# Groundwater modelling of the Chepstow Block, South Wales, UK

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**Abstract—** In this groundwater modelling study, a simplified conceptual model of the Chepstow Block hydrogeological unit was calibrated using the Aquifer Simulation Model (ASM) program under steady-state conditions. The initial aquifer boundaries of the model and its changing conditions were investigated. The model was found to be insensitive to changes in the boundary conditions. It was also found that the Nadern Fault within the Block plays an important role in drawing water from the north to the Great Spring. During the calibration process, it was difficult and impossible to calibrate the model without incorporating a low permeable boundary parallel to the Nadern Fault.

**Abstrak—** Dalam kajian pemodelan air tanah ini, ringkasan model konsepsi aliran air tanah tunak (*steady state*) unit hidrogeologi Chepstow Block telah ditentukurkan dengan menggunakan program *Aquifer Simulation Model* (ASM). Sempadan permulaan akuifer dan kesan perubahannya telah dikaji. Adalah didapati model simulasi adalah tidak sensitif kepada perubahan sempadan akuifer. Juga didapati Sesar Nadern di dalam Blok ini memainkan peranan penting di dalam membawa air tanah dari kawasan utara ke Great Spring. Dalam proses tentukur model adalah didapati amat sukar dan tidak mungkin model akuifer ini boleh ditentukurkan tanpa memasukkan sempadan berketelapan rendah sejajar dengan Sesar Nadern.

**Keywords:** groundwater modelling, hydrogeology, Chepstow Block

## INTRODUCTION

The Chepstow Block hydrogeological unit of South Wales extends south-westwards from Chepstow on the River Wye for some 14 km along the Welsh coast (Figure 1). The Block is a massive Carboniferous Limestone which acts as a single karstic aquifer unit, drained mainly by the Severn Tunnel's Great Spring. The Caerwent basin, within the Chepstow Block, is the main area for the spring catchment (Booker, 1984; Booker & Clark, 1984).

The Great Spring is an important water resource for the Chepstow Block. Its water is pumped to the surface for public and industrial water supplies, particularly for brewery and paper mill industries. The Great Spring discharges water at 20 to 60 thousand $m^3$/day with an average yield of about 650 l/s or 0.650 $m^3$/s (Clark & Aldous, 1987). Since the 1960s, many geological and hydrogeological investigations have been carried out within the Chepstow Block, in order to protect the Great Spring's water resources (i.e. Drew *et al*., 1970; Booker, 1984; Clark & Aldous, 1987: Aldous, 1988). The main fundamental issues in many hydrogeological studies is to determine the catchment area of the Great Spring, e.g. Caerwent basin, (Clark & Aldous, 1987) and hence, the behaviour of groundwater flowpath and the tracer dispersion.

Drew *et al*., (1970) carried out water tracing experiments using fluorescein dye (negative result) and Lycopodium spore (positive result) to ascertain the spring catchment area. The Lycopodium spore showed an extremely low recovery, with a travel time of ten days. Clark & Aldous (1987) repeated the test using fluorescein dye at the same point of injection (i.e. a sinking stream at Cas Troggy) and produced a positive result.

Although a few tracer tests have been successfully carried out, and the major groundwater flowpaths with reasonable travel times and dilution rates identified, the hydrogeological condition of the Chepstow Block needs to be further examined. This is based on the fact, as pointed out by Clark & Aldous, (1987), the geological and hydrogeological settings of the Great Spring are now known and that detailed in their summary report of hydrogeological investigation for the Block.

This modelling study tried to resolve these issues by using the available geological and hydrogeological information, along with valuable data from unpublished reports. The main objectives of this modeling study are:

1. To simulate a hydrogeological condition of the Block, and more importantly, to explore the groundwater flowpatterns and boundary conditions, some of them being summarised by Clark & Aldous, (1987).
2. To obtain the regional transmissivity value (i.e. steady state model) of the aquifer and to identify any area with higher transmissivity and possibly any area with a very low transmissivity or an impermeable boundary. This may provide some insight on the karstification of the aquifer. If karstification of the aquifer does exist, a sensitivity analysis of that particular feature will be carried out.
3. To investigate the sensitivity of the simplified aquifer model with respect to the changing of regional transmissivity, boundary condition and groundwater recharge.

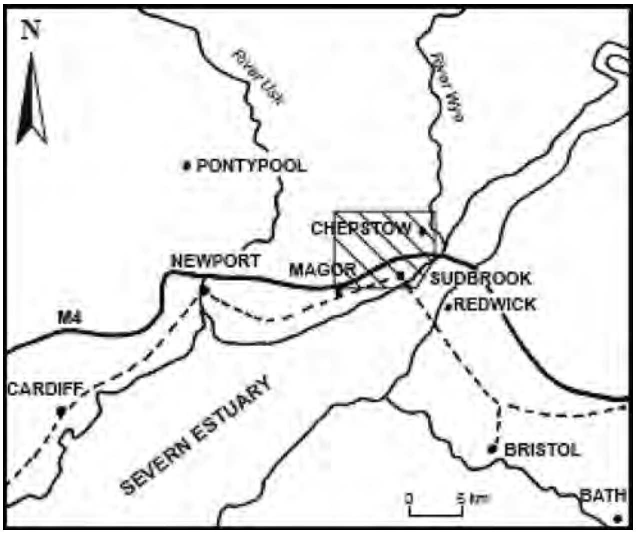


**Figure 1:** Location map of the Chepstow Block.

The modelling study would also be used to test the idea whether the hydraulic behaviour of the aquifer and the dispersion behaviour of the tracer can be modelled without incorporating the karstic element in the model by utilising the concept of an Equivalent Porous Medium (EPM) model. The concept has been used by many other groundwater modellers (e.g. Anderson & Woessner, 1992), to test the stated hypothesis.

