Urban Groundwater Extraction in Kuala Lumpur, Malaysia

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Summary

The purpose of this study is to evaluate the feasibility of groundwater extraction in Kuala Lumpur, Malaysia as a potential source of potable water. Kuala Lumpur's current water supply is provided by large reservoirs that are dependent on rainfall. In 1998 a long period of drought caused a severe water shortage, demonstrating the vulnerability of these reservoirs.

Since that time, the city's water supply infrastructure has been expanded in line with its fast-growing economy and population. In the Ninth Malaysia Plan, an important policy document, the Malaysian government stated its intention to further expand Kuala Lumpur's water supply, including from alternative sources such as groundwater, to meet growing water demand (EPU, 2005).

This makes a study on the feasibility of groundwater extraction in Kuala Lumpur very timely. Three aspects of groundwater extraction are evaluated: technical feasibility, economic feasibility and institutional feasibility. Together, they provide a comprehensive picture.

Technical feasibility is evaluated by constructing a groundwater flow model capable of predicting the physical effects of groundwater extraction. The model uses borehole data (groundwater depth), remote sensing data (elevation, evaporation) and water balance data (rainfall, hydrological measurements, leakage from water pipes). Because of Kuala Lumpur's complex geology some model parameters, such as hydraulic conductivity, cannot be measured directly and must be calibrated.

The model results suggest that two extraction strategies are feasible: small scale permanent extraction (2.5% of water demand) or large scale temporary extraction (25% of water demand). The weakness of the model results lies in the underlying model assumptions that cannot be verified with the available data.

Accepting the model results at face value, an economic comparison with the Selangor Pahang Water Transfer Scheme suggests the costs of groundwater extraction are competitive, especially for a large scale temporary extraction. Nevertheless, uncertainty remains over the potential cost of necessary environmental remediation and how groundwater extraction costs compare to alternatives, such as programs to reduce non-revenue water.

The institutional feasibility of groundwater extraction is hindered by a lack of knowledge and the large number of agencies that have unclear responsibilities and jurisdictions with respect to groundwater resources management. Furthermore, Kuala Lumpur's water utility is loss-making and the state governments, who carry a constitutional responsibility for water supply and water resources management, have a weak financial position relative to the federal government (Jomo, et al., 2003).

To stimulate the establishment of a coherent groundwater policy, a federal government grants scheme which requires agencies to cooperate to obtain funding seems like the most promising option. The scheme would be easy to implement and does not disrupt the existing institutional structure. The scheme should be phased to ensure the necessary interaction between gathering new information, evaluating the information to make decisions and setting new research goals to further reduce uncertainty.

The study does not allow a definitive conclusion about the feasibility of groundwater extraction in Kuala Lumpur to be drawn, but the positive results do suggest that further research should be conducted to explore the full potential of the city's urban groundwater resources.

Cover photograph: Malaysia from the air, shot while skydiving and using a tripod.
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Contents

1 Introduction

1.1 Background and Research Scope

Kuala Lumpur is a major economic centre in Southeast Asia (Figure 1) with a rapidly growing population and economy. This growth has been accompanied by a rapid expansion of the city's infrastructure, including its water supply infrastructure. Kuala Lumpur relies almost exclusively on rain-fed reservoirs which make its water supply susceptible to disruptions when there is inadequate rainfall. A serious three-month water shortage in 1998 demonstrated the vulnerability of the city's reservoirs.

To prevent a recurrence of the 1998 drought and to expand the city's water supply, the Malaysian federal government announced in the Ninth Malaysia Plan (2006-2010), its most important policy document, that "... *development of groundwater* will be promoted as interim [an] measure[s] to address the anticipated shortage of water in Selangor, *Kuala Lumpur* and Putrajaya" (EPU, 2005).

Figure 1 – Map of West Malaysia. Labeled are Selangor state and the federal territories of Kuala Lumpur and Putrajaya.

Groundwater is often seen as a reliable source of clean water that is available close to the point of consumption, making it an ideal source for meeting the demand for potable water in urban areas. But in urban areas in particular, aquifers are often threatened by pollution and over-extraction which can destroy these groundwater resources.

To preserve groundwater resources Safe Yield rules were first adopted in the United States during the 1920's. The rules simply entail that groundwater extraction should not exceed recharge in order to maintain the groundwater resource. Being very limited in scope, the Safe Yield concept was replaced by the Sustainability concept from the 1980's onwards. The Sustainability concept extended the scope of groundwater management to include water quality, environment, land-use, economy and even governance and social concerns (World Bank, 2000; Custodio, 2002).

