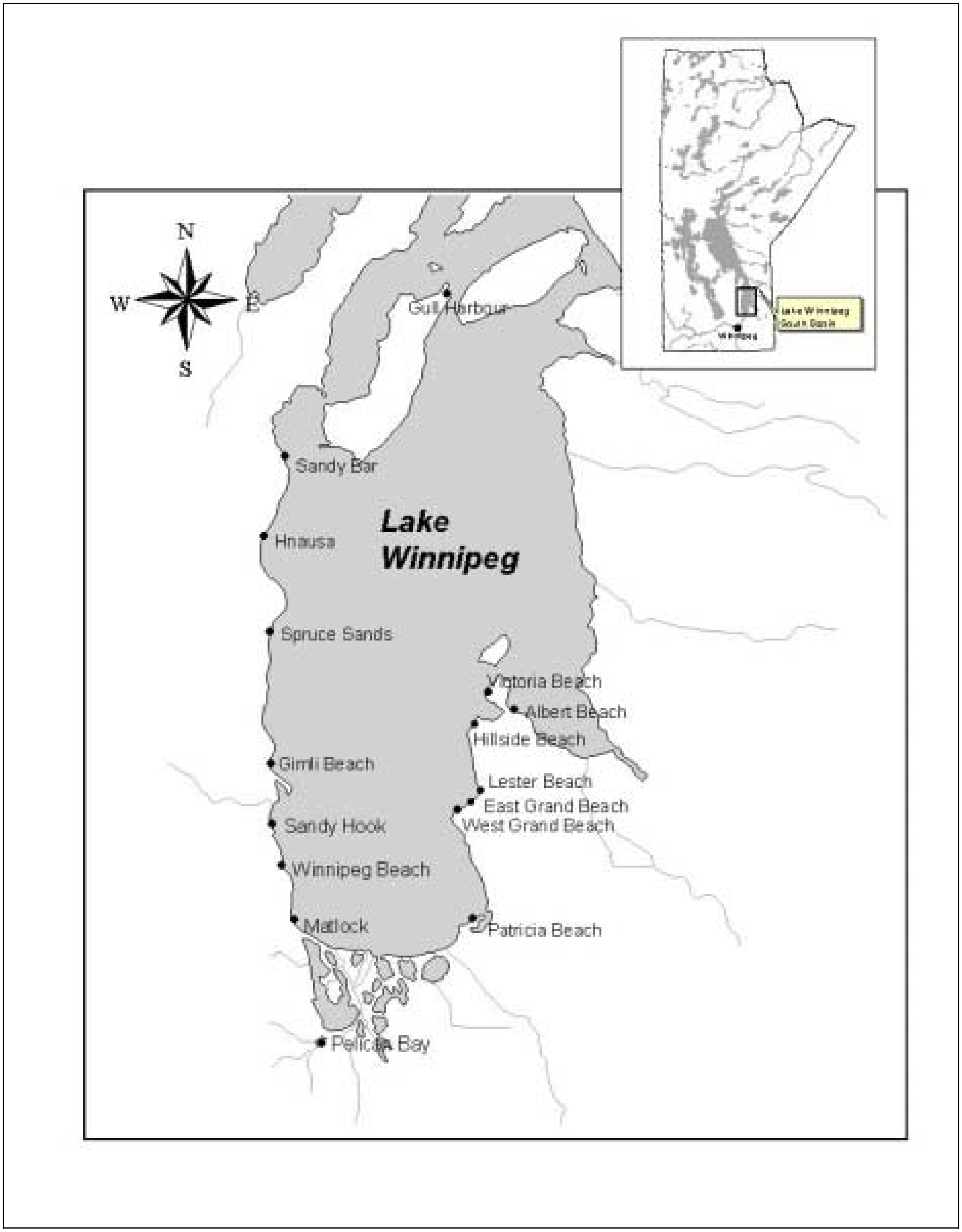

Figure 1. Major beaches located along the shoreline of the south basin of Lake Winnipeg.

extensive studies with these advanced techniques were undertaken to identify the source or sources of fecal bacteria being periodically dispersed to Lake Winnipeg bathing water and to identify the likely transport mechanism. If the major source was identified to be either human or livestock, it was thought that potential remedial measures could be implemented.

Studies undertaken in 2003 involved six major components: (1) five separate techniques were employed to identify the source of *E. coli* being contributed to Lake Winnipeg; (2) experiments were conducted to determine survival duration of *E. coli* in both Lake Winnipeg water and bottom sediments to indicate whether survival was sufficient to allow transport from major point or nonpoint sources to beach areas; (3) experiments were conducted to determine whether *E. coli* could potentially re-grow in both Lake Winnipeg water and bottom sediments; (4) widespread sampling was conducted of bathing water, bottom sediments, and surficial water underlying foreshore beaches to identify *E. coli* reservoirs potentially available for transport to bathing areas; (5) DNA profiles of *E. coli* were assessed to determine whether major clonal groups were present, thus indicating whether or not the observed populations may have arisen from re-growth; and (6) modelling was undertaken to statistically link physical lake processes with observed bacteria densities in bathing water.

