Sustainable Groundwater Diversion near Lake

Q.L. Dai, T.S. Chau
Alberta Environment
Red Deer, AB, T4N 6K8, Canada

ABSTRACT
Groundwater supply development near a lake requires an assessment of sustainable pumping that does not produce adverse effects on water quantity and quality of a lake. This study provides the mathematical development of water quantity and water quality lumped parameter models to account for lake-groundwater interaction in response to groundwater diversion. Three cases of groundwater pumping, which depend on the pumping well location and the water level in the pumping well with reference to the lake level, were evaluated for a lake-groundwater system using the models. Water quantity analysis results show that sustainable groundwater pumping comes from reduction of flow system components including surface water outflow from lake, lake evaporation and groundwater discharge through system boundary. Analysis results show that water quality sustainability requires the mass intercepted by pumping equal to or greater than the retained mass in the lake resulting from reduced lake outflow. Impact assessment results on lake water quality are presented for the three pumping cases.

RÉSUMÉ
Approvisionnement en eau souterraine à proximité d'un lac de développement exige une évaluation du développement durable de pompage qui ne produit pas d'effets négatifs sur la quantité d'eau et la qualité de l'eau. Cette étude fournit des mathématiques au développement de l'eau en quantité et qualité de l'eau paramètres des modèles 'lumped' pour tenir compte de l'interaction des eaux du lac à la suite de détournement des eaux souterraines. Trois cas de pompage des eaux souterraines, qui dépendent de la localisation et le pompage et le niveau d'eau dans la pompe et en référence à niveau du lac, ont été évalués pour lac-eaux système souterraines à l'aide des modèles. L'eau quantité l'analyse montrent les résultats que le développement durable vient de pompage des eaux souterraines de la réduction des flux de composants, y compris les sorties d'eau de surface du lac, l'évaporation des lacs et des eaux souterraines par le biais de limites du système. Les résultats de cette analyse montrent que la qualité de l'eau suppose la masse interceptée par pompage égale ou supérieure à la retenue dans le lac de masse résultant de la réduction des sorties du lac. Impact sur les résultats de l'évaluation de la qualité de l'eau du lac sont présentés pour les trois cas de pompage.

1. INTRODUCTION

Canadian Water Resources Association (1992) described sustainability as "wise management of water resources achieved by a genuine commitment to social equity for present and future generations." Groundwater sustainability is commonly defined in a broad context as the development and use of groundwater resources in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences (Alley and Leake, 2004). A conservative definition of safe yield is that groundwater abstraction should not normally exceed recharge to attain sustainable abstraction. (Dottridge and Jaber, 1999). Groundwater development requires a sustainable pumping rate that does not adversely affect human and environmental health (Devlin and Sophocleous, 2005).

Groundwater overexploitation can produce negative consequences such as higher pumping cost, as well as depletion of aquifers and surface water bodies (Villarroya and Aldwell, 1998). Non-sustainable groundwater development can lead to de-coupling of interaction between groundwater and surface water, reduction or elimination of groundwater exchange with lake, river, wetland or spring, and affect aquatic life (Bromley, et al. 2006).

Many different approaches were applied to sustainable groundwater management. An early study was based on using a combined simulation-optimization model to maximize total withdrawal from an aquifer while satisfying constraints involving hydraulics of groundwater flow, drawdown, water demand and hydraulic gradient (Chau, 1988). There were other recent groundwater modeling studies on sustainability. An aquifer model was used to estimate recharge rate and sustainable groundwater yield (Islam and Kanungoe, 2005). A groundwater planning model based on optimization formulation was developed to satisfy water demands for agricultural, drinking and industrial uses, environmental preservation and pollution control (Minciardi, 2004). In addition to apply groundwater modeling to analyze different development scenarios, stakeholder participation was emphasized as an effective approach for addressing complex groundwater management issues (Mödinger & Kobus, 2005).

The purpose of this study is to provide the mathematical development for the evaluation of water quantity and water quality sustainability of a lake-groundwater system in response to groundwater diversion near a lake. The following two questions underlying sustainable groundwater development are to be addressed:

- What are the sources of sustainable groundwater pumping?
- How does groundwater diversion affect water quantity and water quality of a lake?