## HYDROGEOLOGY AND CONCEPTUAL MODEL

### Hydrogeology

The Carboniferous Limestone is the most important aquifer in South Wales (Figure 2). The outcrop is mainly in a narrow coastal band 24-32 km wide between Pembroke and the Severn Bridge at Chepstow. It has been divided by the Water Research Centre (WRC) into two major areas; the Chepstow Block and the Cardiff - Cowbridge Block (Aldous, 1988). The major difference between those two Blocks is that the Carboniferous Limestone outcropping within the Cardiff - Cowbridge Block is not continuous.

The geological succession in the Chepstow area fall in the hydrogeologic division (Clark & Aldous, 1987) and is shown in Table 1. As noted by Clark and Aldous, (1987), the Devonian sequences basically act as the basal aquiclude and the hydrogeological influences of the Old Red Sandstone (ORS) is considered to be negligible except that it provides baseflow for the brooks flowing onto the Carboniferous Limestone aquifer unit (i.e. Cas Troggy Brook, St. Bride's Brook and Mounton Brook). The Lower Limestone shale may form part of the ORS basal aquitard or aquiclude but, where it is formed of flaggy limestone, it will be part of the aquifer. The Triassic series over much of the area act as a confining aquiclude but it is better to treat this series as an aquitard due to limited data suggesting that the series is entirely impermeable (Clark & Aldous, 1987).

The Carboniferous Limestone series is regarded as being a single aquifer unit in which gross hydraulic continuity exists between the various lithologic and stratigraphic subdivisions (Halcrow & Partners, 1991). The steeply-dipping western limb of the Shirenewton Anticline forms the eastern edge of an aquifer unit (the Caerwent basin), comprising the western half of the Chepstow Block (Clark & Aldous, 1987). Several north-south plunging synclines which pass southwards beneath the Severn Estuary can be identified within the Chepstow Carboniferous Limestones Block (Booker, 1984) as shown in Figure 2. These are the Mounton Brook Basin and the Wye Valley System.

Jointing in rocks which were found at a few limestone quarries (e.g. Ifton Quarry and Caerwent Quarry) have been widened by solution weathering or karstification (Clark & Aldous, 1987). Water flowing along joints and fractures tends to dissolve the limestone and widens the features, ultimately forming large underground cavities. The joints of this area tend to be spaced at between 0.2 m to 1 m with width from 2-3 cm to several metres (Connelly & Sadler, 1994a, b). The swallow holes, where surface streams disappear, are present around the periphery of the Caerwent Basin and the main swallow hole is located along the Cas Troggy Brook (Clark & Aldous,1987).

The principal hydrogeological features of the Carboniferous Limestone are shown in Figure 2, together with preliminary inferences on groundwater movement. The water table of this limestone aquifer slopes gently towards the Severn Estuary (i.e. south-easterly). The water-table gradient is generally low, of about $10^{-3}$ - $10^{-4}$ (e.g. 0.001 between Caerwent and Tyne Cottage), as suggested by Clark & Aldous (1987). The seasonal fluctuation of the water table of this area is about 5 - 20 m (Connelly & Sadler, 1994a, b). At present, the groundwater level in other units is unknown. Springs other than the Great Spring, in this area, appear to discharge water only under extreme wet conditions; however, all the sinks are active (Drew *et al*., 1970).

The limestone aquifer in the study area is recharged by two mechanisms; direct rainfall and streams flowing onto the outcrop. A notable point of inflow for the Great Spring is at the Cas Troggy Brook and the major discharge point from the system is the Spring itself (Clark & Aldous,1987). Other discharge areas are to the Nadern Brook at time of high-water level and to the St. Bride's Brook to the west.

Clark & Aldous, (1987) summarised the catchment area of the Great Spring. The suggested principal groundwater catchment boundaries are:

1) in the north, the edge of the Carboniferous Limestone outcrop;
2) in the east, to the east of Ifton sinkhole, probably at apex of Shirenewton Anticline, *i.e* the boundary is to the west of Mounton Brook;
3) in the west, to the east of the Wentwood reservoir sinkhole; and
4) in the south, the Nadern Fault.

The most speculative boundary is the Nadern Fault. As noted by Clark & Aldous, (1987), this fault, which trends northwest to southeast with a downthrow to the north in southerly- dipping strata, indicates that the groundwater is able to pond in the area behind the Fault plane. The oblique angle between fault orientation and dip of the bedding planes suggests that water is funnelled rapidly along the fault zone toward the Great Spring. Another speculative suggestion is that the limestone block at Ifton Quarry is hydraulically isolated from the Great Spring and Nadern Fault zone. There are a few reasons to support these suggestions as summarised by Clark & Aldous, (1987). They are:

1. The absence of pollution from Ifton at the Great Spring.
2. The failure of the Ifton tracer test in which no tracer was detected at the Great Spring.
3. The difference in groundwater level between the NRA monitoring boreholes and the Ifton boreholes.
4. The direction of the groundwater gradient at Ifton.

Clark & Aldous (1987) carried out a water balance study of the Great Spring catchment (Figure 2) and indicated that approximately 75% of the recharge to the Carboniferous Limestone aquifer flows to the Great Spring but some flow could not be quantified. This value indicates that the groundwater flows in this aquifer are highly channelled and is strong evidence of extreme heterogenity in the aquifer resulting from karstification (Connelly & Sadler, 1994a, b). Halcrow & Partners (1991) reviewed the Great Spring water quality data and suggested that the elevated chlorine levels at the spring itself may be related to leakage from the River Severn locally. Clark & Aldous (1987) made the same suggestion.

## Conceptual Model

A conceptual model is a pictorial representation of the groundwater flow system, frequently in the form of a block diagram or a cross-section. Its purpose is to simplify the field problem with associated field data so that the system can be analyzed (Anderson & Woessner, 1992). The geological and hydrogeological information discussed earlier were utilized during the construction of the conceptual model. Figure 3 shows the schematic hydrogeological cross-section of the Carboniferous Limestone aquifer from northwest to southeast. A conceptual model for this aquifer, which is a two-dimensional diagram, is shown in Figure 4. The conceptual model has been used in the numerical model with a few assumptions in terms of boundary and initial conditions. These assumptions have been used in the model calibration. It should be remembered that, if the conceptual model is correct, the mathematical solution (i.e numerical model) may capture the essence of the groundwater flow. If the conceptual model is incorrect or incomplete, the mathematical models may be misleading (Dominico & Schwartz, 1990).