METHODS

Water samples from bathing areas were collected in approximately 0.75 m of water at approximately 0.25 m below the surface. Bottom sediments were collected by hand from near-shore regions with water depths up to approximately 0.75 m and with either Ponar or Ekman dredges from deeper, off-shore regions. Surficial water underlying foreshore beach sand was obtained by excavating a shallow pit (usually less than 0.25 m in depth) then allowing the excavation to fill with water. Densities of *E. coli* were measured in bathing water, bottom sediments, and surficial water underlying foreshore beaches by standard membrane filtration and most probable number techniques by EnviroTest Laboratories (Winnipeg MB). Experiments to determine survival of *E. coli* in water and bottom sediments were conducted by HydroQual Laboratories Ltd. (Calgary AB) along with experiments to assess re-growth potential. HydroQual Laboratories Ltd. analyzed samples for the presence of human gene biomarkers on enterococcus and compared these to local fecal reference material with multiple antibiotic resistance methods. Animal versus human sources of isolated *E. coli* were assessed with DNA ribotyping techniques by Source Molecular Corporation (Miami FL). Isolated *E. coli* were also compared to local fecal reference material by Source Molecular Corporation with similar DNA analysis. Source Molecular Corporation also analyzed samples for the presence of human viruses. Local fecal reference specimens were collected and provided to both HydroQual Laboratories Ltd. and Source Molecular Corporation from ring-billed gulls, Canada geese, common tern, dairy cattle along with beef cattle from pasture and range lands, swine, horse, and dog. Lake Winnipeg water level data were obtained from Water Survey of Canada and meteorological data were obtained from Environment Canada's weather stations at Gimli and Victoria Beach.

RESULTS AND DISCUSSION

Recent publications by Whitman and Nevers (2003) and Alm *et al.* (2003) clearly identify beach sand as a reservoir capable of supplying large densities of *E. coli* and other organisms to near-shore bathing water at several Lake Michigan beaches. Although the actual mechanism leading to the initial population of the Lake Michigan beaches with *E. coli* or other fecal organisms is not well understood, strong relationships have been statistically linked between densities of these organisms in beach sand and densities in nearby bathing water. Following studies at the 63rd Street Beach in Chicago IL, Whitman and Nevers (2003) concluded that beach sand:

(1) *"plays a major role in bacterial lake water quality";*
(2) *"is an important source of indicator bacteria to the water rather than a net sink";*
(3) *"may be environmentally, and perhaps hygienically, problematic";*
(4) *"is possibly capable of supporting an autochthonous, high density of indicator bacteria for sustained periods, independent of lake, human, or animal input".*

Assessment of point and nonpoint sources of *E. coli* populations that could have been dispersed to bathing beaches on Lake Winnipeg during the summer and fall of 2003 failed to identify sufficient sources to account for the periodic observed densities in near-shore bathing water. Indeed, much of south and central Manitoba including the Lake Winnipeg region, experienced drought during the summer of 2003 resulting in little or no flow from many small regional streams. Despite this, relatively high densities of *E. coli* were measured periodically and led to the posting of bathing advisory signs at two beaches on separate occasions. Experiments conducted to determine survival times of *E. coli* in water and bottom sediments confirmed results well documented elsewhere (*e.g.,* Bowie *et al.* 1985) that die-off is rapid in water with densities declining from 1000 organisms / 100 mL to 200 organisms / 100 mL within approximately 48 hours (Figure 2). This precludes direct contamination from the large urban population located within the City of Winnipeg since travel time via the Red River from the City of Winnipeg to Lake Winnipeg, located approximately 65 km downstream, is much longer than 48 hours. Experiments confirmed however, that *E. coli* could survive for relatively long periods of time in Lake Winnipeg bottom sediments (Figure 3). Theoretically, *E. coli* contaminated sediments could be transported to beach areas. However, a reservoir of bottom sediments containing elevated *E. coli* densities in the south basin of Lake Winnipeg that could account for the observed densities in near-shore bathing water has not been detected despite repeated sampling over several years.

Surficial water samples collected from sand underlying the foreshore beaches yielded relatively high densities of *E. coli* at a number of beaches (Table 1) with densities generally higher at beaches located along the west side of the south basin relative to beaches on the east shore (Figures 4 and 5). However, simply identifying a nearby reservoir of *E. coli* was not sufficient by itself to address Lake Winnipeg beach water quality issues since a mechanism must also exist to transport *E. coli* from the foreshore beach area to bathing water. Consequently, daily lake level and meteorological data were statistically regressed with mean *E. coli* densities at

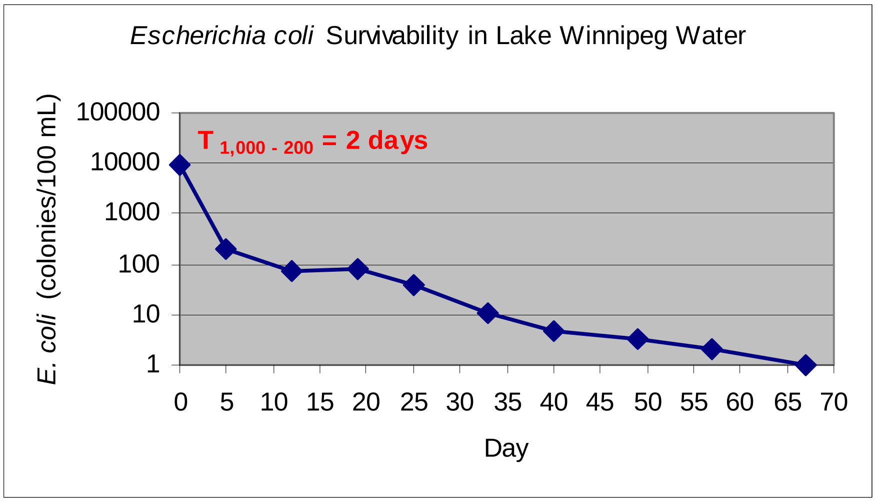

Figure 2. Survival of *E. coli* in Lake Winnipeg water with time of initial die-off from 1000 organisms / 100 mL to 200 organisms / 100 mL calculated to be approximately 2 days.

