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Modelling stream-aquifer interactions: a case study of environmental risk assessment for a proposed groundwater abstraction scheme in northeast Scotland

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Abstract The Lower Old Red Sandstones in northeast Scotland form an aquifer suitable for groundwater development. A groundwater abstraction scheme was proposed for augmenting water supplies to local villages. A production borehole was drilled into the sandstones which has a design yield of 2420 m^3 day^{-1}. However, the scheme was abandoned because of concerns that the abstraction would reduce flows in a nearby stream which is important for salmonids. This study demonstrates the potential value of using a stream-aquifer numerical model (MODFLOW) in an environmental risk assessment for the scheme. Results indicate that the proposed abstraction would not cause streamflows to fall to a level where flow compensation will be needed to maintain salmonid habitats.

INTRODUCTION

The Lower Old Red Sandstones in northern Strathmore, Scotland, have been classified as highly permeable aquifers (Robins, 1989). Groundwater investigations in the region have been carried out and exploratory drillings have led to the identification of two production boreholes (Causeywell and Huntershill), which were drilled into the Edzell Sandstones and have yields of 2400 m^3 day^{-1} and 1900 m^3 day^{-1} respectively (Robins, 1989). These boreholes were to be used to supply water to the Laurencekirk and Stonehaven areas (Fig. 1(a)). Despite significant yields, each site has been abandoned because of concerns that abstractions would substantially reduce flows in local streams which are important spawning and nursery areas for salmonids (CHW, 1991).

A risk assessment of the hydrological impacts of the proposed abstractions was thus necessary, requiring groundwater modelling techniques that adequately describe stream-aquifer interactions. This paper describes such a risk assessment, for the Causeywell borehole. Particular attention is paid to simulating the hydrological effects of the abstraction on stream-aquifer interactions and related streamflows.

DESCRIPTION OF THE STUDY AREA

In Strathmore, the Lower Old Red Sandstones are gently folded along the northeast-southwest trending Mearns syncline, which is parallel to the Highland Boundary Fault (Fig. 1(a)). The Strathmore Group, the youngest subdivision, consists of volcanic rocks, red or brown sandstones, mudstones and conglomerates. The area is covered by poorly permeable till and, in places, glacial and fluvial gravels.

The Edzell Sandstone is the best potential aquifer in northern Strathmore. It comprises a weakly cemented, cross-bedded, fine to coarse grained sandstone and occupies the axial region of the Mearns syncline. It has a thickness of 160 m where the Causeywell production borehole is situated; this has a depth of 100 m and a design yield