2. GROUNDWATER QUANTITY BUDGET

Figure 1 presents a groundwater system in hydraulic communication with a lake under natural (non-pumping) condition. Although illustrated in this figure as a two-dimensional flow system, the concepts to be presented are applicable to three-dimensional flow.

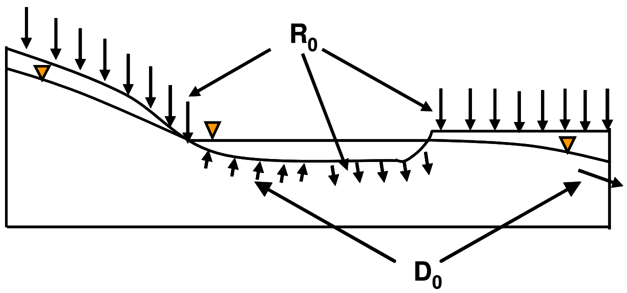


Figure 1. Groundwater quantity budget (natural condition)

The flow components and boundary conditions for the groundwater system are described below:

- Upgradient of a lake, rainfall infiltrates to the water table to recharge the shallow groundwater flow system, which eventually discharges to the lake.
- Downgradient of a lake, rainfall and lake outflow recharge shallow groundwater, which eventually discharges outside the system's downstream boundary
- The upgradient boundary is an impervious boundary (a groundwater divide).
- The downgradient boundary is a groundwater outflow boundary.
- The water table and the lake bottom form the top boundary of the groundwater system. The water table serves as a recharge boundary. Depending on the difference in elevation between lake level and groundwater level, the lake bottom can serve as a mixed recharge and discharge boundary.
- The bottom boundary is an impervious boundary (a flow line or an aquitard).

2.1 Natural Condition

Under natural (non-pumping) condition, application of the mass conservation principle to a groundwater flow system at steady state (Figure 1) gives Equation 1:

$$R_0 = D_0 \qquad [1]$$

where R_0 is natural groundwater recharge rate (L^3/T), and D_0 is natural groundwater discharge rate (L^3/T).

2.2 Pumping Condition

Since groundwater diversion is near a lake, the induced recharge to groundwater comes mainly from the lake. The upgradient and bottom boundaries of the groundwater system are assumed to locate sufficiently far away from the pumping well such that these boundaries are not affected by pumping. In response to pumping, a portion of the lake bottom can change from a discharge to a recharge boundary and vice versa.

After the initiation of pumping, groundwater diversion induces changes to different flow components of the groundwater system, including changes in recharge, discharge and storage (Figure 2)

$$(R_0+\Delta R_0) - (D_0+\Delta D_0) - P + dV/dt = 0 \qquad [2]$$

where ΔR_0 is the rate of change in recharge due to pumping (L^3/T), ΔD_0 is the rate of change in discharge due to pumping (L^3/T), P is the pumping rate (L^3/T), and dV/dt is the rate of change in the aquifer storage (L^3/T). (Devlin and Sophocleous, 2005).

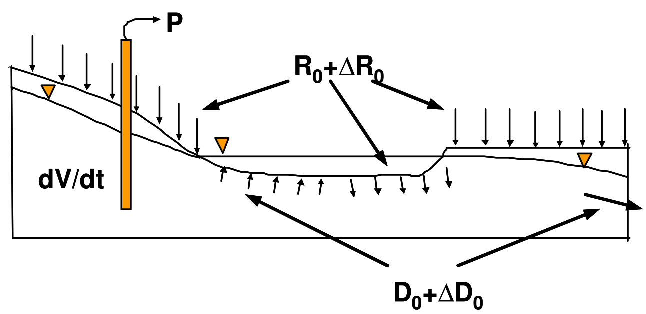


Figure 2. Groundwater quantity budget (pumping condition)

At the initial pumping stage, the source of groundwater pumping includes water released from aquifer storage ($dV/dt \neq 0$). To achieve sustainable pumping from an aquifer without causing its depletion, the rate of change in aquifer storage needs to be reduced to zero ($dV/dt = 0$). After reaching a new steady state condition, Eq. 2 becomes

$$(R_0 +\Delta R_0)- (D_0+\Delta D_0) - P = 0 \qquad [3]$$

Combining Eq. 1 with Eq. 3 results in Eq. 4

$$P = \Delta R_0 -\Delta D_0 \qquad [4]$$

Eq. 4 indicates that sustainable groundwater pumping comes from changes in recharge and discharge induced by the pumping well.