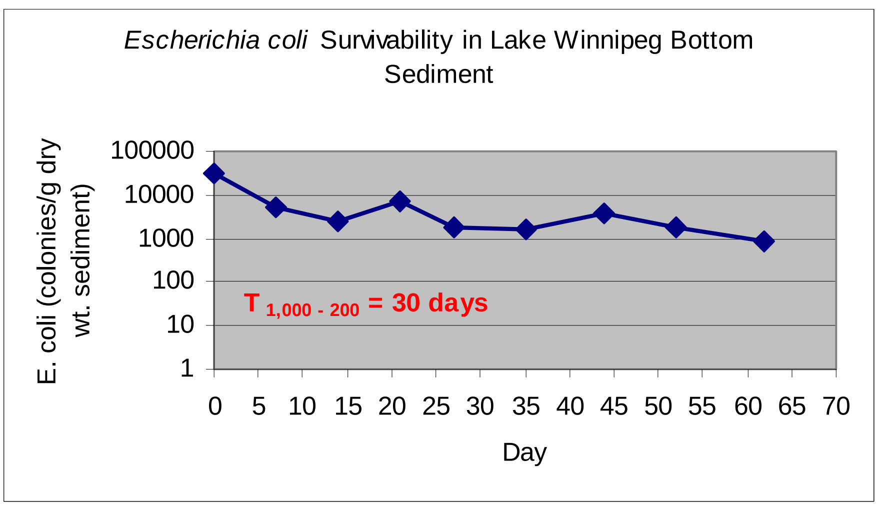

Figure 3. Survival of *E. coli* in Lake Winnipeg bottom sediments with time of initial die-off from 1000 organisms / 100 mL to 200 organisms / 100 mL calculated to be approximately 30 days.

Table 1. Summary of *E. coli* densities (organisms / 100 mL) in bathing water and in surficial water underlying foreshore beaches during the summer and fall of 2003.

	Bathing Water		Surficial Water Underlying Foreshore Beaches	
	Geometric Mean	Maximum Daily Geometric Mean	Geometric Mean	Maximum Individual Sample
East-Side Lake Winnipeg Beaches				
Albert Beach	18	178	25	120
Victoria Beach	12	25	47	2300
Hillside Beach	26	382	41	230
Lester Beach	19	172	8	43
East Grand Beach	31	311	32	350
West Grand Beach	42	489	93	1500
Patricia Beach	47	392	8	230
West-Side Lake Winnipeg Beaches				
Gull Harbour Beach	92	209	71	4300
Sandy Bar Beach	34	390	19	80
Hnausa Beach	146	834	272	3600
Spruce Sands Beach	39	260	259	9300
Gimli Beach	70	1211	359	24000
Sandy Hook Beach	37	105	35	240
Winnipeg Beach	44	881	213	4300
Matlock Beach	49	703	11	20
Pelican Bay Beach	13	22	47	430