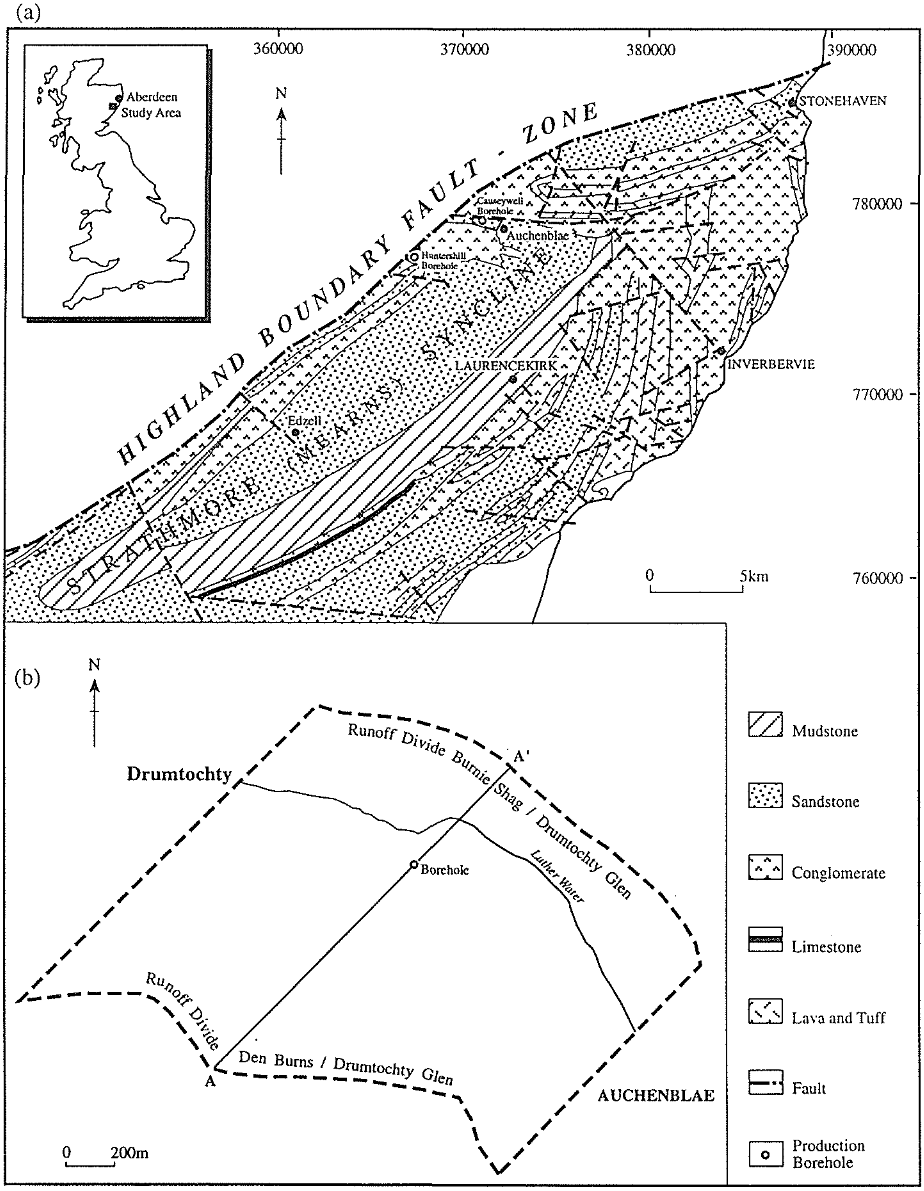

Fig. 1 The study area showing (a) a simplified regional geology and (b) the model boundary.

of 2420 m^3 day^{-1} (Fig. 1(a)). The sandstone is generally fissured, and acts as an unconfined aquifer. It has a transmissivity in the order of 100 m^2 day^{-1} and storativity of 10^{-2}-10^{-4}, capable of sustaining borehole yields up to 3500 m^3 day^{-1} (Robins, 1989). The annual rainfall is 900 mm and effective recharge to the unconfined aquifer ranges from 100 to 300 mm $year^{-1}$ (Robins, 1989; CHW, 1991).

The northeastern and southwestern boundaries of the study area coincide with the surface runoff divides of Drumtochty Glen. Northwestern and southeastern boundaries are arbitrarily taken to be normal to the regional groundwater flow direction (Fig. 1(b)). A long term average streamflow at Drumtochty has been estimated from a downstream gauging station.

MODELLING APPROACH

MODFLOW, a three-dimensional finite-difference groundwater model developed by USGS was used in conjunction with a streamflow routing package to simulate the stream-aquifer interactions. The model takes account of seasonal variations of recharge and streamflow, thus allowing a more rigorous assessment of the impact of abstraction on streamflow fluctuations.

A stream is divided by the model discretization into a number of reaches, which are each contained in a single model cell. Stream-aquifer interactions (SAI) consist of two components: groundwater contributions to the stream, and the stream leakage into aquifer. SAI (i.e. the sum of these two components) between each reach and the model cell that contains the reach, is computed using a version of Darcy's Law (Chen & Soulsby, 1997).