The most important aquifer in the system is the Carboniferous Limestone and the main discharge is the Great Spring. However, water could continue to flow past the Great Spring and follow the deep groundwater circulation (Clark & Aldous, 1987). Table 2 gives the transmissivity values of the aquifer from a few pumping tests carried out by the National River Authority (NRA).

Halcrow & Partners (1991) stated that in general, the high transmissivity value is supported by the more circumstantial evidence of the high outflow at the spring but low regional water level gradient (i.e 0.001 between Caerwent and Tyne Cottage). Most of the boreholes with higher transmissivity lie along the Nadern Fault, except the Caerwent Borehole (Clark & Aldous , 1987).

The rapid rise in groundwater levels in response to rainfall indicates a low storage coefficient (Clark & Aldous, 1987) but the values shown in Table 2 do not reflect this. Regionally, the storage coefficient of the fissured limestone would be expected to be low and it may be that the pumping test data represent the local condition (Halcrow & Partners, 1991).

The hydraulic conductivity of the limestone is likely to range between 0.1 m/day and 1 m/day, with local areas of higher hydraulic conductivity (e.g. along Nadern Fault up to 10 m/day; Connelly & Sadler, 1994a). This estimated value has been confirmed by the falling head test; the value ranging from 0.02 m/day to 0.6 m/day (Connelly & Sadler, 1994b). To summarise, the estimated range of conductivities of this aquifer is between 0.02 to 10 m/day. By assuming an aquifer thickness of 450 m, with the range of hydraulic conductivities, the transmissivity value of this aquifer is between 9 and 4500 $m^2d^{-1}$ (where transmissivity = hydraulic conductivity x aquifer thickness).

It was suggested to ascertain the effective porosity value based on the pumping test data and the tracer breakthrough data. By using the cubic model equation, the value of the fracture aparture and spacing of the aquifer could be estimated. All estimated values are summarised in Table 3. The value in the table could be compared with the modelling result. The effective porosity values for this Carboniferous Limestone aquifer is between $10^{-8}$ to $10^{-4}$. Due to a limitation in ASM programme (i.e. : the minimum value for effective porosity is $10^{-4}$), the effective porosity for this aquifer is 0.0001 and it was utilised in the model. By using the effective porosity and the hydraulic conductivity values with the cubic model to determine the values of aperture (b) and spacing (N), it give an unrealistic value of N with a value more than 14 m.

# MODEL DESIGN AND CALIBRATION

## General Approach

The groundwater modelling study of the Chepstow Block applied a two-dimensional groundwater flow and transport model. The Aquifer Simulation Model (ASM) was utilized. The input parameters for the model were obtained from different sources and are given in Table 4.

## Model Boundary Conditions

Boundary conditions are mathematical statements specifying the dependent variable (heads) or the derivatives of the dependent variable (fluxes) at the boundaries of the problem domain. In steady state simulations, the boundaries largely determine the flow pattern and are subject to serious