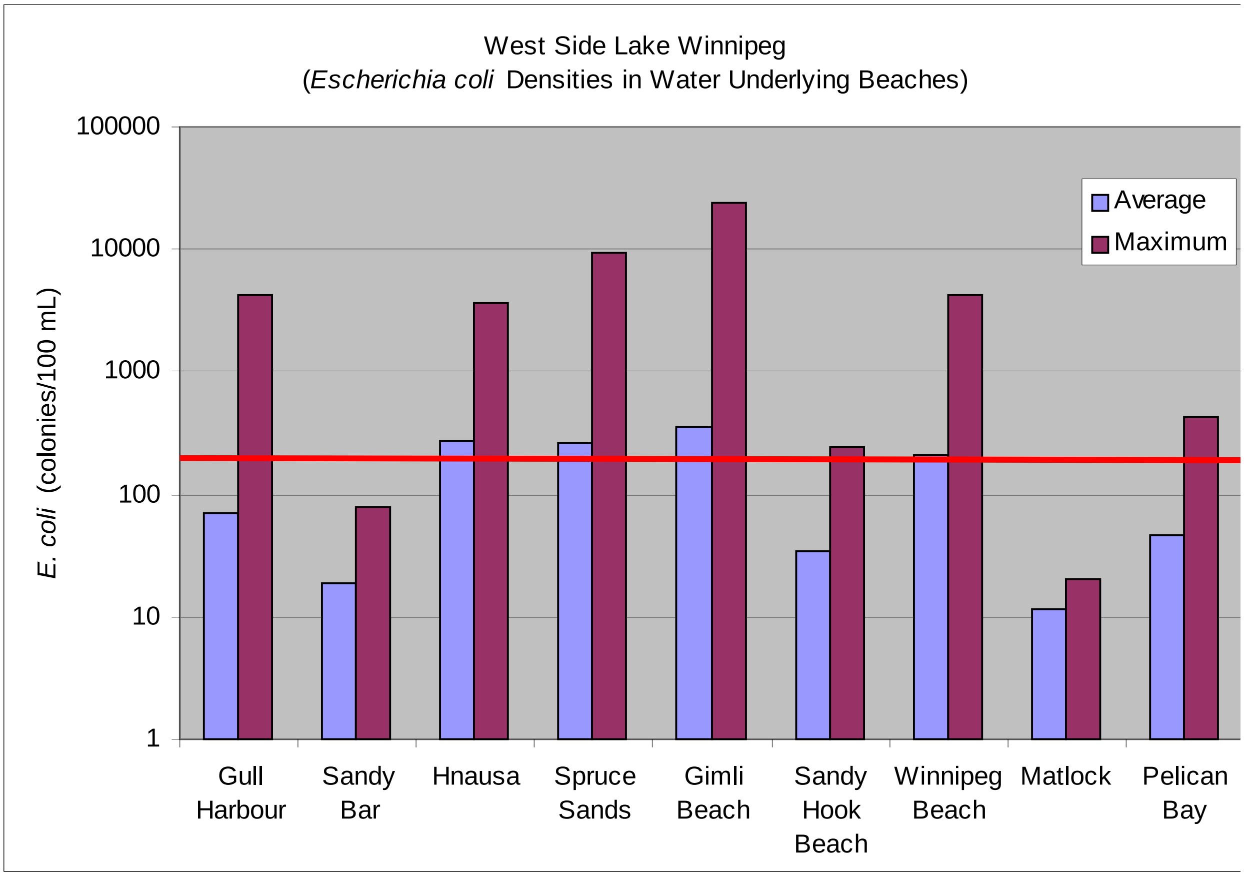

Figure 4. Average and maximum densities of *E. coli* measured in surficial water underlying the foreshore region of beaches located on the western shore of Lake Winnipeg.

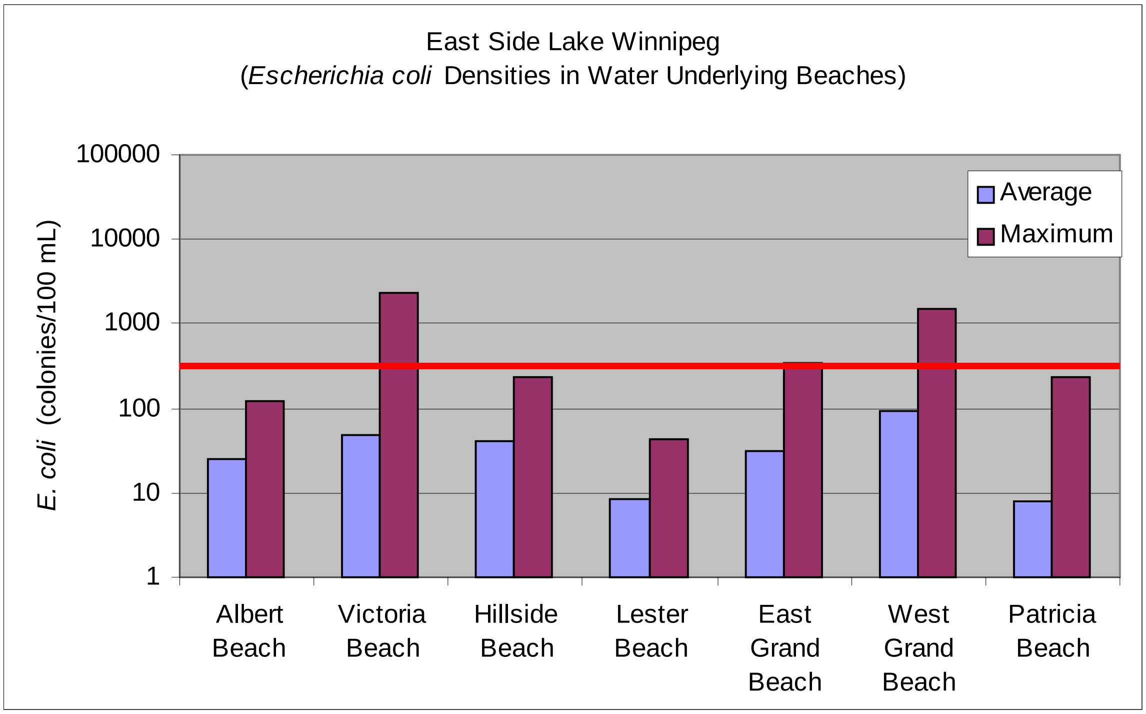

Figure 5. Average and maximum densities of *E. coli* measured in surficial water underlying the foreshore region of beaches located on the eastern shore of Lake Winnipeg.

Gimli and West Grand beaches. Focus was placed on these two locations because these were the beaches at which advisory signs were posted during 2003 and consequently, more bacteriological data were available relative to other beaches.

