

An integrated groundwater, pipe and open-channel flow model for simulation of aquifer-adit systems

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Abstract The Chalk is the most important aquifer in the UK. In the Chalk aquifer, the yield from the wells was often increased by driving adits (or tunnels) in different directions. The flow in an adit is pipe or open-channel flow. Introducing a fictitious narrow slot (Preissmann slot) above the adit makes equations for open-channel flow also valid for pipe flow. MODBRNCH, an integrated groundwater and open-channel flow model, is adopted. The combination of a slot approach and modified MODBRNCH enables us to simulate groundwater-adit interrelations by coupling groundwater with pipe flow, groundwater with open-channel flow, and groundwater with the transition from pipe flow to open-channel flow. An application to Cottingham pumping station including both steady state and transient modelling, demonstrates that the model calibration is good, and the method is successful and valuable.

INTRODUCTION

The Chalk forms the most important and most widespread aquifer in the UK; 60% of UK groundwater abstraction is from Chalk (Beeson *et al.*, 1995). In the Chalk aquifer, the yield from wells was often increased by driving adits (or tunnels) in different directions and at different levels or by inter-linking wells with adits. Figure 1 shows the Cottingham adit layout, which is the case study introduced in this paper. Systems of adits, typically 1.2 m wide and 1.8 m high, are usually below the groundwater table and can be up to 7 km long. Generally the adits were driven to intersect the principal fissure direction. Velocity calculations indicate that the flow in the adit is turbulent when pumping is taking place, so it is difficult to predict groundwater flow and delineate source protection zones in these areas.

However, the turbulent adit flow can be represented as pipe flow (the adit is full of water) or subcritical open-channel flow (the adit is partially full), for groundwater modelling purposes. Therefore, a model, which couples groundwater with pipe flow, groundwater with open-channel flow, and groundwater with the transition from pipe flow to open-channel flow, is needed for simulation of aquifer-adit systems.

CAVE (Carbonate Aquifer Void Evolution) is a model coupling groundwater flow and pipe flow (Clemens *et al.*, 1996); conduits are assumed to be permanently saturated. MODBRNCH (Swain & Wexler, 1996) is a model that couples groundwater flow and open-channel flow models to simulate the groundwater and open-channel flow and their interaction. However, a scheme, which couples groundwater with pipe flow, groundwater with open-channel flow, and the transition from pipe flow to open channel flow, has not been developed.

This paper introduces a new approach to modelling adits and an application.

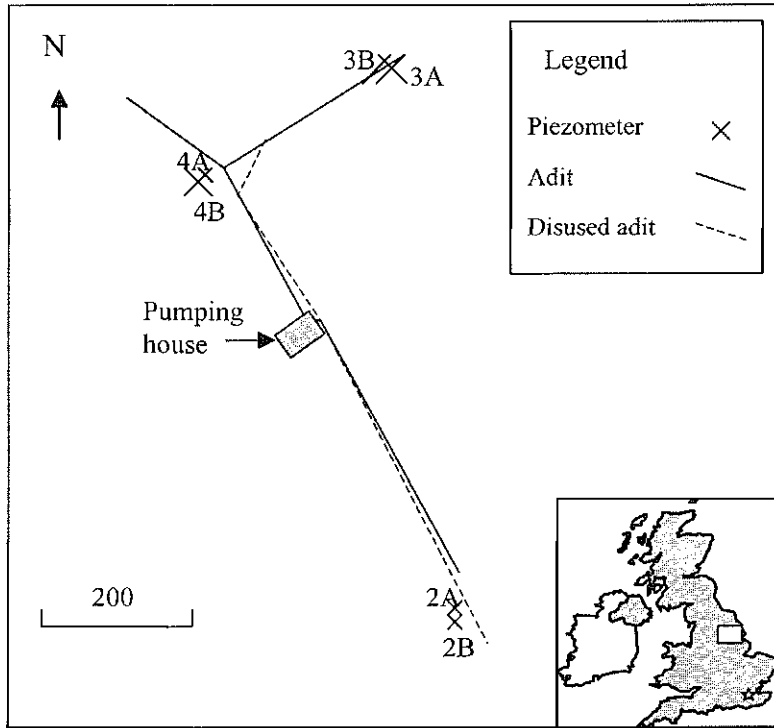


Fig. 1 Cottingham adit layout.

ADIT MODELLING APPROACH

Modelling of aquifer-adit systems requires a model handling all the following situations: groundwater with pipe flow, groundwater with open-channel flow, and groundwater with transition from pipe flow to open-channel flow. The pipe flow case can be made equivalent to open-channel flow by introducing an artificial, narrow slot above the adit (Preissmann slot, Preissmann & Cunge, 1961). The slot allows the open-channel equations to be valid for all cases. If the adit is full, the calculated cross-section remains the same as the actual water conveyance cross-sectional area because the slot is narrow (1–10 mm). The water level within the slot represents the pressurized water head, which can be used to calculate water exchange between aquifer and adit according to their head difference. Figure 2 illustrates the slot approach and the aquifer layers for the case study introduced in this paper.