Figures 3 and 4 present three groundwater pumping cases that depend on the pumping well location and the water level in the pumping well with reference to the lake level. Assuming groundwater pumping does not produce changes to rainfall recharge to the lake-groundwater system, the sources of groundwater pumping are presented below for the three cases:

Case 1a, the pumping well is located upgradient of the lake and the groundwater level in the well is equal to or higher than the lake level; the source of groundwater pumping is derived from intercepted groundwater to the lake ($-\Delta D_0$).

Case 1b, the pumping well is located upgradient of the lake and the groundwater level in the well is lower than the lake level; the source of groundwater pumping is derived from intercepted groundwater to the lake and induced recharge from the lake.

$$P = P_R - \Delta D_0 \quad [5]$$

where P_R is the change in lake recharge to groundwater induced by pumping (L^3/T).

For cases 1a and 1b, the lake loses the amount of water pumped.

Case 1b

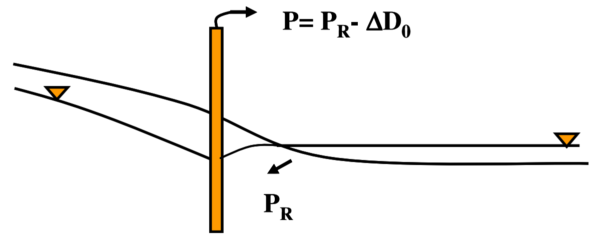


Figure 3. Cases 1a & 1b, pumping at upgradient of a lake

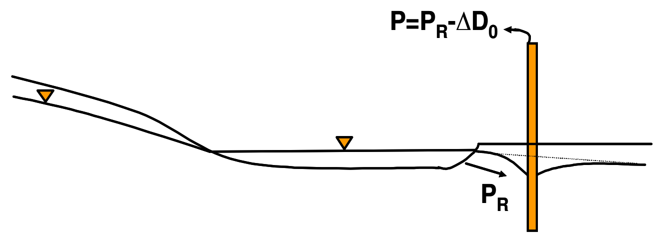


Figure 4. Case 2, pumping at downgradient of a lake

Table 1. Summary of Pumping Cases

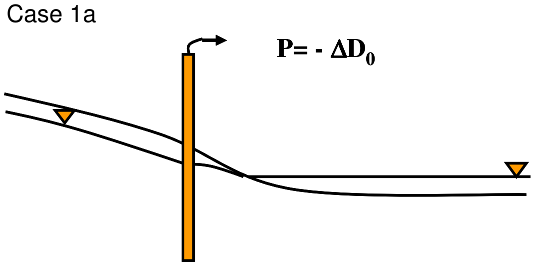
Case	Pumping well location	Water level	Sources of pumping
1a	Upgradient of the lake	Groundwater level in the pumping well is equal to or higher than the lake level	$-\Delta D_0$
1b		Groundwater level in the pumping well is lower than the lake level	$P_R - \Delta D_0$
2	Downgradient of the lake	Groundwater level in the pumping well is lower than the lake level	$P_R - \Delta D_0$

Case 2, the pumping well is located downgradient of the lake; the source of groundwater pumping is derived from induced recharge from the lake and intercepted groundwater discharge through the downgradient system boundary ($P_R - \Delta D_0$).

For case 2, the lake loses the amount of water as recharge to groundwater induced by pumping (P_R).

Table 1 presents a summary of results for the three pumping cases.