It was found that *E. coli* densities at both Gimli and West Grand beaches were significantly correlated with daily water level changes and that, during days when water levels were increasing, there was a much higher probability that *E. coli* would also increase to densities above the objective of 200 organisms / 100 mL. Conversely, during those days when water levels were receding, there was a much higher probability that *E. coli* densities would be low and well within compliance with the recreational water quality objective. At Gimli Beach, daily water level changes were calculated as the difference between the measured elevation on any given day relative to the mean lake level elevation observed during the previous six days and at West Grand Beach, daily water level changes were calculated as the difference relative to the mean observed during the previous five days.

The relationship between *E. coli* densities at Gimli Beach and water level changes during 2003 (Figure 6) followed the typical linear form ($p = 0.00017$; $r^2 = 0.4252$):

Log (Daily Geometric Mean *E. coli* Density (organisms / 100 mL))	=	2.00814	+	4.4042	×	Departure from Mean Water Level Observed During Previous 6 Days (m)

The relationship at Gimli Beach became slightly weaker when extended to 1999, but nevertheless, remained statistically significant.

The relationship between *E. coli* densities at West Grand Beach and water level changes for the period 1999 to 2003 (Figure 7) was as follows ($p = <0.0000$; $r^2 = 0.3951$):

Log (Daily Geometric Mean *E. coli* Density (organisms / 100 mL))	=	1.55813	+	2.55166	×	Departure from Mean Water Level Observed During Previous 5 Days (m)

To better understand the reason for this relationship, it is first necessary to describe several physical attributes of Lake Winnipeg that result in significant daily water level changes. A satellite image of Lake Winnipeg is shown in Figure 8. Lake Winnipeg is comprised of three major regions. Water flows into the south basin from the Red and Winnipeg rivers, and flows northward through the narrows region, eventually leaving the north basin via the Nelson River. However, during periods of northerly or north-westerly wind events, water from the north basin is moved upstream, through the narrows region and into the south basin. Consequently, water levels in the south basin periodically rise and fall due to the wind-induced southward flow of water from the north basin. As well, water levels can fluctuate from east to west or west to east within the south basin, again due to predominant wind patterns, but these latter water level changes are relatively minor compared to the north to south changes. Water level changes observed at Gimli during 2003 are shown in Figure 9. During one 6-day period in mid-June, water levels fluctuated by 0.6 m.

Second, it is necessary to understand the effect that water level changes and wave action have on a typical Lake Winnipeg beach. A beach profile is shown in Figure 10. The swash zone is defined as that area of the foreshore beach that is swept by wave action, with waves advancing up the beach due to wind action, receding back to the lake, then to be repeated at frequent intervals. As water levels increase due to the movement of large volumes of water into the south basin from the north basin due to wind action, the swash zone moves up the beach to a region that may not have been under wave action for some period of time (Figure 11). The regression analysis indicates that when this new swash zone is created, albeit temporarily, there is a much higher probability that *E. coli* densities in the bathing water will be elevated. This is likely because waves acting in the new swash zone will extract suspended sediments and surficial water underlying the new swash zone, along with associated *E. coli,* and then disperse these bacteria to the bathing area. As previously mentioned, *E. coli* populations are short-lived in water, and die-off to relatively low levels fairly quickly until the cycle is repeated.

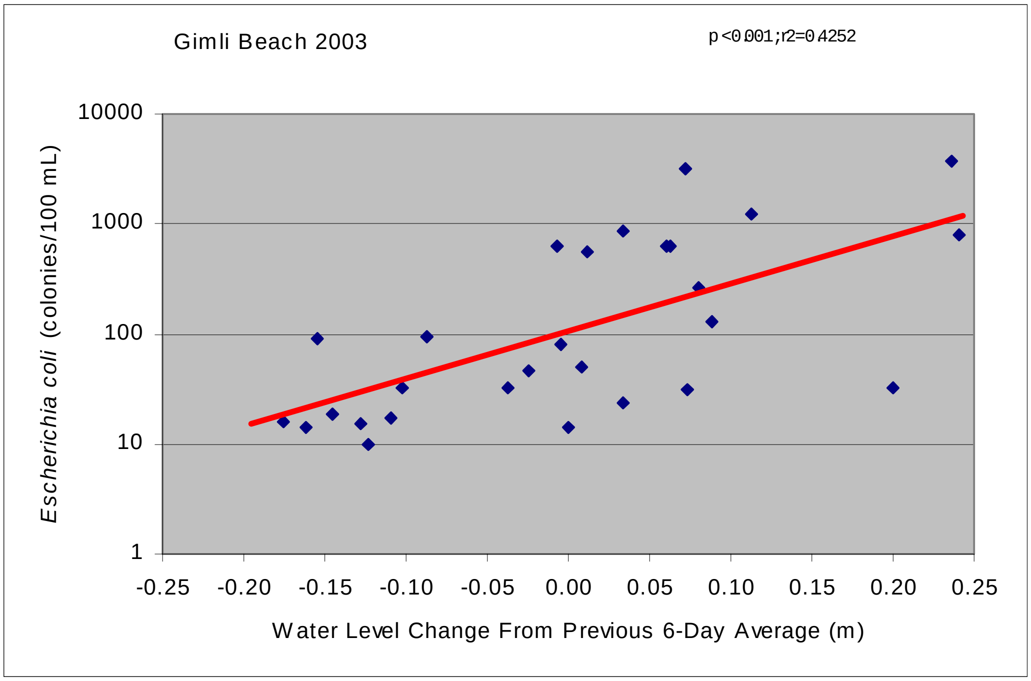

Figure 6. Relationship between *E. coli* densities at Gimli Beach and wind-induced water level changes during 2003.