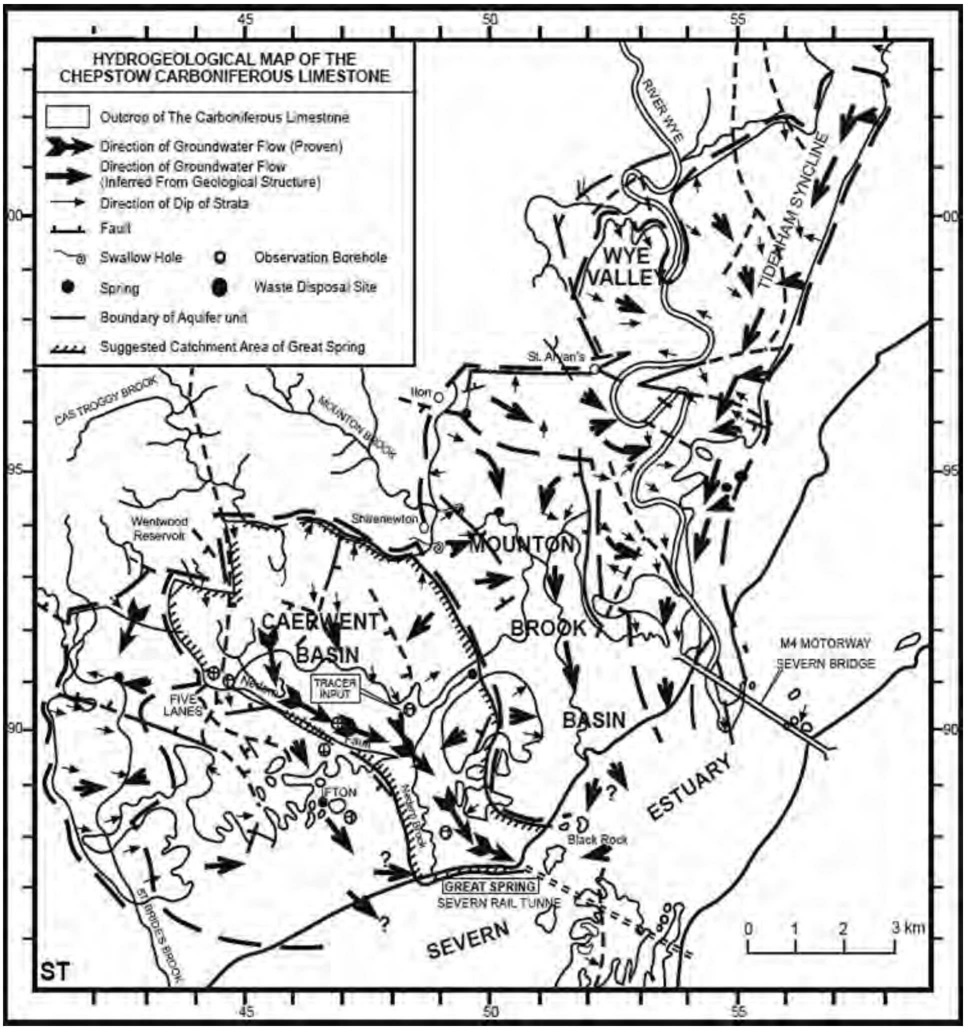


**Figure 2:** Hydrogeological map of Chepstow Block Carboniferous limestone.

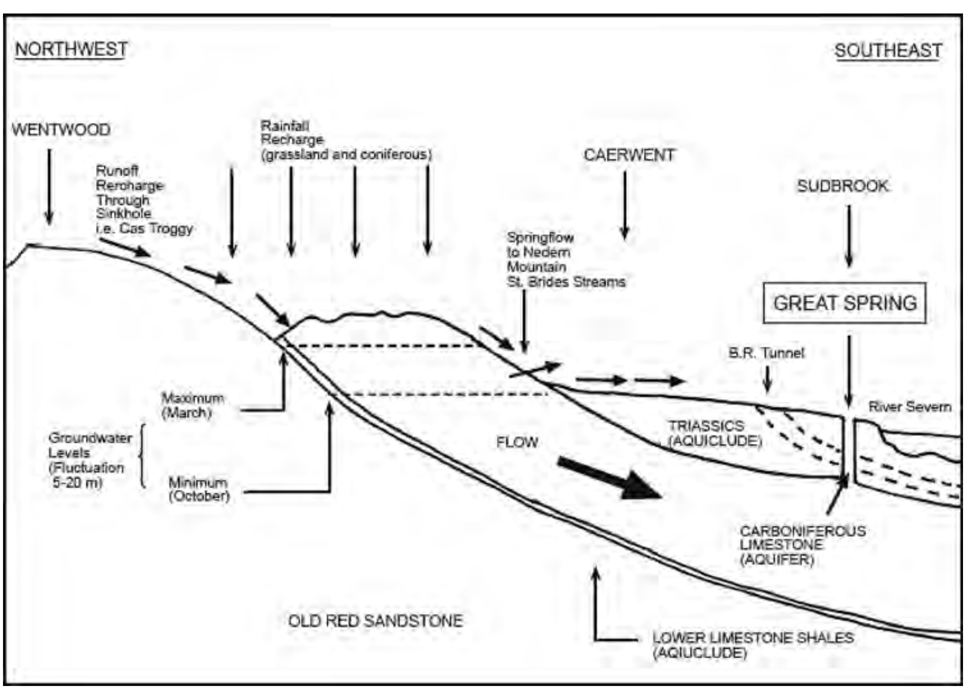


**Figure 3:** Hydrogeological cross section of the Carboniferous limestone aquifer from Northwest to Southeast.

**Table 1:** Hydrogeological division in the Chepstow area. (adapted from Clark & Aldous,1987 and Halcrow & Partners, 1991)

| Geology | Hydrogeology | Characteristics |
|---|---|---|
| Recent and Pleistocene | Minor aquifer | Variable lithology, water bearing where arenaceous. Includes perched water. |
| Triassic and Upper Carboniferous | Aquiclude or aquitard | Main confining layer to underlying limestone which is the source rock for the Great Spring, but may be leaky. |
| Carboniferous Limestone Series | Aquifer | Regional aquifer which feeds the Great Spring and is characterised by a karstic fissure system. |
| Devonian | Aquiclude or aquitard | Forms low permeability base to limestone. |

**Table 2:** Carboniferous limestone aquifer characteristics from pumping tests (adapted from Connelly & Sadler, 1994a,, b).

| Borehole | Location | Aquifer Characteristics | |
|---|---|---|---|
| | | Transmissivity | Storage |
| RAF Caerwent | North of A48 at Caerwent Approx NGR 4750 9050 | 3100 $m^2$/day | 0.003 |
| RAF Caerwent | | 2400 $m^2$/day | - |
| RAF Caerwent | | 3100 $m^2$/day | 0.008 |
| Five Lanes | NGR 4476 9085 | 200 $m^2$/day | 0.01 |
| Tyne Cottage | NGR 4721 8989 | 2000 $m^2$/day | 0.01 |
| Dewstow Rd | NGR 4706 8851 | 14 $m^2$/day | 1 x $10^{-7}$ |
| Caldicot Country Park | NGR 4885 8825 | 2 $m^2$/day | 0.0004 |

**Table 3:** Estimated values of effective porosity.

| T ($m^2$/s) | b (m) | k (m/s) | q (m/s) | v (m/day) | $\eta_e$ |
|---|---|---|---|---|---|
| 3100 | 450 | 8.0 E-05 | 8.0 E-08 | 36 | 1.92 E-04 |
| | | | | 174 | 4.00 E-05 |
| 2400 | 450 | 6.2 E-05 | 6.2 E-08 | 36 | 1.50 E-04 |
| | | | | 174 | 3.10 E-05 |
| 2 | 450 | 5.1 E-08 | 5.1 E-08 | 36 | 1.20 E-07 |
| | | | | 174 | 2.50 E-08 |

T=transmissivity; b=aquifer thickness; k=hydraulic conductivity =T/b; q=flux = k x grad. h; grad. h=0.001; v=groundwater velocity =36-174 m/day from tracer test; and $\eta_e$=effective porosity.