Case 1a



3.0 LAKE WATER QUANTITY BUDGET

Figure 5 presents a lake-groundwater system for lake water budget analysis. The hydrologic components of the lake include

- Recharge to the lake through surface water runoff, groundwater inflow and rainfall.
- Discharge from the lake through surface water outflow, groundwater outflow and evaporation.

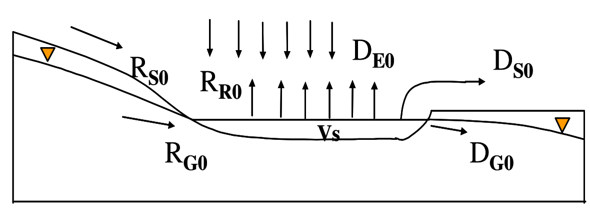


Figure 5. Lake water quantity budget (natural condition)

3.1 Natural Condition

Under natural (non-pumping) condition, application of the mass conservation principle to a lake at steady state (Figure 5) gives Eq. 6

$$R_{S0} + R_{G0} + R_{R0} = D_{G0} + D_{S0} + D_{E0} \qquad [6]$$

where R_{S0} is surface water runoff (e.g., overland flow, stream discharge) to the lake (L^3/T), R_{G0} is groundwater recharge to the lake (L^3/T), R_{R0} is direct rainfall recharge to the lake (L^3/T), D_{G0} is discharge from the lake to groundwater (L^3/T), D_{S0} is surface water discharge from the lake (L^3/T), and D_{E0} is lake evaporation (L^3/T).

3.2 Pumping Condition

Cases 1a & 1b, groundwater pumping at upgradient of the lake induces changes to hydrologic components of the lake (Figure 6)

$$(R_{S0}+\Delta R_{S0}) + (R_{G0}+\Delta R_{G0}-P) + (R_{R0}+ \Delta R_{R0}) - (D_{E0}+ \Delta D_{E0}) - (D_{G0}+ \Delta D_{G0}) - (D_{S0}+ \Delta D_{S0}) + dV_s/dt = 0 \qquad [7]$$

where ΔR_{S0} is the change in surface water recharge to the lake due to pumping (L^3/T), ΔR_{G0} is the change in groundwater recharge to the lake due to pumping (L^3/T), ΔR_{R0} is the change in rainfall recharge to the lake due to pumping (L^3/T), ΔD_{E0} is the change in lake evaporation due to pumping (L^3/T), ΔD_{G0} is the change in lake discharge to groundwater due to pumping (L^3/T), ΔD_{s0} is the change in surface water discharge from the lake due to pumping (L^3/T), and dV_s/dt is the rate of change in lake storage (L^3/T).

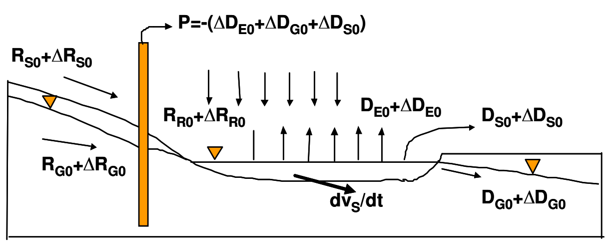


Figure 6. Lake water quantity budget (upgradient pumping)

In response to upgradient pumping, the lake eventually reaches a new steady state ($dV_s/dt = 0$). Groundwater pumping near a lake generally does not produce changes to surface water run off, rainfall recharge and groundwater recharge (ΔR_{S0}, ΔR_{R0} and $\Delta R_{G0} = 0$). Combining Eqs. 6 and 7 gives the sustainable pumping rate as

$$P = -(\Delta D_{E0} + \Delta D_{G0} + \Delta D_{S0}) \qquad [8]$$

Eq. 8 indicates that sustainable groundwater pumping comes from reduced surface water outflow from the lake, reduced lake evaporation and reduced lake discharge to groundwater.