Given a streamflow (Q_0) for the first reach of the stream, the model first calculates stream stage (d) using the Manning's formulae. The resultant stream outflow (Q_1) from the first reach is then computed by taking the difference between the initial (assigned) streamflow (Q_0) and the stream-aquifer interaction ($Q_{(\mathrm{SAI})1}$). This is then used as a stream inflow (Q_2) for the second reach, and this process continues until the last reach within the model domain, as summarized in equation (1):

$$Q_1 = Q_{i-1} \pm Q_{(\mathrm{SAI})_i} \tag{1}$$

where $i = 1, 2, 3, \ldots, k$ (where k is the total number of reaches). A negative sign before $Q_{(\mathrm{SAI})i}$ indicates stream leakage with a positive sign implying groundwater seepage into the stream.

CONCEPTUAL MODEL, MODEL SET UP AND DATA INPUT

The conceptual model of the study area consists of a single hydrostratigraphic unit representing the unconfined Edzell Sandstones (Fig. 2). The northern and southern boundaries of the modelled area were assigned fixed hydraulic heads. Eastern and western boundaries and bottom of the modelled layer were taken as no-flow or streamline boundaries.

The modelled area was discretized using a finite-difference grid of 57 rows and 59

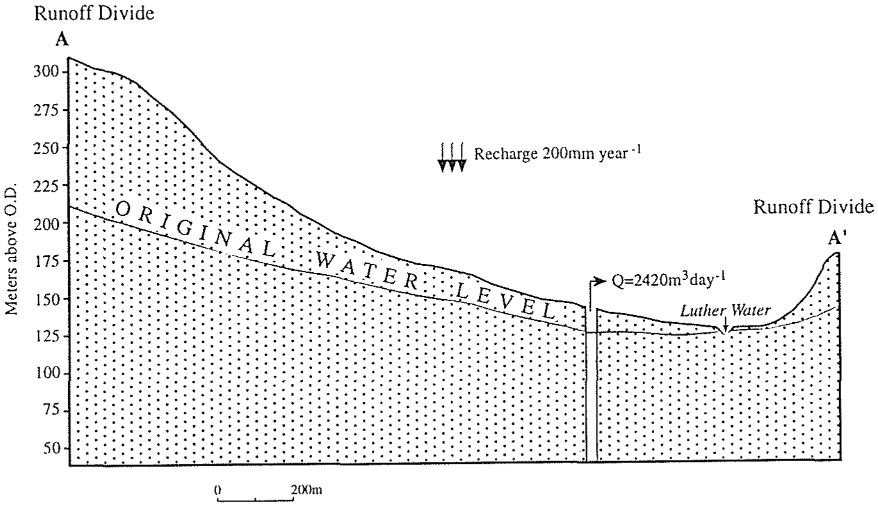

Fig. 2 Conceptual model of stream-aquifer system (along section A-A′ in Fig. 1(b)).