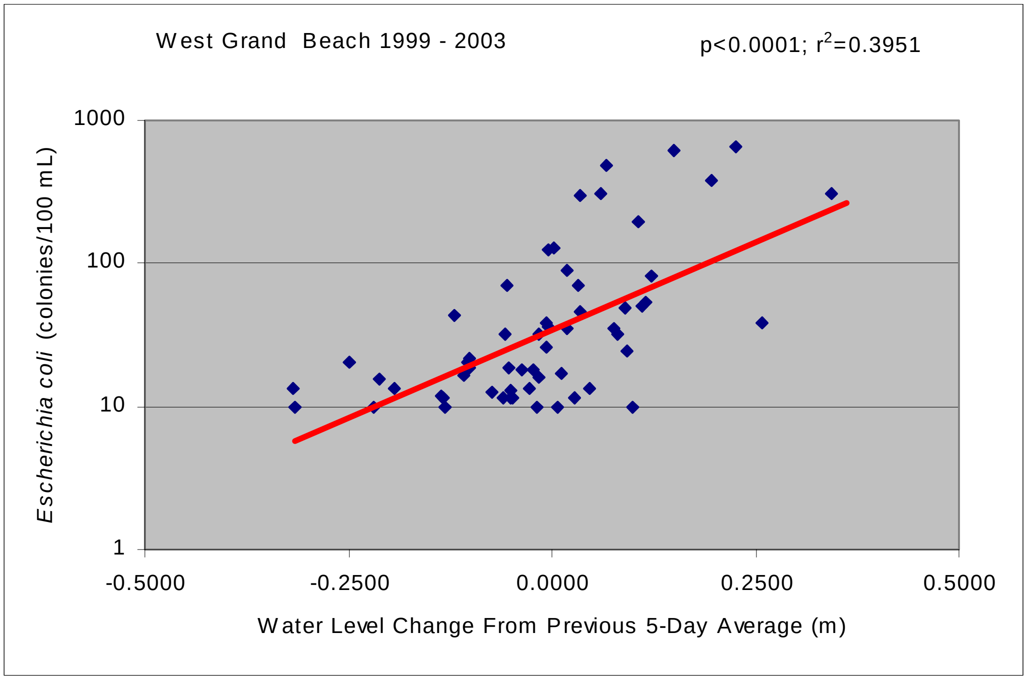

Figure 7. Relationship between *E. coli* densities at West Grand Beach and wind-induced water level changes during the period from 1999 to 2003.

Figure 8. Satellite image of Lake Winnipeg showing the south basin, narrows region, and north basin.

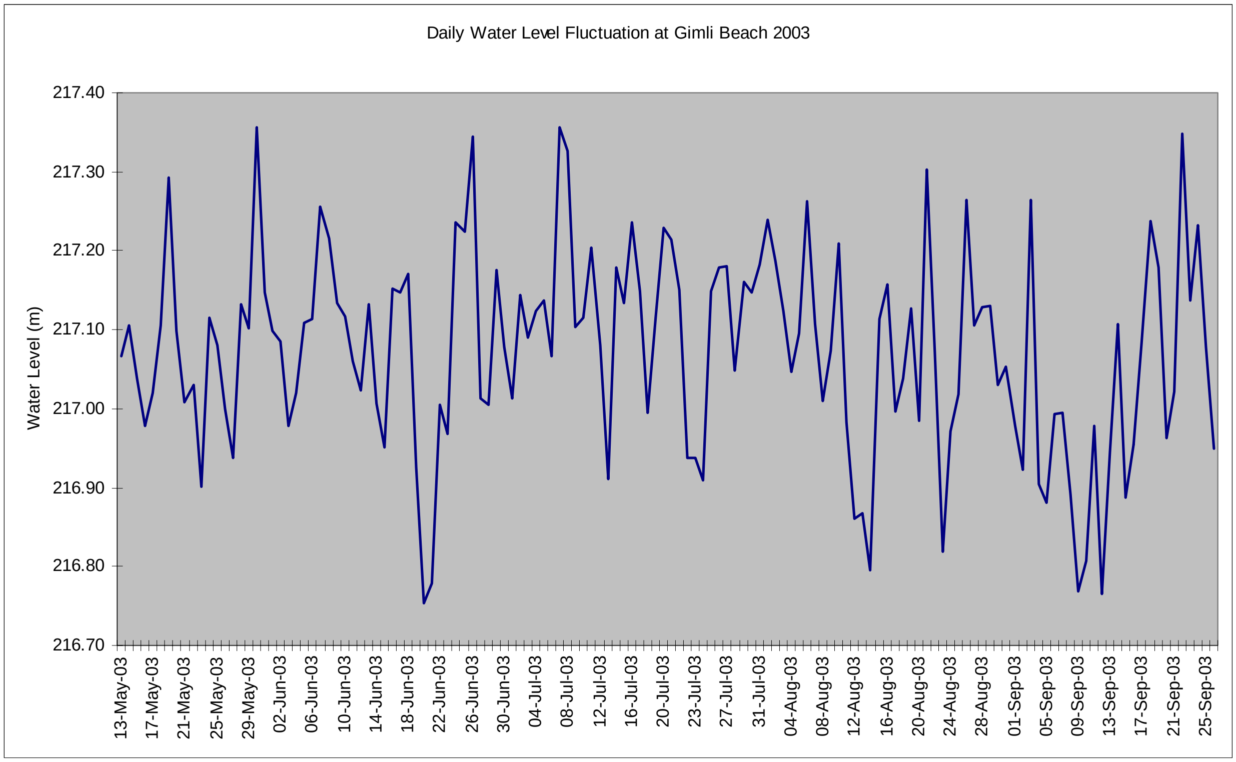

Figure 9. Daily water level changes observed at Gimli Beach during 2003.