Case 2, groundwater pumping at downgradient of the lake induces changes to hydrologic components of the lake (Figure 7)

$$(R_{S0}+\Delta R_{S0}) + (R_{G0}+\Delta R_{G0}) + (R_{R0}+\Delta R_{R0}) - (D_{E0}+\Delta D_{E0}) - (D_{G0}+P_R) - (D_{S0} + \Delta D_{S0}) + dV_s/dt = 0; \qquad [9]$$

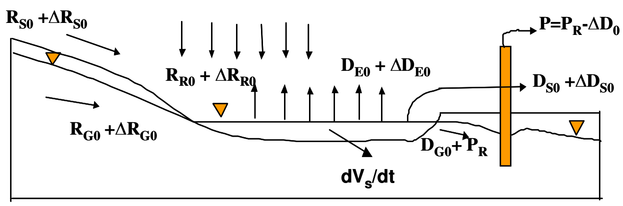


Figure 7. Lake water quantity budget (downgradient pumping)

In response to downgradient pumping, the lake eventually reaches a new steady state condition ($dV_s/dt = 0$). Groundwater pumping generally does not produce changes to surface water run off, rainfall recharge and groundwater recharge (ΔR_{S0}, ΔR_{R0} and $\Delta R_{G0} = 0$). Combining Eqs. 6 and 9 gives P_R, change in the lake recharge to groundwater induced by pumping

$$P_R = -(\Delta D_{E0} + \Delta D_{S0}) \qquad [10]$$

To maintain constant lake level, Eq. 10 indicates that the induced lake recharge to groundwater has to be balanced by reduced surface water discharge and reduced lake evaporation.

Based on $P = P_R - \Delta D_0$ (case 2 in Table 1) and Eq. 10, the sustainable pumping rate becomes

$$P = -(\Delta D_{E0} + \Delta D_0 + \Delta D_{S0}) \qquad [11]$$

Eq. 11 indicates that sustainable pumping comes from reduced surface water outflow from the lake, reduced lake evaporation and intercepted groundwater discharge through the downgradient system boundary.

Based on Eqs. 8 and 11, the surface water outflow from a lake can serve as a screening criterion for evaluating sustainable groundwater diversion near a lake. If the groundwater diversion is less than surface water outflow from a lake, water supply is likely sustainable for a lake-groundwater system.

4.0 LAKE WATER QUALITY BUDGET

4.1 Natural Condition

Consider a lake at steady state under natural (non-pumping) condition, the mass balance of a chemical in the lake for a given time period can be represented by the following equation (assuming no internal sources and sinks):

$$C_S R_{S0} T + C_G R_{G0} T + C_R R_{R0} T + C_L V_S = C_{S1} D_{G0} T + C_{S1} D_{S0} T + C_E D_{E0} T + C_{S1} V_S \qquad [12]$$

where C_s is the chemical concentration of surface water that recharges the lake, C_G is the chemical concentration of groundwater that recharges the lake, C_R is the chemical concentration of rainfall that recharges the lake, C_E is the chemical concentration of evaporation from the lake, which is generally zero, T is a given time period, C_L is the chemical concentration of the lake at the beginning of the time period, C_{S1} is the chemical concentration of a well-mixed lake at the end of the time period.

Rearranging terms in Eq. 12,

$$[(C_{s1}-C_L)/T]*V_s = C_S R_{S0} + C_G R_{G0} + C_R R_{R0} - C_{S1} D_{G0} - C_{S1} D_{S0} \qquad [13]$$

Based on Eq. 13, the following three scenarios are considered:

Scenario 1 ($C_L = C_{S1}$), the concentration in the lake is unchanged which implies no impact on water quality.

Scenario 2 ($C_L > C_{S1}$), the concentration in the lake decreases which generally implies positive impact on water quality.

Scenario 3 ($C_L < C_{S1}$), the concentration in the lake increases which generally implies negative impact on water quality.

If water quantity of the lake is non-sustainable under pumping, its water quality is likely not sustainable. Even if its water quantity is sustainable, sustainable water quality may or may not occur depending on different pumping situations.

4.2 Pumping Condition

Corresponding to three groundwater pumping cases considered previously in Table 1, the following discussions focus on impacts of pumping on lake water quality.