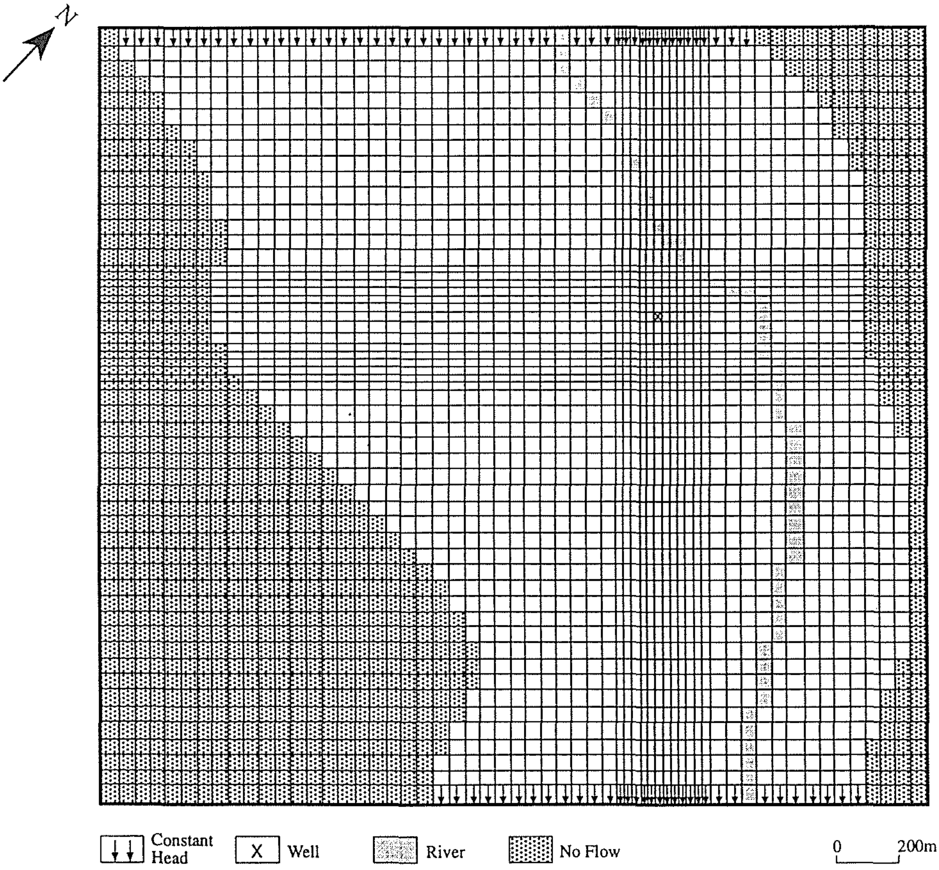

Fig. 3 Model grid and boundary conditions of the Luther Water stream-aquifer system.

columns. A finer grid was specifically designed around the borehole to allow for a more accurate representation of stream-aquifer interactions (Fig. 3). Both steady state and transient state simulations were performed. In transient mode, a monthly stress period was used to simulate varying monthly recharge and streamflows. A total of six year periods were used with the first four years allowing the model to achieve a stable monthly cyclic pattern as the initial starting water level for each model cell within each month was not known. Results of the simulation from the fifth and sixth years were used to analyse the simulation effects representing transient conditions without and with pumping respectively.

The evaluation of pumping test data indicated hydraulic conductivity and storativity values of 3 m day^{-1} and 2×10^{-4} respectively. Saturated aquifer thickness is about 55 m, giving an aquifer transmissivity of 165 m^2 day^{-1}.

Initial stream stages and channel widths were measured during fieldwork, and Manning's roughness coefficient was estimated from measured streamflow and stage. An annual recharge of 200 mm was distributed into each month (model stress period) proportioned according to the monthly effective rainfall. This gives approximate recharge of 0.13 and 1.00 mm day^{-1} for the summer and winter months respectively. The mean monthly streamflows were estimated from the downstream gauging station. Detailed model calibration and sensitivity analysis are described by Chen & Soulsby (1997).

SIMULATION RESULTS

Volumetric water budgets

The steady state volumetric budgets indicated a total groundwater inflow of 6797 m^3 day^{-1}, which includes the recharge contribution (3442 m^3 day^{-1}), boundary inflow from the fixed heads (3002 m^3 day^{-1}) and a small amount of stream leakage (354 m^3 day^{-1}) (Table 1). Boundary outflow from the fixed heads represents 82% of the total groundwater inflow, and the remainder contributes to baseflow. The average stream-aquifer interaction is 870 m^3 day^{-1}, indicating that groundwater contributions to the stream dominate under natural conditions.

Boundary inflows are highest between April and August, which corresponds to the lowest boundary outflows (Table 1(a)). Boundary outflows are highest between September and February. Stream leakage is fairly uniform in each month. Groundwater contribution to the stream varies greatly; in summer months, when recharge and streamflows are lower, groundwater contributions to the stream exceed 500 m^3 day^{-1}, whereas in the winter months when recharge and streamflows are higher, groundwater contributions to the stream are more than doubled.