Multiple *E. coli* source tracking techniques were used to identify whether observed bacteria in both surficial water underlying the foreshore beaches and bathing water were contributed by humans or animals, and if the contributions were of animal origin, to determine the main contributing species. Overall, it was determined that approximately 8 % of the *E. coli* in both surficial water underlying the foreshore beaches and bathing water was of human origin, with the majority of the remainder conclusively identified as being contributed from animal sources (Table 2). Of the specific animal sources, while a large proportion remained unidentified, contributions from ring-billed gulls and common terns comprised the largest single source (Table 3). It is likely that the large proportion of animal source remained unmatched because of insufficient local fecal specimens provided to the laboratories. It is now known that significant variability in DNA ribotype patterns can occur within any single species particularly within gulls, thus requiring analysis of large numbers of local fecal specimens (Whitman and Nevers 2003).

Although re-growth or replication of *E. coli* outside of the digestive tract of warm-blooded animals is rare, it has been documented in a number of cases, and is thought to occur periodically at the 63rd Street Beach in Chicago IL (R.L. Whitman[1], pers. comm.). Strong evidence indicated that *E. coli* populations in both surficial water underlying foreshore beaches

[1] Richard L. Whitman, U.S. Geological Survey, Lake Michigan Ecological Research Station, Porter IN.

and bathing water in Lake Winnipeg is comprised of five major clonal groups and that such groups were not present in the local fecal specimens submitted for comparison. Propagation of *E. coli* occurs through asexual reproduction. Cell division occurs such that exact replicates are created and are therefore, clonal to each other. Waters widely contaminated with *E. coli* tend to be comprised of a large number of ribotypes whereas the presence of only a few clonal groups may indicate that re-growth is occurring outside of the digestive tract of the contributing human or warm-blooded animals (T.S. Tamers[2], pers. comm.). Early in this investigation, re-growth experiments were initiated on Lake Winnipeg water and bottom sediments prior to discovery of the *E. coli* reservoir in the foreshore beach region. These experiments indicated that re-growth was not occurring in either lake water or lake bottom sediments (S. Rowsell[3], pers. comm.). Although presumptive, the presence of a small number of major clonal groups indicates that re-growth or replication may be occurring in or near the Lake Winnipeg environment and, combined with the demonstrated absence of re-growth in lake water or bottom sediments, strongly suggests that such re-growth may be occurring in the wet sand in the foreshore beach region.

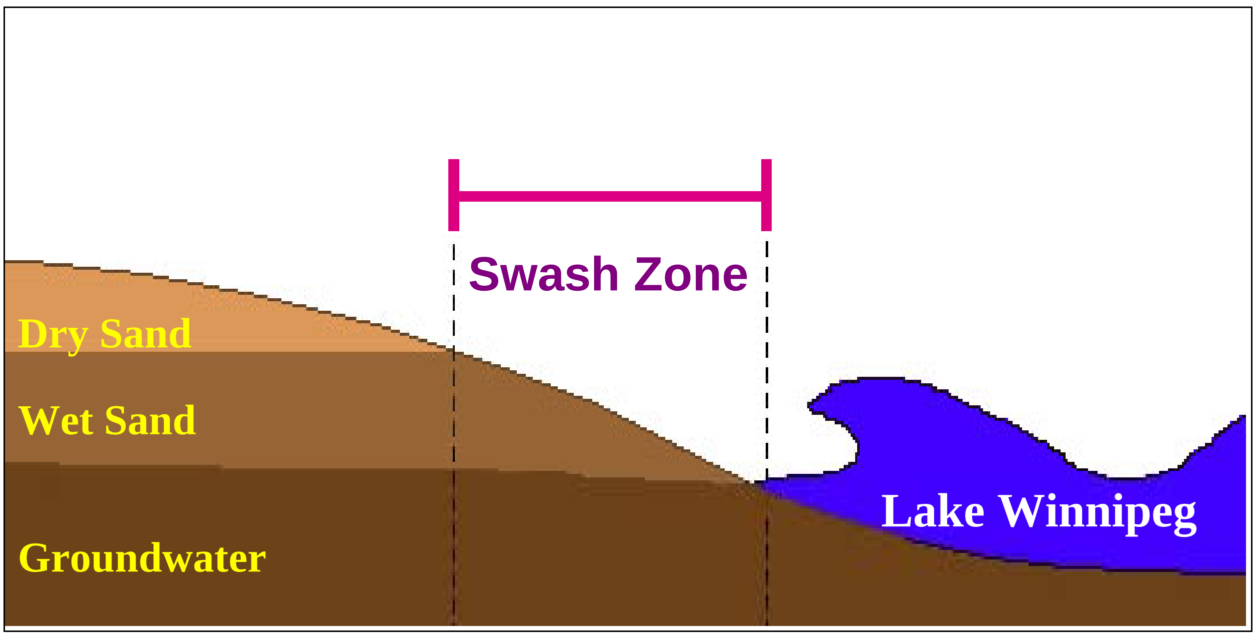

Figure 10. Typical beach profile showing the swash zone (modified from Kinzelman *et al* (2002).