The US Geological Survey model BRANCH (Schaffranek *et al.*, 1981), which simulates one-dimensional, unsteady, non-uniform flow by solving the St Venant equations, is a model commonly used for simulation of open-channel flow. MODBRNCH incorporates BRANCH into MODFLOW (McDonald & Harbaugh, 1988). The coupling of BRANCH and MODFLOW simulates aquifer–stream interaction using the deterministic response of both systems, and is a highly dynamic model. It allows users to define the channel geometry by defining channel cross-sections. Therefore MODBRNCH was selected for adit modelling because the slot can

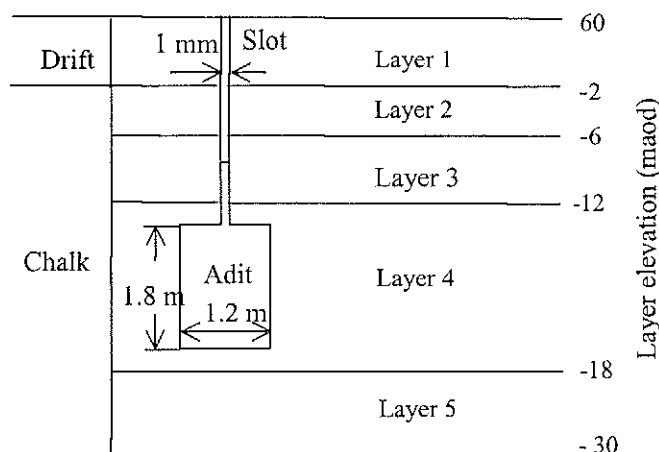


Fig. 2 Illustration of artificial slot, and aquifer layers in the Cottingham case study for this paper (not to scale).

be constructed by defining the channel cross-section. A small modification has been made for handling the slot approach (Zhang & Lerner, 1998).

APPLICATION TO COTTINGHAM STATION

Cottingham pumping station is one of the largest groundwater sources that Yorkshire Water Services has in the Hull area, with a licensed abstraction of $68\,182\text{ m}^3\text{ day}^{-1}$. The Cottingham source is complex comprising of two pumping shafts, 20 other shafts and about 1000 m of adit in use (see Fig. 1). The Cottingham adits consist of two main systems at -15 m a.o.d. and -29 m a.o.d. (metres above ordnance datum). The lower system is not used and is not connected to the higher system. The existing bores below the higher adits were plugged to ensure there was no connection with the lower adits (Crease, 1998).

The Cottingham source is located in the "Yorkshire Chalk" to the north of the Humber Estuary (Green, 1950). The Chalk outcrops in the west, and in the east the Chalk is covered by a thick sequence of boulder clay and thin sandy drift. The regional groundwater flows in a southeast direction to the abstraction sites.

The regional model presented in this paper uses MODFLOW. It covers an area of 660 km^2 and is simplified to a one layer model. The Cottingham local model, having an area of 2 km by 2.5 km, was taken from the regional model by means of Telescopic Mesh Refinement (TMR) (Ward *et al.*, 1987), and is simulated using the slot approach and modified MODBRNCH.

To simulate the pumping test, which took place in September 1998, the modelling started from a steady state model representing the condition in August 1998. The calibrated groundwater head distribution in the steady state model was taken as the initial head for the transient model. The permeability and leakage coefficient were mainly calibrated in the steady state model calibration, while the storage coefficient was calibrated with the transient model.

The Cottingham adits and shafts were constructed at the end of the last century and early this century. Most of shafts show seepage through joints in the brickwork, and have occasional bricks omitted, probably to allow inflow to the shaft (Crease, 1998). To integrate this phenomenon into the modelling, it assumed that a proportion of the pumping water is contributed by shaft seepage in Layer 3. This proportion was adjusted during model calibration.