Although necessary, sustainable groundwater management is complex and it requires extensive technical knowledge (World Bank, 2000). Unfortunately in many cases even elementary groundwater data such as hydraulic conductivity and recharge cannot be obtained through direct measurements or it is prohibitively expensive to do so (Lerner, 2002; Lubczynski, et al., 2005). Therefore groundwater models play an important role in estimating parameters, organising data and studying the dynamics and sensitivity of the groundwater system (Anderson, et al., 1992).

The lack of reliable data causes uncertainty. Uncertainty, along with the problem's complexity, the long-term time-scale of groundwater changes and pluralism (i.e. the presence of multiple policy actors) can prevent effective decision-making, especially if there is a lack of incentives to explore win-win situations or profitable trade-offs between policy actors (Bressers, et al., 2003).

In Kuala Lumpur the lack of knowledge about groundwater has been highlighted in several water resource studies, but no comprehensive groundwater monitoring and modelling efforts have been undertaken as yet to reduce this knowledge deficit (Binnie dan Rakan, 1980; LESTARI, 1997; SMHB, 2000; Madsen, et al., 2003; Hamsawi, 2007). At present groundwater is not used as a source of potable water for Kuala Lumpur. Large surface water reservoirs are used instead to capture and store the necessary water and their capacity continues to be expanded (Hamsawi, 2007; LESTARI, 1997).

Nevertheless, there are a growing number of incentives that make groundwater an attractive potential source of potable water for Kuala Lumpur. Besides the growth in water demand due to an expanding population and economy and the threat from pollution to lakes and rivers, Kuala Lumpur's rain-fed reservoirs are sensitive to prolonged periods of drought which led to a serious water shortage in 1998 (EPU, 2005; JAS, 2007; Hamirdin, et al., 2004). A recurrence of a water shortage like the one in 1998 is possible given the tight balance between water supply and demand and the effects of climate change (Hamirdin, et al., 2004).

Hence it is timely to re-evaluate the potential of Kuala Lumpur's groundwater resources as a source of potable water. In doing so, attention should be given to two clear deficits in current knowledge. Firstly, the technical feasibility of groundwater extraction must be addressed. Secondly, it should become clear why, given the prevalence of several incentives mentioned in the previous paragraph, no comprehensive studies of groundwater resources have yet been undertaken in Kuala Lumpur and no comprehensive groundwater management policy has been formulated.

1.2 Objectives and Research Questions

The knowledge deficits highlighted in the previous section may appear unrelated at first glance: one pertains primarily to hydrogeology, the other to governance; both are very different fields. But in practice the two fields are closely related: groundwater studies require significant financial resources, usually provided by governments. Governments require information on which they can base their decisions; information that is provided by groundwater studies. So to study groundwater extraction, both issues must be tackled at once.

Hence, the objective of this study is: *to evaluate the feasibility of urban groundwater extraction in Kuala Lumpur as a source of potable water*.

Feasibility is usually assumed to consist of three factors: technical feasibility, economic feasibility and institutional feasibility. These three factors are congruent with the knowledge deficits mentioned earlier: hydrogeology (technical feasibility) and governance (economic and institutional feasibility). Economic considerations are regarded as the primary incentives for cooperation and decision-making by policy actors and are therefore an important governance issue.

These considerations lead to the formulation of three research questions related to the objective stated above:

1. What are the physical effects of groundwater extraction?
2. What is the economic value of groundwater extraction?
3. What is the current institutional setting with respect to groundwater resource management and how can it be changed to enable groundwater extraction?

1.3 Outline

The outline of this thesis is based on the research questions: in Chapter 2 the physical effects of groundwater extraction are quantified. This is followed by a discussion of the governance of groundwater resources in Chapter 3, essentially addressing the first part of the third research question. Chapter 4 addresses the incentives, economic and institutional, that can induce groundwater developments. The second research question (economic value) and the second part of the third research question (institutional change) are explored in Chapter 4. Chapter 5 contains the conclusions and several concrete recommendations.

2 Quantification of Groundwater Resources

2.1 Introduction

The quantification of groundwater resources often proves to be a formidable challenge. It is difficult to quantify groundwater resources because required data acquisition can be prohibitively expensive. Just like the exploitation of oil and gas reserves, exploration costs account for a large part of the investment needed to safely exploit groundwater resources. Hence it is important to quantify groundwater resources accurately and cheaply early on in the development process so that the necessary information is available for timely decision-making.

There are several different methods of groundwater quantification, one of them is modelling. Groundwater models can be used to study the sensitivity and dynamics of the groundwater system and to organize available field data (Anderson, et al., 1992). This gives modelling a significant advantage when analysing Kuala Lumpur's very inhomogeneous hydrogeology over other quantification methods such as pumping tests and groundwater potential mapping.