Case 1a, groundwater level in the upgradient pumping well is equal to or higher than the lake level; the source of pumping comes entirely from groundwater. The intercepted groundwater mass (M_p) is given as

$$M_P = C_G PT \qquad [14]$$

Under sustainable groundwater pumping, water level and surface area of a lake is not usually affected; this implies that the change in lake evaporation is not significant in Eqs. 8 & 11 (i.e., $\Delta D_{E0}=0$). This assumption may not be valid if the hydrologic system is influenced by global climate change that can result in significant lake evaporation (Drake, 2005).

As a result of reduced lake discharge to groundwater and reduced surface water outflow from the lake, the total mass retained in the lake (M_R) is given as

$$M_R = C_{S1} (\Delta D_{G0} T + \Delta D_{S0} T) = C_{S1} PT \qquad [15]$$

The mass change in the lake due to pumping (ΔM) is provided by

$$\Delta M = M_P - M_R = C_G PT - C_{S1} PT = (C_G - C_{S1}) PT \qquad [16]$$

Based on the difference in values between C_G and C_{S1}, the following three scenarios are considered:

Scenario 1 ($C_G = C_{S1}$) implies $\Delta M = 0$. The intercepted mass is equal to the retained mass, which implies no impact on water quality.

Scenario 2 ($C_G > C_{S1}$) implies $\Delta M > 0$. The intercepted mass is greater than the retained mass; concentration in the lake decreases which generally implies positive impact on water quality.

Scenario 3 ($C_G < C_{S1}$) implies $\Delta M < 0$. The intercepted mass is less than the retained mass; concentration in the lake increases which generally implies negative impact on water quality.

Case 1b, groundwater level in the upgradient pumping well is lower than the lake level; the source of pumping comes from groundwater and the lake. The intercepted groundwater mass (M_p) is given by

$$M_P = C_G (P-P_R)T + C_{S1} P_R T \qquad [17]$$

As a result of reduced lake discharge to groundwater and reduced surface water outflow from the lake, the total mass retained in the lake (M_R) is given as

$$M_R = C_{S1} PT \qquad [18]$$

The mass change in the lake due to pumping (ΔM) is provided by

$$\Delta M = M_P - M_R = (C_G - C_{S1})(P-P_R)T \qquad [19]$$

Based on ΔM given in Eq. 19, conclusions identical to Case 1a can be drawn for the three scenarios of Case 1b.

Case 2, groundwater level in the downgradient pumping well is lower than lake level; the source of pumping comes from induced lake recharge to groundwater (P_R) and reduced groundwater discharge through the downgradient system boundary ($-\Delta D_0$).

Table 2. Summary of Lake Water Quality Impacts under Different Pumping Cases

Case	Scenario	Relationship between pumped groundwater concentration (C_G) and lake water concentration(C_{S1})	Impact
1a	1	$C_G = C_{S1}, \Delta M = 0$.	No
	2	$C_G > C_{S1}, \Delta M > 0$.	Positive
	3	$C_G < C_{S1}, \Delta M < 0$.	Negative
1b	1,2,3	Same as Case 1a	Same as Case 1a
2	1	$C_G = C_{S1}$, ΔM =0.	No

For the induced lake recharge to groundwater, the mass discharged from the lake to groundwater (M_{PI}) due to pumping (P_R) is given as (C_G=C_{S1})

$$M_{PI} = C_G P_R T = C_{S1} P_R T \quad [20]$$

Assuming ΔD_{E0} = 0, Eq. 10 gives $P_R = \Delta D_{S0}$. As a result of reduced surface water outflow from the lake, the total mass retained in the lake (M_R) is given as

$$M_R = C_{S1}\ \Delta D_{S0} T \quad [21]$$

The mass change in the lake due to pumping (ΔM) is provided by

$$\Delta M = M_{PI} - M_R = C_{S1}\ (P_R - \Delta D_{S0})T = 0 \quad [22]$$

Eq. 22 indicates that, as long as pumping is sustainable, pumping at the downgradient of the lake produces no impact on lake water quality.

Based on the previous discussions, a summary of lake water quality impacts for different pumping cases is presented in Table 2.