During development stage the groundwater abstraction comes from significantly increased boundary inflow, and a minor amount of induced stream leakage (Table 1(b)). Groundwater contributions to the stream have been considerably reduced to 1000 m^3 day^{-1}, and there is no groundwater contribution in the summer months. Stream leakage has been increased to 250 m^3 day^{-1}. Boundary inflows have been increased by more than 1000 m^3 day^{-1}, and boundary outflows reduced only slightly. Increased inflows arise due to an increasing horizontal hydraulic gradient caused by the pumping,

Table 1 Transient water budgets (a) without pumping and (b) with pumping (all units m^3 day^{-1}).

Month	Sources					Discharges				
	Sout	Bin	Rch	StrL	Total	Sin	Bout	Well	GtoS	Total
(a)										
Jan	0.00	1269.20	4436.50	541.58	6247.30	0.08	4606.60	0.00	1640.60	6247.30
Feb	5.43	1840.90	3058.20	582.92	5487.40	0.00	4260.60	0.00	1226.80	5487.40
Mar	5.08	2424.90	1679.80	620.82	4730.60	0.00	3912.90	0.00	817.63	4730.60
Apr	4.70	2933.40	559.96	727.02	4125.10	0.00	3597.80	0.00	527.22	4125.00
May	0.34	2970.90	559.96	556.81	4088.00	0.00	3570.00	0.00	518.37	4088.40
Jun	0.27	3000.20	559.96	497.77	4058.20	0.00	3547.80	0.00	512.51	4060.30
Jul	0.16	3017.80	559.96	462.87	4040.80	0.00	3534.40	0.00	507.78	4042.20
Aug	0.00	2522.50	1679.80	442.34	4644.70	4.48	3842.40	0.00	798.05	4645.00
Sep	0.00	2259.90	2282.90	437.84	4980.50	2.40	4001.60	0.00	976.68	4980.60
Oct	0.00	1508.60	4005.80	447.87	5962.30	6.47	4452.00	0.00	1503.90	5962.30
Nov	0.00	1005.30	5168.80	499.35	6673.40	4.59	4794.80	0.00	1873.90	6673.40
Dec	2.51	1280.60	4436.50	519.88	6239.50	0.00	4598.00	0.00	1641.40	6239.40
(b)										
Jan	10.13	2111.50	4436.50	753.69	7311.90	0.00	4297.90	242	593.98	7311.80
Feb	6.36	2753.50	3058.20	800.35	6618.40	0.00	3931.20	242	266.95	6618.20
Mar	6.23	3413.80	1679.80	874.52	5973.40	0.00	3538.50	242	14.75	5973.30
Apr	7.50	4065.10	559.96	885.38	5517.90	0.00	3098.80	242	0.00	5518.80
May	0.94	4133.30	559.96	767.25	5461.40	0.00	3042.30	242	0.00	5462.30
Jun	0.76	4186.20	559.96	668.36	5415.30	0.00	2997.80	242	0.00	5417.80
Jul	0.43	4218.50	559.96	610.85	5389.80	0.00	2972.60	242	0.00	5392.60
Aug	0.00	3555.70	1679.80	627.96	5863.50	7.86	3435.60	242	0.00	5863.40
Sep	0.00	3248.10	2282.90	593.66	6124.60	3.17	3628.10	242	73.16	6124.50
Oct	0.00	2395.90	4005.80	615.53	7017.20	7.89	4130.20	242	459.48	7017.50
Nov	0.00	1809.80	5168.80	684.32	7663.00	5.35	4472.40	242	765.36	7663.10
Dec	2.82	2130.10	4436.50	725.05	7294.50	0.00	4285.90	242	588.56	7294.40

Note: Sout = releases from storage; Sin = uptakes into storage; Bin = boundary inflow; Bout = boundary outflow; Rch = recharge; StrL = stream leakage into aquifer; GtoS = groundwater contribution to stream.

while induced stream leakage comes from the lowering water levels and increasing the vertical hydraulic gradient adjacent to the stream.