Pumping tests[a] are primarily influenced by local hydrogeological conditions and therefore, if the hydrogeology is highly variable, the results are not valid for a wider area and therefore of limited value in larger-scale groundwater studies (Lubczynski, et al., 2005). Groundwater potential mapping[b] is a very powerful tool for estimating groundwater recharge in large vegetated areas. However in urban areas recharge is heavily influenced by factors such as leaking pipes and complex land use for which groundwater potential mapping methods are ill-suited (Lerner, 2002).

The purpose of the groundwater flow model described in this chapter is to answer the first research question: *What are the physical effects of groundwater extraction?* By predicting the effects of groundwater extraction using the model, different extraction strategies can be compared.

In this chapter the theory of modelling and the selection of an appropriate model are addressed first (Section 2.2). After this, the available data is analysed and processed so that it can be used as an input for the model (Section 2.3). Next are the setup and calibration of the model (Section 2.4), followed by the evaluation of several different extraction strategies to provide an answer to the research question (Section 2.5).

2.2 Modelling Theory and Model Selection

In this section the relevant literature about groundwater and groundwater modelling is reviewed as it pertains to Kuala Lumpur. This leads to the selection of a modelling method (the Equivalent Porous Medium method) and a model (MODFLOW). Both the theory and equations behind the model and the modelling method are described. Lastly, the concept of dual-porosity

[a] Pumping Test: a method for determining the transmissivity (hydraulic conductivity x aquifer thickness) and storativity (volume of water released from storage per unit decline in the hydraulic head) of an aquifer and to establish the reliable yield of a well and to find out if the well affects other wells and springs.
[b] Groundwater Potential Mapping: a method for estimating groundwater recharge using climate (e.g. rainfall, evaporation), geophysical (e.g. slope, soil type) and land-use data (e.g. vegetation type). Recharge is then used to estimate the *potential* amount of groundwater that can be extracted.

media is mentioned. Although the concept is not applied in the modelling process, it does offer some valuable insights.

The hydrogeology of Kuala Lumpur is complex. Granite, Hawthornden (mostly schist), Kenny Hills (mostly sandstone) and Kuala Lumpur Limestone formations are overlaid by fluvial deposits (. The latter three formations: Kenny Hills, Kuala Lumpur Limestone and the fluvial deposits have groundwater potential, and thus a relatively high hydraulic conductivity and storage (LESTARI, 1997; Yin, 1986; Freeze, et al., 1979).