[2] Thierry Sam Tamers, Director, Source Molecular Corporation, Miami FL.
[3] Susan Rowsell, Environmental Microbiologist, HydroQual Laboratories Ltd., Calgary AB.

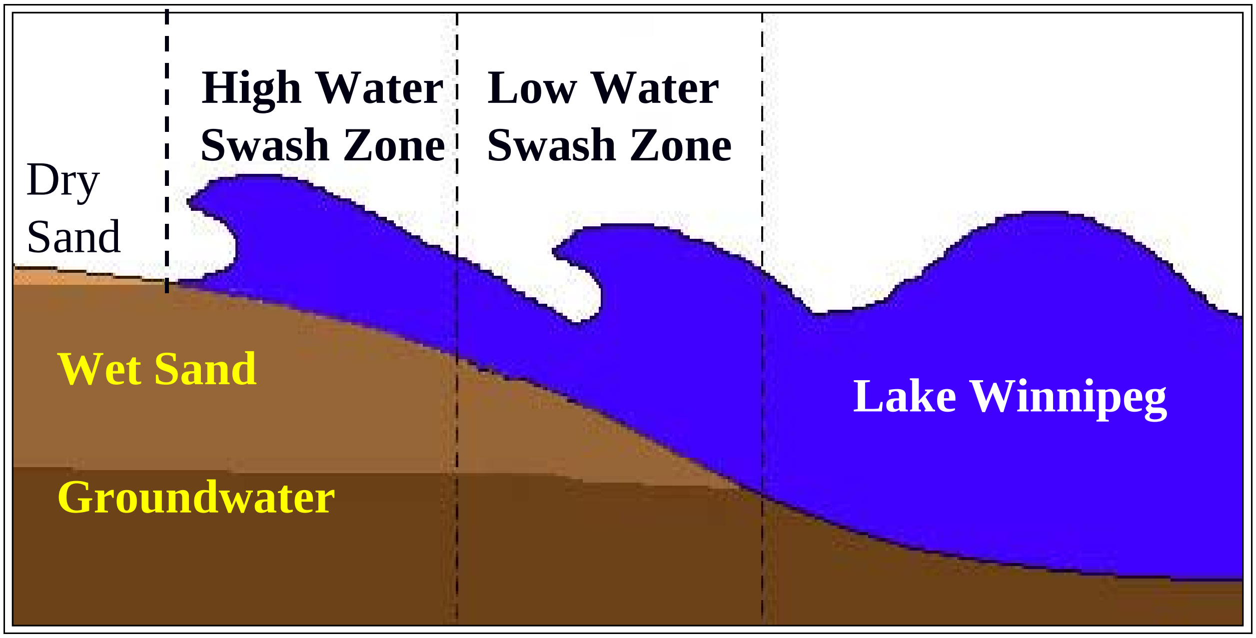

Figure 11. Typical Lake Winnipeg beach profile showing the shifted swash zone arising from wind-induced water level increases.

Table 2. Summary of human versus animal sources of *E. coli* in Lake Winnipeg bathing water and in surficial water underlying foreshore beaches.

Lake Winnipeg Beaches Human vs Animal Sources of *E. coli*		
	Bathing Water	Beach Sand Water
Human	8 %	8 %
Animal	73 %	83 %
Indeterminate	1 %	3 %
Unmatched	18 %	6 %

Table 3. Summary of animal sources of *E. coli* in Lake Winnipeg bathing water and in surficial water underlying foreshore beaches.

Lake Winnipeg Beaches Probable Animal Source of *E. coli*		
	Bathing Water	Beach Sand Water
Horse / Dog	5.4 %	1.7 %
Dog	0.3 %	0.2 %
Ring-Bill Gull / Tern	8.5 %	12.9 %
Horse	1.5 %	0.4 %
Swine	1.1 %	0.0 %
Cattle	2.7 %	3.6 %
Horse / Cattle / Goose	1.9 %	0.8 %
Unidentified Animals	78.8 %	80.3 %

CONCLUSIONS

It was concluded that:

- Surficial water underlying foreshore beach sand provided a reservoir of *E. coli* available for dispersion to bathing water of beaches located along the shoreline of the south basin of Lake Winnipeg.
- Wind-induced water level changes in the south basin of Lake Winnipeg significantly contribute to the transfer of *E. coli* from the foreshore beach region to bathing water. Water level changes account for approximately 40 % of the variability in *E. coli* densities observed during 2003 at Gimli Beach and from 1999 to 2003 at West Grand Beach.
- The majority of *E. coli* were from non-human sources with gulls and terns being the largest single contributors.
- There is strong presumptive evidence based upon clonal groupings that the *E. coli* population in both surficial water underlying the foreshore beach region and bathing water has arisen to a large degree from re-growth and that this re-growth is likely occurring in the wet sand of the foreshore beach region.

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