The Cottingham local model was divided into five layers (Fig. 2) according to adit geometry and elevation, seepage horizon and elevation, lithology, and piezometer elevation. Although the local groundwater levels were continually monitored by pressure transducers throughout the pumping test, the model calibration was focused on the dates when the manual dips were carried out because some of the logger data are not reliable. The locations of the observation boreholes are shown in Fig. 1. All piezometers were grouped in pairs, set into a small borehole but at different elevations. Also, all the observation boreholes were grouped in pairs (i.e. 2A and 2B etc.), Therefore the four piezometers grouped in two nearby boreholes were considered as one location during model calibration. The elevations of the piezometers can be seen in Fig. 3, which shows the comparison of observed data and simulated data for both

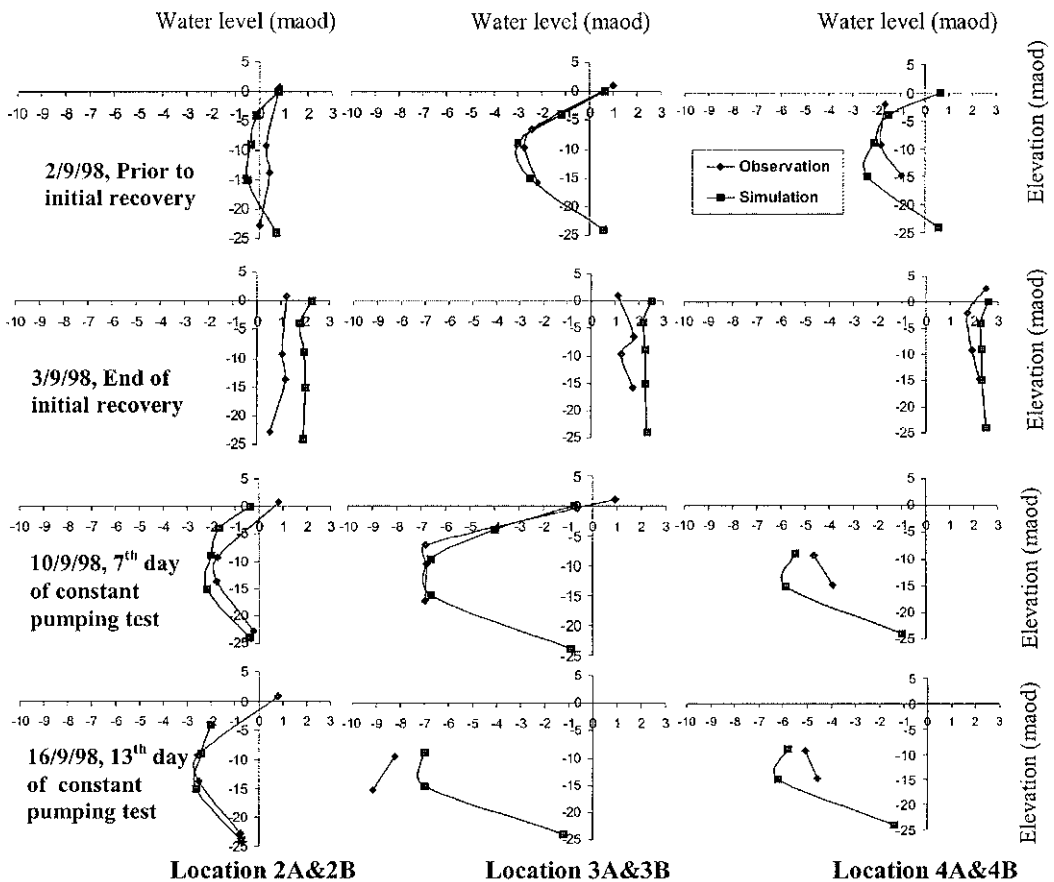


Fig. 3 Model calibration for steady state (prior to initial recovery) and transient models.

