Introduction. Groundwater from the Quaternary succession is an important source of water for both domestic and industrial use in the Cold Lake – Beaver River (CLBR) drainage basin in east-central Alberta (Figure 1). Growing demands on groundwater by expanding thermal in-situ heavy oil extraction projects in the basin, coupled with an extended period of drought, has increased the need for a regional groundwater numerical model to help assess groundwater flow and manage its use in the basin. Two major steps were necessary to complete the study: a) a detailed hydrogeological characterization of the Quaternary succession, and b) the development of a numerical groundwater flow model. One example for the practical usage of the calibrated numerical model is the transition curve analysis for various pumping scenarios in different aquifers and locations in relation to surface water bodies. Herein, transient numerical simulations are used to establish the transition from water produced from elastic storage to water produced from induced infiltration from surface water, and to determine the source of the latter (induced recharge, decreased leakage to lakes and rivers). This analysis can help to evaluate the time frames of various pumping scenarios with respect to “water mining”, and to establish which surface water bodies are most susceptible to groundwater extraction and therefore should be monitored.

Figure 1. Location of the Cold Lake – Beaver River Basin study area, showing grid discretization and boundary conditions.
**Hydrostratigraphy.** Channel incisions in the bedrock topography by pre-glacial and glacial river systems have created depositional basins in which up to 250 m of drift have accumulated. The hydrostratigraphy of the Quaternary units in this drift sequence is characterized by a succession of sand and gravel aquifers that are separated by, or embedded within, thick glacial tills representing at least four major glacial events. Confinement of some Quaternary units to bedrock channels, combined with stratigraphic superposition resulting from fluvial down-cutting and successive stacking, have produced a complex hydrostratigraphy with a combination of confined, leaky, and unconfined aquifers. For the development of a numerical groundwater flow model, the hydrostratigraphy was simplified to a 12-layer (Figure 2), glacial-drift aquifer system. The mapping of the top structure of the aquifer and aquitard layers was performed using three-dimensional mapping software.

![Figure 2. South - north cross section through the eastern part of the model area in a) ortho view and b) true-layer view.](image)

**Numerical Model.** Groundwater flow in the CLBR basin was modeled numerically with the Groundwater Modelling System (GMS 4.0), which employs the modeling package MODFLOW. MODFLOW is a finite difference model developed by the United States Geological Survey (USGS), and is a well-established and globally used groundwater modelling software. The surface-elevation grids of the hydrostratigraphic units were directly mapped to a three-dimensional model grid in the groundwater modeling software using a “true layer” approach. The model grid consists of 233 columns and 150 rows, and the cell dimensions are 800 by 800 m (Figure 1). The total number of grid cells is 454,350, of which 186,866 are active cells within the study area of the CLBR drainage basin (~ 11000 km²). Each hydrostratigraphic unit was assigned material properties in the form of hydrogeological parameters (horizontal hydraulic conductivity,
vertical anisotropy, and specific storage). In the “true layer” approach, the various hydrostratigraphic units have to be present continuously. Therefore, in places where a unit is absent, the respective layer has to become “very thin” (2 - 20 cm) and these thin cells are assigned material properties of the under- or overlying unit. All outer lateral boundaries in the model are defined as “no-flow” boundaries because they either represent flow divides or areas of flow parallel to the boundary. The exceptions are areas where channel aquifers extend beyond the limits of the surface drainage basin. In these areas, either “general-head” or “constant-head” nodes model the potential in- and outflows. The base of the Quaternary succession is formed by low-permeability shales and is modeled as a “no flow” boundary. Recharge rates in the CLBR Basin are not well known and therefore, instead of assigning recharge fluxes, recharge is simulated through a general-head type boundary at the top layer. Wetlands cover large parts of the CLBR Basin, which indicates that the water table is at or near the ground surface and head values were specified to the respective ground surface elevation. Only the major rivers in the study area were simulated with river nodes in the top layer of the model. Water levels in most lakes in the CLBR Basin only vary within a few meters. Therefore, lakes are simulated in the model by assigning constant hydraulic heads according to the respective lake level. The model was calibrated to static water level measurements in water wells (steady-state) and hydrographs in wells in the vicinity of sites performing long-term (15 years) pumping associated with oil sands development.

**Results.** Steady-state water balances calculated by the calibrated model suggest that the majority of water entering the groundwater system is derived from recharge due to infiltration from wetlands or precipitation (~232,000 m$^3$/d or 8 mm/year), while minor amounts of water are provided by leakage from recharging lakes (~30,000 m$^3$/d). Discharge of groundwater occurs through the major rivers (~141,000 m$^3$/d), secondary drainage (~30,000 m$^3$/d) and lakes (~87,000 m$^3$/d), while approximately 4000 m$^3$/d leave the drainage basin through flow in channels extending beyond its boundaries. The simulated hydraulic head distribution is very sensitive to the hydraulic rock properties of the aquitards and the lowermost post-channel aquifer. Apparently, the hydraulic parameters of shallow till aquitards control vertical flow of recharge-derived water into the deeper hydrostratigraphic units. The hydraulic conductivity in the lowermost post-channel aquifer, due to its large extent, contiguity, and hydraulic connection to rivers and lakes, governs the lateral flow and drainage into the discharge features. With respect to the modeling of groundwater – surface water interaction, a key step forward has been the incorporation of lake-bottom bathymetry into the digital elevation model to map aquifer outcrops on the bottoms of lakes.

Transition curve analyses for potential pumping scenarios in the CLBR Basin show that, depending on aquifer depth and location in the groundwater flow system, the time between groundwater mining from aquifer storage and produced water being balanced by induced infiltration ranges between approximately 10 days to 3 years (Figures 3 and 4).

**Conclusions.** Due to the complexity of the Quaternary hydrostratigraphy and interaction between groundwater flow and surface water bodies in the CLBR Basin, impacts of groundwater extraction can only be accurately evaluated using a regional numerical flow model. A proper geological characterization of the subsurface, and the adequate representation of fluid sources and sinks are essential for developing a well-calibrated numerical model and managing water resources in the Cold Lake – Beaver River drainage basin.
Figure 3. Transition curves for various pumping scenarios from different aquifers (names in brackets) at selected locations.

Figure 4. Graph showing an example of the transition from produced water derived from storage to induced leakage from/to surface water bodies.