**Table 4:** The input parameters for the model and their sources.

| Model Parameters | Sources and description |
|---|---|
| Model boundaries and thickness | Geological map and Hydrogeological map (BGS) Clark & Aldous (1987), and Connelly & Sadler 1994a, b). |
| Initial transmissivity value | Pumping test data obtained from the Welsh Office, which is summarized in Connelly & Sadler (1994a, b). |
| Groundwater head | Welsh Office (Data from May 1986 to April 1996 for four NRA's boreholes) and Connelly & Sadler, (1994a, b); (i.e Ifton Quarry boreholes). |
| Groundwater recharge | Welsh Office (MOREC'S data for Cardiff Rhoose from 1961 - 90). |

error (Anderson & Woessner, 1992). Le Blanc (1984) suggested that boundaries used in groundwater models consists of two types; physical boundaries (e.g. impermeable rock) and hydraulic boundaries (e.g. groundwater divide). Figure 5 shows the model boundaries of the study area. The A'B' boundaries follow the edges of the arcuate ORS outcrop which act as an aquiclude in the system.

This boundary is a no-flow boundary in the model. The B'C' boundary is a constant head boundary (physical boundary) and lies along the River Wye. The fixed head for this boundary was ascertained from the topography map with the elevation of the river. Other boundaries with no fixed head (*i.e* C'D', D'E' and A'E') are the no flow boundaries. Basically, C'D' and D'E' (*i.e* Ridgeway Fault) boundaries are on the faults. Difficulties arose in defining the physical extent of the fault (may be thrust fault) because the faults are not continuous on the surface. The sensitivity analysis was carried out to gain the effect of the boundary to the aquifer system.

## Model Calibration

The purpose of calibration is to establish a model that can reproduce field-measured heads and flows (Anderson & Woessner, 1992). These measured heads and flows are known as calibration values. Calibration is accomplished by finding a set of parameters, boundary conditions and stresses that produce simulated heads and fluxes that match field-measured values with an acceptable degree of error. Due to time constraints and difficulties in accessing time-dependent data of the discharge at the Great Spring, it was suggested to limit the modelling study to the steady-state model only. The preferred trial and error calibration method in the model simulation was employed in this study. In the trial and error calibration, parameter values are assigned to each node or element in the grid (Figure 6).

During calibration, parameter values are adjusted in sequential model runs to match simulated heads and flows to the calibration target (Anderson & Woessner, 1992). The calibration target were the groundwater head at a few boreholes and the discharge at the Great Spring together with the correct flow-patterns at the Spring, Otter Hole's Cave and rivers. To achieve a calibrated model, a modelling strategy was performed. The simulation steps run have been guided by this strategy. Figure 7 summarizes the principle stages of the modelling strategy.

The pathlines module of ASM was used to estimate the flow directions in the aquifer system. By using these pathline patterns, the catchment area of the Great Spring could be estimated. The ASM program used the velocity interpolation scheme for the computation of pathlines. The location of Nadern Fault and Otter Hole with their descriptions are shown in Figure 8.

For this modelling study, an error of head (i.e. mean absolute error) less than 5 m and an error of inversion of not more 10% for the flow of the Great Spring were acceptable. The initial transmissivity value of the model was 0.029 $m^2$/s (~ 2500 $m^2$/d). With the initial boundary