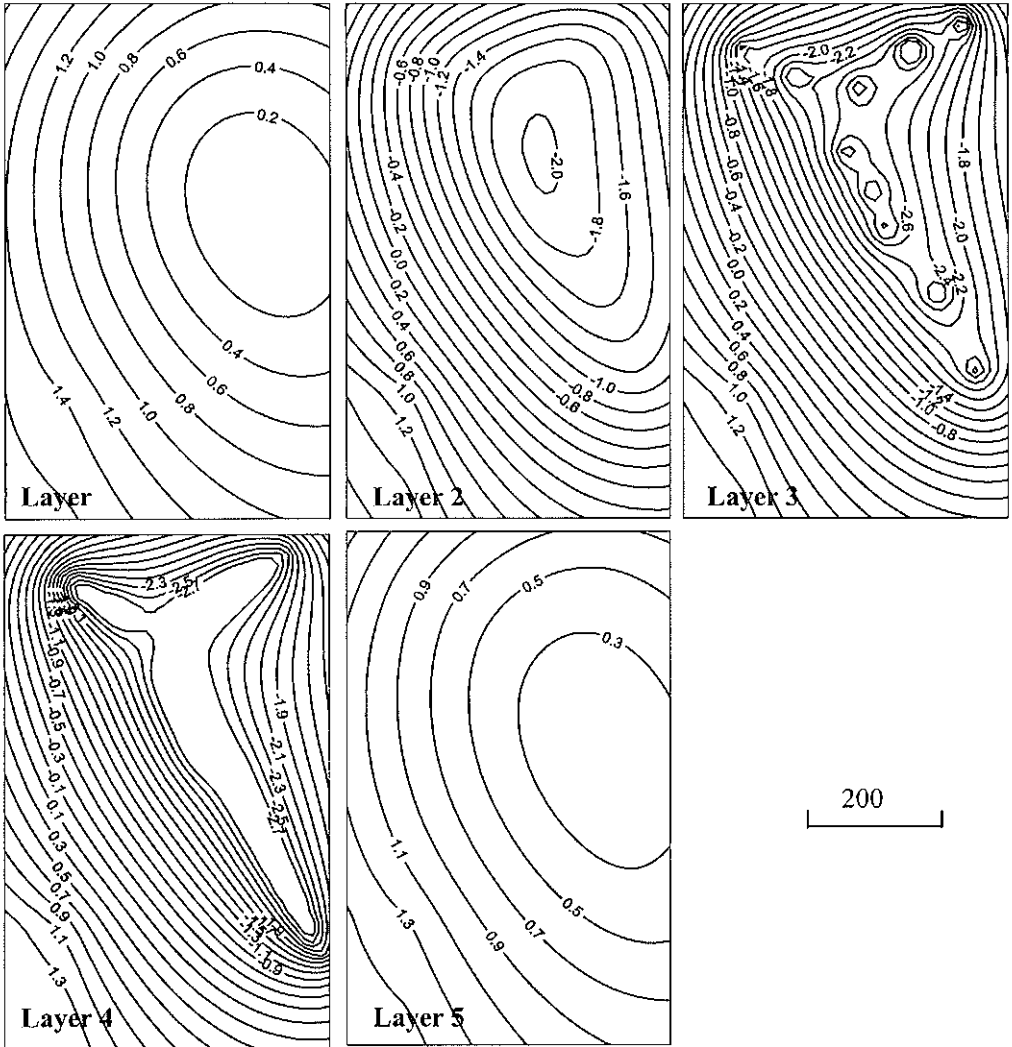


Fig. 4 Simulated groundwater contour maps for steady state model.

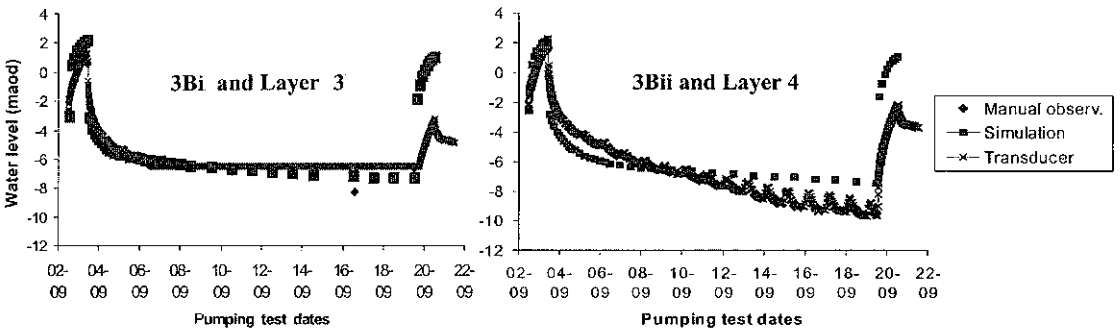


Fig. 5 Comparison of 3Bi and 3Bii observations and simulation of Layer 3 and Layer 4 at that location for the whole pumping test.

steady state and transient models. The simulated data are quite close to the observed data. The simulated steady state groundwater head distribution for various layers is shown in Fig. 4. It indicates that the adit affects Layer 4 (the layer containing the adit), Layer 3 and Layer 2, but has little effect on Layer 1 and Layer 5. Figure 5 shows the simulation of the whole pumping test. 3Bi and 3Bii are the piezometers nearest to the adit, so are selected and compared with Layer 3 and Layer 4 simulations at that location, respectively.

DISCUSSION

The model calibration is generally good. the simulated data are quite close to the observed data for all manual dips (Fig. 3). this indicates that the adit modelling approach is reasonable for modelling of aquifer-adit interrelationships and is able to simulate both steady state and transient hydrogeological situations.

Regarding the entire pumping test process, the simulation of initial recovery and early stages of the constant pumping test is good. However, there is a discrepancy between simulated and observed data for the later stages of the pumping test, especially for the layer containing the adit (3Bii, and layer 4 in Fig. 5). this probably has two causes. The chalk aquifer is a fissured aquifer, and the distribution of fissures is unknown, so MODFLOW can not simulate it accurately enough. The other cause is that the permeability was mainly calibrated with the steady state model, representing water level prior to the pumping test, whereas it was not really a steady state situation. The regional groundwater level declines in summer, therefore the steady state model can not fully present the real hydrogeological controlling factors although the steady state model could produce similar groundwater level distributions to the observed data.

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