5. CONCLUSIONS AND DISCUSSIONS

Water quantity budget analyses show that sustainable groundwater pumping comes from reduction of flow system components including surface water outflow from lake, lake evaporation and groundwater discharge. Since groundwater pumping does not produce significant changes in lake evaporation that can be generally neglected in water quantity and water quality sustainability study.

Water quality budget analyses show that water quality sustainability requires that the mass intercepted by pumping is equal to or greater than the retained mass in the lake resulting from reduced surface water and groundwater outflow from the lake. Three cases of pumping on lake water quality were considered. Groundwater diversion from a pumping well located upgradient of the lake can produce negative impact on lake water quality if the mass intercepted by pumping is less than the retained mass in the lake. Groundwater diversion from a pumping well located downgradient of a lake produces no impact on lake water quality.

Internal sources and sinks (e.g., dissolution, precipitation and biodegradation) were not considered in this study; these mechanisms can be incorporated into the present formulation of the lake water quality model.

The present study of lake-groundwater interaction is based on a lumped parameter modeling approach. It is also viable to apply a distributed parameter modeling approach through the use of numerical models to quantify groundwater interaction with lakes (Winter, 1978, Merritt & Konikow, 2000).

ACKNOWLEDGEMENTS

This paper was prepared in support of groundwater resources evaluation program of Central Region, Environmental Management Division of Alberta Environment. The contents of this paper do not necessarily reflect the views and polices of Alberta Environment, nor does mention of software brand names constitute their endorsement by Alberta Environment.

REFERENCE

Alley W.M. and Leake S.A., 2004, The Journey from Safe Yield to Sustainability. *Ground Water*, 42 (1) 12-16.

Bromley J., Cruces J., Acreman M., Marti´Nez L. & Llamas M. R., 2001, Problems of Sustainable Groundwater Management in an Area of Over-exploitation: The Upper Guadiana Catchment, Central Spain, *International Journal of Water Resources Development,*, Vol. 17, No. 3, 379–396.

Canadian Water Resources Association, 1992. *Sustainability Principles for Water Management in Canada*. Cambridge, Ontario.

Chau T.S., 1988. Analysis of Sustained Ground-Water Withdrawals by the Combined Simulation-Optimization Approach, *Ground Water*, Vol.24, No. 4, 454-463

Devlin J. F. and Sophocleous, M., 2005, The Persistence of The Water Budget Myth and Its Relationship to Sustainability, *Hydrogeology Journal*,13:549-554.

Mödinger J. and Kobus, H., 2005, Approach and Methods for the Assessment of Sustainable Groundwater Management in the Rhine–Neckar Region, Germany, *International Journal of Water Resources Development,*, Vol. 21, No. 3, 437–451, September.

Dottridge J. and Jaber, N. A. 1999, Groundwater Resources and Quality in Northeastern Jordan: Safe Yield and Sustainability, Applied Geography, 19, 313–323.

Drake, H. J., 2005, Climate Change and Groundwater Sustainability, *Geological Society of America*, vol.37, no.5, pp.6, Apr 2005.

Islam Md. M. and Kanungoe, P., 2005, Natural Recharge to Sustainable Yield from The Barind Aquifer: A Tool in Preparing Effective Management Plan of Groundwater Resources, *Water Science & Technology*, Vol 52, No 12, pp 251–258.

Merritt, M.L.. and L.F. Konikow. 2000. Documentation of a computer program to simulate lake-aquifer interaction using the MODFLOW ground-water flow model and the MOC3D solute-transport model. *USGS Water-Resources Investigations Report 00-4167*, Reston, Virginia: USGS.

Minciardi R., Robba M., Sacile R., 2004, A General Decision Model for A Sustainable Groundwater Planning, *Proceedings of the 15th International Workshop on Database and Expert Systems Applications* (DEXA'04).

Villarroya F. and Aldwell C. R., 1998, Sustainable Development and Groundwater Resources Exploitation, *Environmental Geology* 34 (2/3).

Winter T.C., 1978, Numerical Simulation of Steady State Three-Dimensional Groundwater Flow Near Lakes, *Water Resources Research*, Vol. 14, No. 2, 245–254.