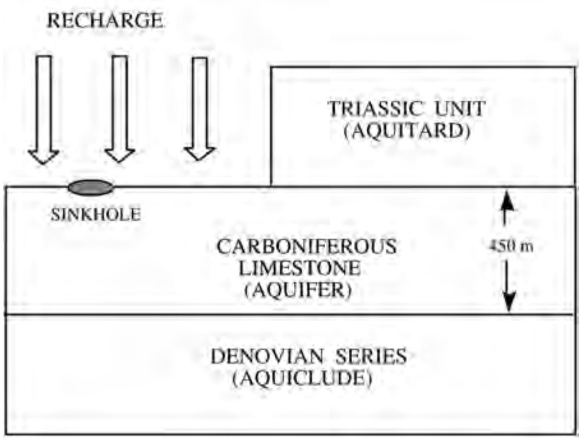


**Figure 4:** Conceptual model of the Chepstow Block limestone aquifer.

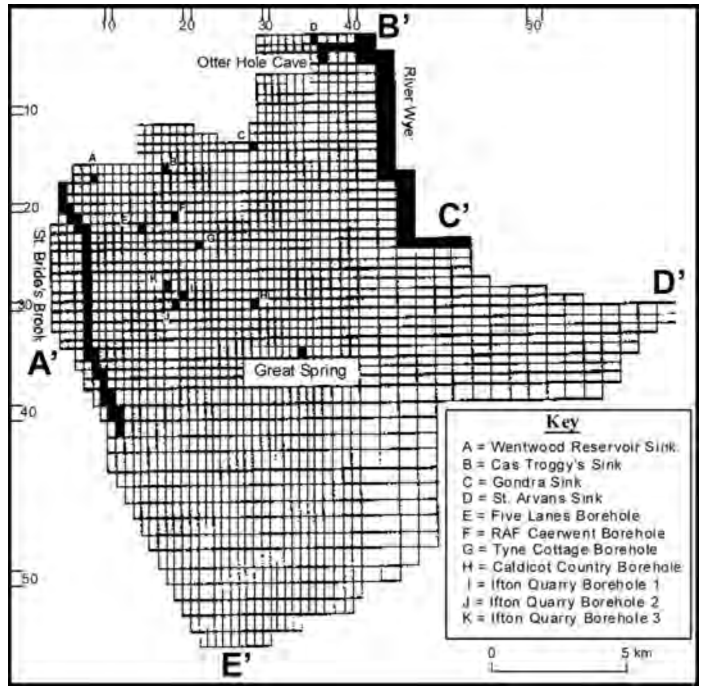


**Figure 5:** Model boundary conditions.

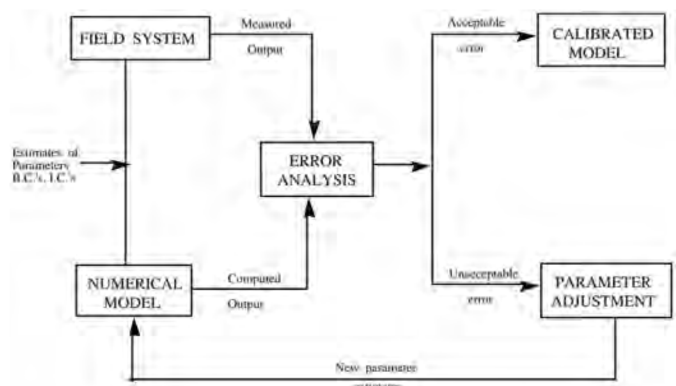


**Figure 6:** Trial-and-error calibration procedure (modified from Anderson & Woessner, 1992).

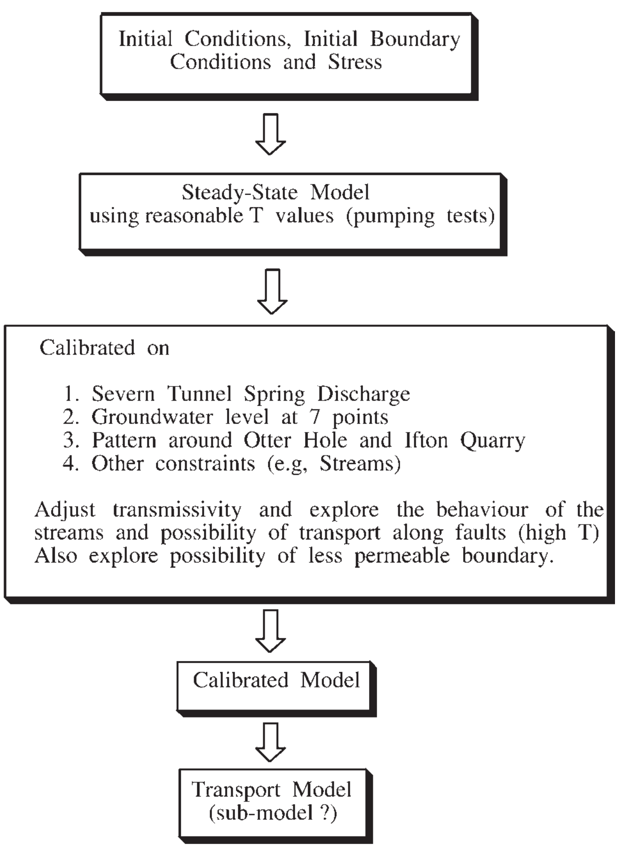


**Figure 7:** Modelling strategy for Chepstow Block groundwater model.

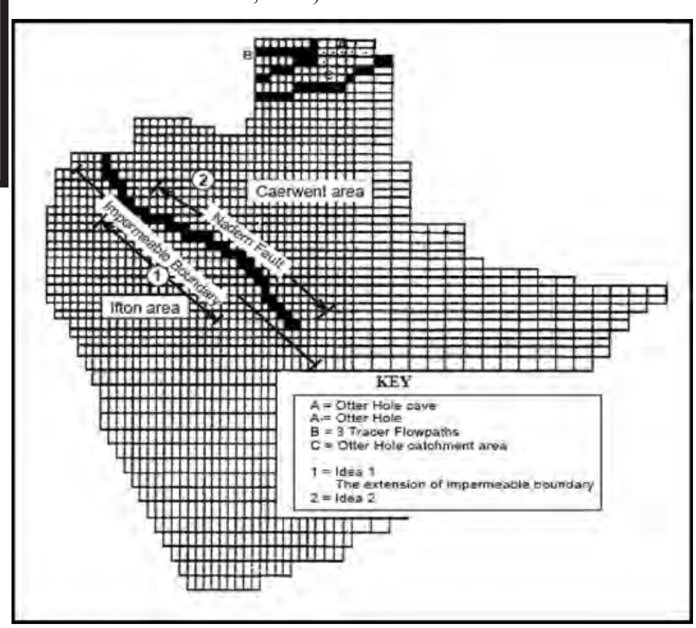


**Figure 8:** Location and description of Nadern Fault and Otter Hole.

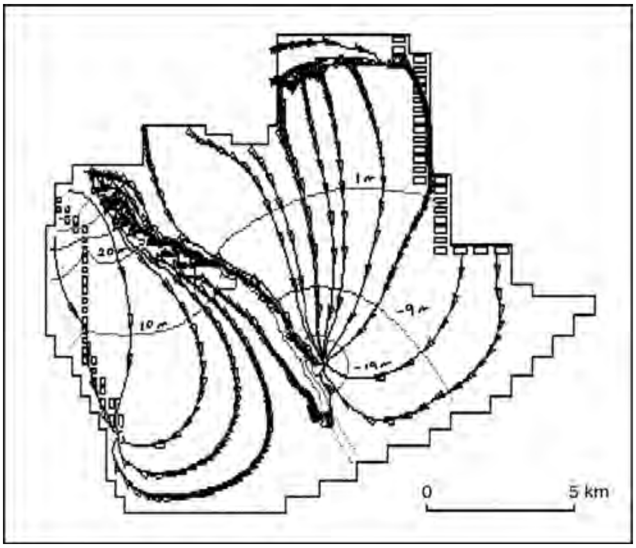


**Figure 9:** Flow-patterns diagram for calibrated simulation.

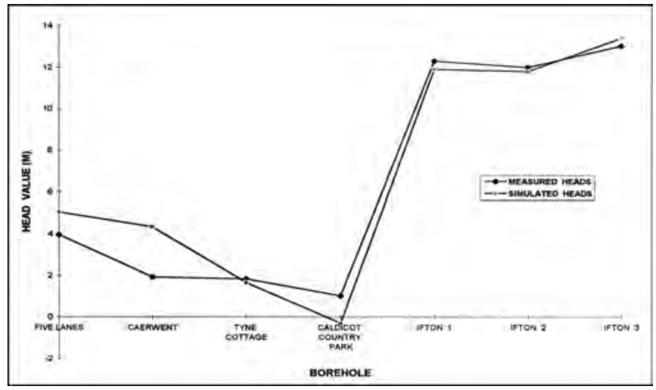


**Figure 10:** Comparison of measured and simulated heads.

**Table 5:** Results of the calibrated simulation.

| Calibrated on | Measured Value | Simulated Value | Error Analysis |
|---|---|---|---|
| Water level: | | | |
| Five Lanes Boreholes | 3.96 m | 5.04 m | Mean |
| Caerwent Borehole | 1.92 m | 4.34 m | absolute |
| Tyne Cottage Borehole | 1.84 m | 1.66 m | error = |
| Caldicot Country Borehole | 1.02 m | -0.30 m | 0.85 |
| Ifton Quarry | | | |
| Borehole 1 | 12.30 m | 11.90 m | |
| Borehole 2 | 12.00 m | 11.80 m | |
| Borehole 3 | 13.04 m | 13.40 m | |
| Discharge at Great Spring | 0.650 $m^3/s$ | 0.715 $m^3/s$ | Discharge difference of 10% |