Hydrological impacts

The degree to which the groundwater abstraction causes a reduction in streamflows indicates the level of disturbance to fish habitat (Johnson *et al.*, 1993). In order to assess such effects, streamflow (after SAIs) out of, and stage at, the last reach are plotted against each stress period (Figs 4(a) and (b)); and stream-aquifer interactions (SAI) within each stress period have been summed over the modelled stream length (Fig. 4(c)). It has been suggested that the pumping system should discharge one third of the abstraction into the Luther Water if the streamflow drops below 2600 m^3 day^{-1} and it should discharge two thirds into the stream if the streamflow is reduced to 1700 m^3 day^{-1} (CHW, 1991). The latter value is based on the estimated Q_{95} of streamflow.

Streamflows The Luther Water is a gaining stream from the local groundwater system under natural transient conditions (pre-development stage without pumping), with streamflows out of the last reach increasing by more than 1000 m^3 day^{-1} during the winter and 500 m^3 day^{-1} during the summer (Fig. 4(a)). There are virtually no noticeable stream-aquifer interactions between March and July, in other words, the stream leakage into the aquifer is balanced by groundwater contributions to the stream. The streamflows out of the last reach in response to the groundwater abstraction are reduced by about 700 m^3 day^{-1} (i.e. negative SAIs), caused primarily by the reduction in groundwater contributions to the stream and induced stream leakage. The lowest simulated stream-