condition and initial condition, the model was calibrated. The model calibration was performed to steady-state data set, also known as the calibration target.

Few interesting observations could be highlighted from the result of simulations during the calibration process. These include:

1. The model shows a linear relationship between the Great Spring discharge and the aquifer regional transmitivity.
2. If all the streams in the area in the model has been included (i.e. as fixed head), the Mounton Brook will act as a source of recharge for the aquifer and loses water. However, it is not realistic for this model, and it was impossible to calibrate the groundwater levels of the 7 boreholes.

Table 5 gives the results of the calibrated simulation. The results show the reasonable tolerence of head (i.e. mean absolute error of 0.85 m) and discharge at the Great Spring (about 10 % difference) together with flow-patterns which are acceptable as a calibrated model. Figure 9 shows the flow-patterns of the simulation whereas Figure 10 illustrates the difference between the simulated heads value and observed field heads.

## SENSITIVITY ANALYSIS

In the groundwater modelling, a sensitivity analysis is performed in order to establish the effect of uncertainty on the calibrated model (Anderson & Woessner, 1992). The uncertainties in the calibrated model are caused by the uncertainties in the estimates of aquifer parameters, stresses (e.g. recharge) and boundary conditions during the calibration process.

In an earlier stage of the calibration process, the model was tested with the changing of the regional transmissivity. The results of this analysis is given in Table 6 and illustrated in Figure 11. It is evident from the Table and Figure, the changes in regional transmissivity have little overall effect on the water balance but influence the flows at the Great Spring. For example, a 30% decrease in regional transmitivity leads to a 23% decrease in flow at the Great Spring.

The changes in regional transmissivity have a very large effect on the groundwater heads. By reducing 30% of the regional transmissivity, the error of heads increase to 5.54 m. The impermeable boundaries (Figure 12, Table 7) were also subjected to sensitivity analysis. To conclude, the impermeable or low permeable boundaries are sensitive to the model. For example if the transmissivity increment of the barrier increases about 100%, the discharge at the Great Spring will decrease 2.8% and the error of the groundwater heads increase 0.72 m.

The transmissivity of the Nadern Fault is also sensitive to the groundwater heads but less sensitive to the flow at the Great Spring but they have a linear relationship. Table 8 gives the results of the sensitivity analysis of the Nadern Fault and illustrated in Figure 13. To summarize, by increasing the transmissivity of Nadern Fault 50%, the discharge of the Great Spring increased to about 2% and the error of groundwater heads increased 0.5 m.

In this modelling study, only the sensitivity of recharge was carried out with the calibration model. Table 9 gives the results of the sensitivity of the model by changing recharge. These results are illustrated in Figure 14. It is clearly seen that the calibrated model is sensitive to changing the recharge. By changing the recharge 10% from the recharge of calibrated model, the flow at the Great Spring increase a 1.8% and the error of groundwater heads increase a 0.5 m.

**Table 6:** Results of regional aquifer transmissivity - Great Spring discharge sensitivity analysis.

| Simulation | Regional Transmissivity ($m^2/s$) | Discharge at Great Spring ($m^3/s$) | Change in Transmissivity (%) | Mean Absolute Error of Heads | Water Balance Total ($m^3/s$) |
|---|---|---|---|---|---|
| | | | (compared to Sim 2) | | |
| Sim 2 | 0.029 | 1.172 | 0 | 0 | 2.18 E-06 |
| Sim 3 | 0.020 | 0.907 | -30 | 5.5 | -2.20 E-06 |
| Sim 4 | 0.017 | 0.642 | -60 | 19.6 | -9.85 E-07 |
| Sim 5 | 0.011 | 0.633 | -61 | 20.4 | -7.25 E-06 |
| Sim 6 | 0.010 | 0.593 | -66 | 24.8 | 2.30 E-06 |
| Sim 7 | 0.003 | 0.377 | -90 | 117.4 | 1.02 E-06 |

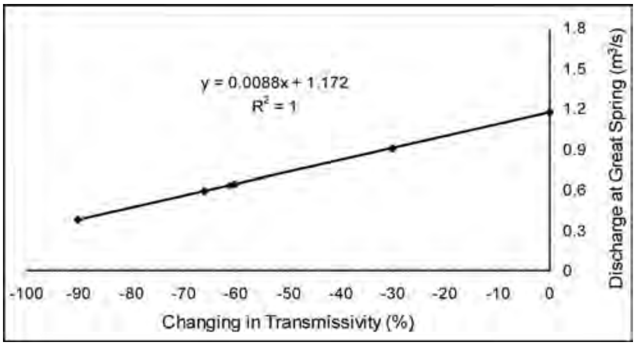


**Figure 11:** Regional transmissivity – Great Spring discharge sensitivity analysis.

**Table 8:** Results of sensitivity analysis of the Nadern Fault.

| Simulation | Transmissivity of Nadern Fault ($m^2/s$) | Discharge at Great Spring ($m^3/s$) | Water Balance Total ($m^3/s$) | Mean Absolute Error of Heads (compared to Sim 52) |
|---|---|---|---|---|
| Sim 52 | 0.2 | 0.578 | 7.11 E-06 | 0 |
| Sim 53 | 0.3 | 0.589 | 3.80 E-05 | 0.48 |
| Sim 54 | 0.5 | 0.603 | 3.50 E-05 | 1.47 |
| Sim 55 | 0.8 | 0.614 | 2.70 E-05 | 1.79 |
| Sim 56 | 1.0 | 0.620 | -1.60 E-05 | 2.00 |

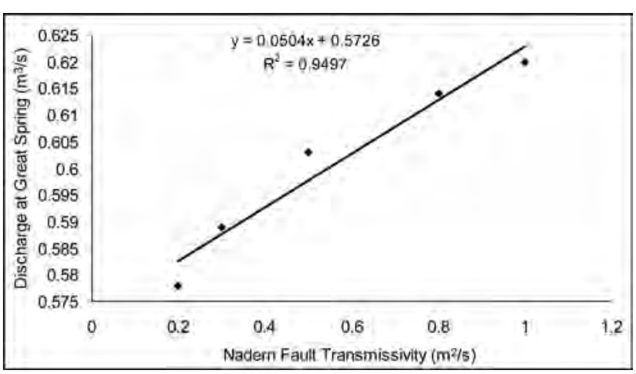


**Figure 13:** Sensitivity analysis of the Nadern Fault.

**Table 7:** Results of sensivity analysis of the impermeable boundary.

| Simulation | Transmitivity of Impermeable Boundary ($m^2/s$) | Discharge at Great Spring ($m^3/s$) | Changing in Transmitivity of Impermeable Boundary (%) | Mean Absolute Error of Heads | Water Balance Total ($m^3/s$) |
|---|---|---|---|---|---|
| | | | (compared to Sim 108) | | |
| Sim 107 | 0 | 0.698 | -100 | 0.72 | 1.1 E-05 |
| Sim 108 | 2 E-05 | 0.715 | 0 | 0 | -1.1 E-06 |
| Sim 109 | 2 E-04 | 0.801 | +900 | 3.0 | -3.2 E-05 |
| Sim 110 | 2 E-03 | 1.010 | +9900 | 7.70 | 6.4 E-05 |

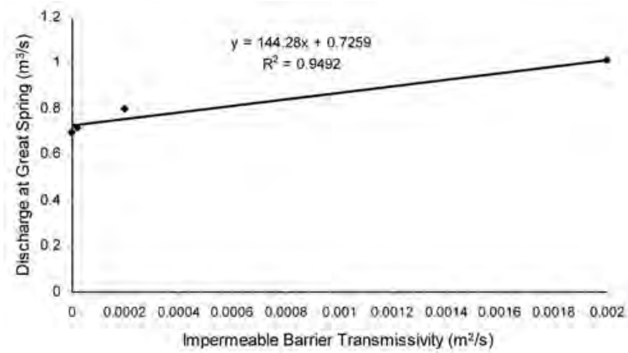


**Figure 12:** Sensitivity analysis of impermeable boundary.

**Table 9:** Results of sensitivity analysis of recharge.

| Simulation | Discharge Great Spring ($m^3/s$) | Change of Recharge (%) | Mean Absolute Error of Heads | Water Balance Total ($m^3/s$) |
|---|---|---|---|---|
| | | (compared to Sim 111) | | |
| Sim 111 | 0.715 | 0 | 0 | 7.50 E-07 |
| Sim 114 | 0.728 | 10 | 0.67 | 6.50 E-06 |
| Sim 115 | 0.743 | 20 | 1.38 | 1.44 E-07 |
| Sim 116 | 0.753 | 30 | 1.95 | 2.17 E-06 |

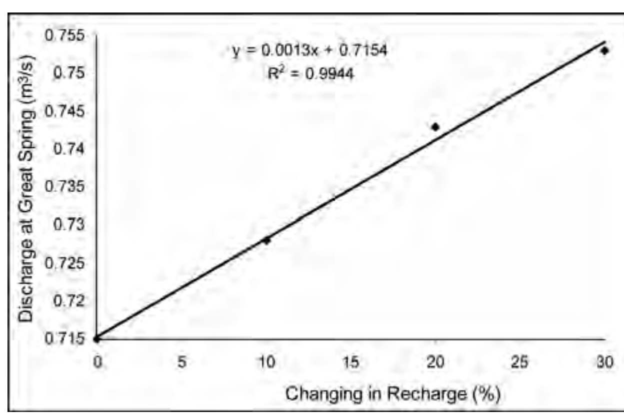


**Figure 14:** Sensitivity analysis of recharge.

## CONCLUSIONS

Despite data limitation, the complexity of hydrogeological and geological conditions and the need for further research in the area, a few meaningful conclusions can still be discerned from the modelling study. The conclusions are as follows:

1. The aquifer showed heterogenous behaviour with the areas of different hydraulic conductivity. However, in general; this aquifer has high transmitivity with a regional transmissivity value of 0.02 $m^2/s$ (~1700 $m^2$/day).
2. The aquifer and the groundwater flow can be modelled without incorporating the karstic element in the model by utilising the concept of an Equivalent Porous Medium (EPM) model.
3. It is impossible to model this aquifer without incorporating the very low impermeable boundary parallel to the Nadern Fault (i.e on the west side). The groundwater head difference between the Great Spring and Caldicot Country Park borehole could be used as evidence to support the existence of the low permeable boundary.
4. The Nadern Fault plays an important role in bringing water from the north to the Great Spring. It acts like a conduit with higher transmissivity (i.e. 0.122 $m^2/s$).
5. The model could also explain the very low transmissivity at Caldicot Country Park borehole from pumping test (i.e 2 $m^2$/day). One of the reasons is the Caldicot Country Park borehole lies on the very low permeable boundary. Other boreholes, except those at Ifton Quarry, are located near to the very high transmissivity Nadern Fault.
6. This aquifer model is insensitive to the boundary conditions, but it is sensitive to the regional tranmissivity, Nadern Fault and low permeable boundary transmissivities. The model also has little effect to the amount of recharge into the system.

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