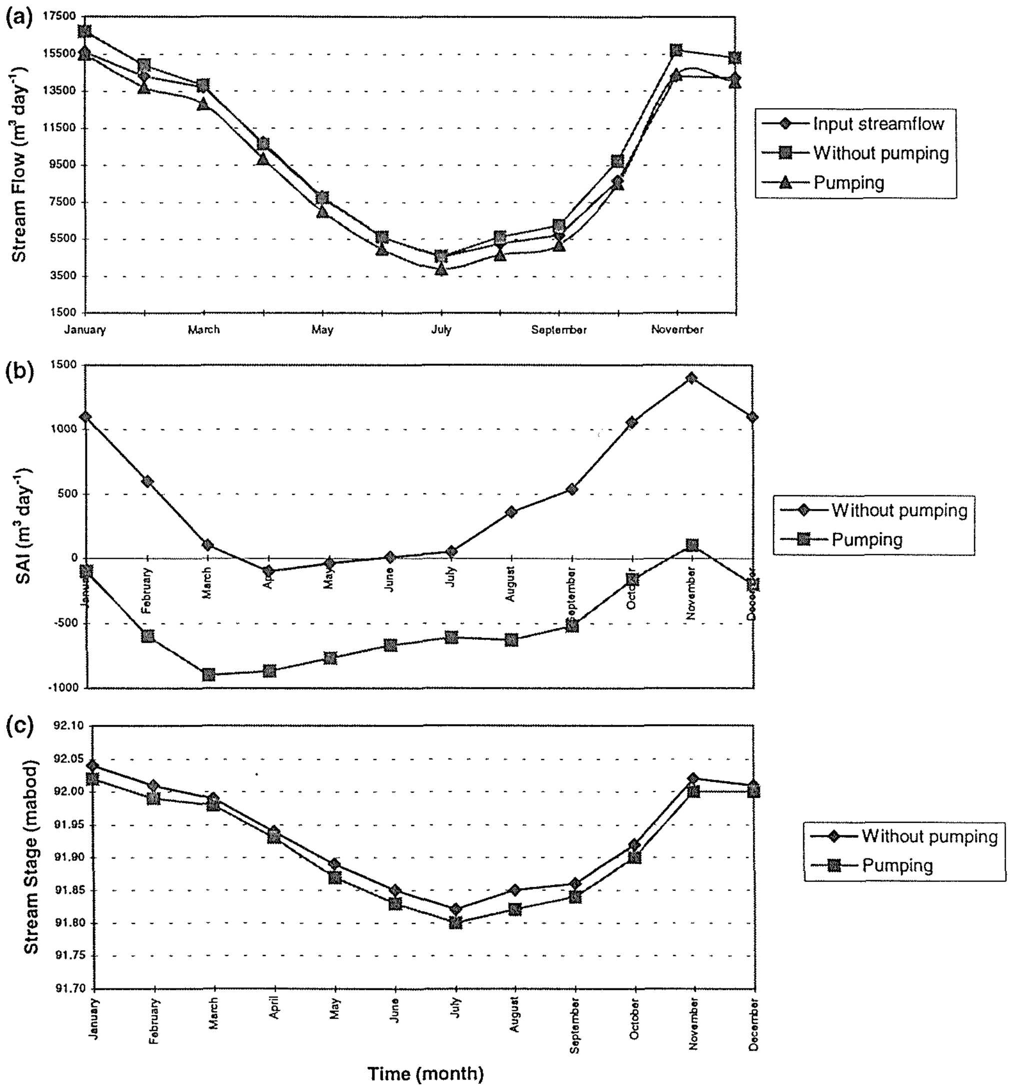

Fig. 4 (a) Predicted streamflows after stream-aquifer interactions (SAI) over the modelled length; (b) SAI summed over the modelled stream length; and (c) predicted stage at the last reach.

flow occurs in July, remaining over 4000 m^3 day^{-1}, and this value is well above the first recommended streamflow of 2600 m^3 day^{-1} for which water compensation is recommended. It can therefore be inferred that further groundwater abstraction may be feasible as far as the recommended streamflows for water compensation are allowed. However, as further groundwater abstraction is likely to cause reduction in streamflows, borehole localities and the abstraction rates would have to be carefully planned.

Stream-aquifer interactions There are significant changes to the stream-aquifer interactions (SAI) due to the abstraction (Fig. 4(b)). Prior to development, positive SAIs indicate that groundwater contributions to the stream are predominant, particularly between September and February, and becoming lower between March and July. SAIs are negative in April and May, indicating that the stream leakage is greater than groundwater seepage into the stream. During abstraction, groundwater contributions to the stream appear to be less significant as indicated by negative SAIs, suggesting a process dominated by stream leakage in all months except November (Fig. 4(b)). The percentages of water abstracted from the stream can be estimated from sub-regional water budgets (SAI divided by the borehole yield), which range from 0 to 4% between October and January, and 9 to 13% during other months. These figures indicate the maximum possible stream leakage that contributes to the groundwater abstraction, as the stream leakage also contributes to the boundary outflows.

Stream stage The stream stage at the last reach will fall during the groundwater abstraction, because of the reduction in groundwater contributions to the stream, increase in the stream leakage into aquifer and subsequent reduction in streamflows. Figure 4(c) shows that the stream stage has fallen by about 0.02 m during the groundwater abstraction throughout the year. This small reduction in stage further suggests that stream leakage due to the abstraction has a minimum impact on habitat conditions in the Luther Water (Fig. 4(c)).

CONCLUSIONS

This study demonstrates the potential for using numerical groundwater flow models in environmental risk assessment, particularly in the early stages of groundwater development when data are limited. The model results suggest that the proposed abstraction has a minimum impact on streamflows, and therefore is unlikely to reduce the quality of the Luther Water as a habitat for young salmonids. The abstraction mainly comes from increased boundary inflows and recharge, with the stream leakage contributing, on average, less than 10% of the abstraction. It has been further demonstrated that when recharge and streamflows are low, the abstraction will probably not lower flows to the point where water compensation is needed.

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