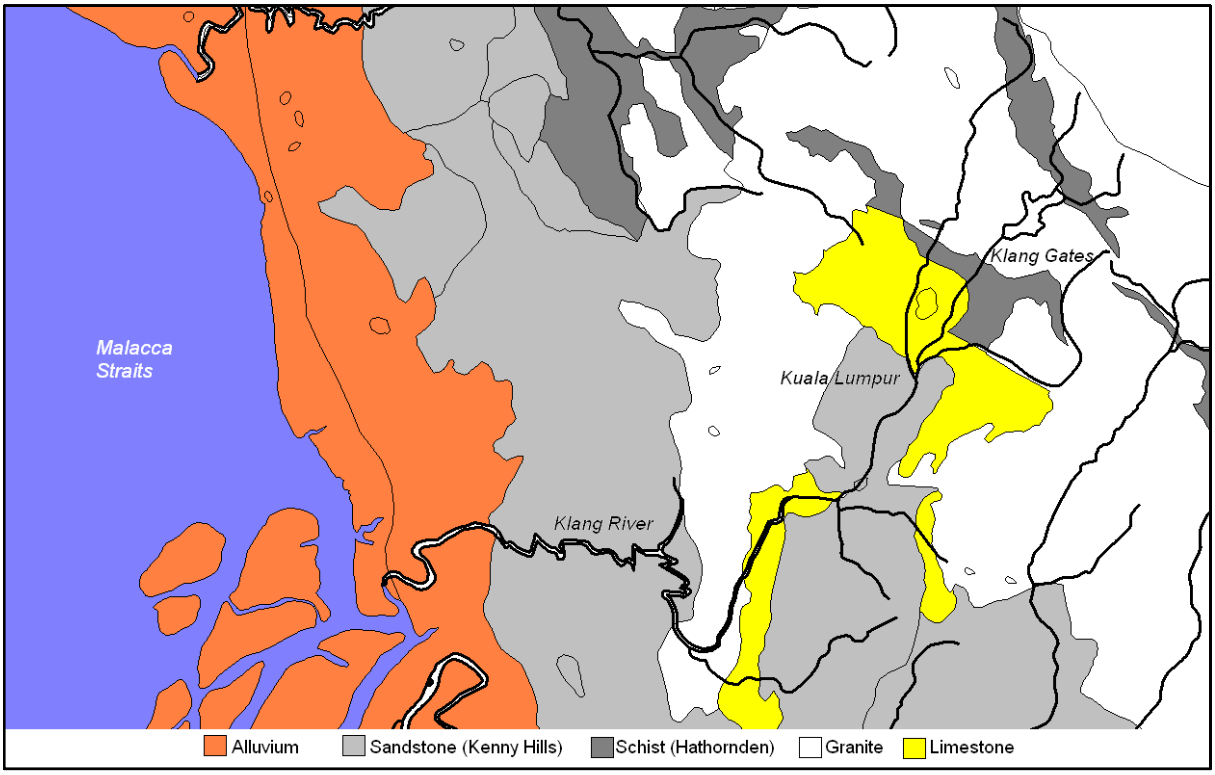

Figure 2 – Geological map of the Klang basin, including Kuala Lumpur.

Hydraulic conductivity, K (m/day), is the main determinant of groundwater flow velocity and a core parameter in any groundwater model. The relationship of hydraulic conductivity to flow, q (m/day) and the hydraulic gradient, $\Delta h/\Delta x$ (m/m) is expressed by Darcy's fluid permeability equation (1). It assumes laminar flow through a porous medium and is given for a single dimension, x.

$$q = -K\frac{\Delta h}{\Delta x} \tag{1}$$

The groundwater flow equation (4) is the basis of any groundwater flow model. It is derived from Darcy's equation (1) and the mass balance equation (2). The groundwater flow equation is valid for a *representative elementary volume*: a theoretical volume that is large enough to have a representative porosity, small enough to have a near-constant hydraulic head and through which there is again laminar flow (Anderson, et al., 1992).

In the mass balance equation (2) there is inflow and outflow from neighbouring cells (which are also representative elementary volumes), injections of water (source) and extractions of water (sink). Together they cause a change in storage. Time, t, is often expressed in days.

$$\frac{\Delta M_{storage}}{\Delta t} = \frac{\Delta M_{in}}{\Delta t} - \frac{\Delta M_{out}}{\Delta t} + \frac{\Delta M_{source}}{\Delta t} - \frac{\Delta M_{sink}}{\Delta t} \tag{2}$$

The mass balance equation (2) can be rewritten into a flux balance equation (3) because water is assumed to be incompressible. Since mass = density × volume and density is constant, density can be left out of the equation. Since we are considering the 1-dimensional situation, volume = Δx.

The storativity coefficient, S (m/m), is introduced on the left-hand-side of the equation to express the storage properties of the aquifer. Storativity expresses the volume of water that is released from an aquifer per unit decline in the hydraulic head. In an unconfined aquifer, storativity is assumed to be equal to specific yield (i.e. drainable porosity) because the elastic storage (water released when aquifer is still fully saturated) is very small relative to the drainable porosity. Typical values of specific yield are: 14% (limestone), 26% (schist), 21% (fine sandstone) and 6% (clay) (Anderson, et al., 1992).

$$S\frac{\Delta h}{\Delta t}\Delta x = q_{in} - q_{out} + q_{source} - q_{sink} \tag{3}$$

By replacing the in- and out-going flux in equation (3) with the Darcy equation we can derive the 1-dimensional groundwater equation (4) which can be re-written as the analytical 3-dimensional groundwater equation (5) that is used in groundwater flow models. Note that q_{source} and q_{sink} have been combined into R (m/day), a generic source/sink term that can also be used to express leakage. Also note that volume (now 3D: x, y, z) and storativity are moved to the right-hand side of the equation and that hydraulic conductivity and storativity are considered to be spatially uniform and isotropic within the representative elementary volume (Anderson, et al., 1992).

$$S\frac{\Delta h}{\Delta t}\Delta x = K\frac{\Delta h}{\Delta x} + q_{source} - q_{sink} \tag{4}$$

$$\frac{\partial h}{\partial t} = \frac{K}{S}\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2}\right) - R \tag{5}$$

Although the groundwater flow equation is very elegant and widely used, the assumptions on which it is based, such as uniformity and laminar flow, cannot always be satisfied in practise.

The fluvial deposits and the Kuala Lumpur Limestone formation violate the model assumptions. The limestone formations contain many fractures, conduits and cavities created by chemical erosion of the carbonate. This creates a two-phase system of nearly impermeable carbonate rock and conduits with rapid, non-laminar flows (Yin, 1986; Anderson, et al., 1992). In the fluvial deposits, the transmissivity can vary by 2 to 3 orders of magnitude due to the grain size distribution, making it difficult to measure or to define the boundaries of a representative elementary volume (Freeze, et al., 1979; Lubczynski, et al., 2005).

The solution to this problem is provided by the Equivalent Porous Medium method. Because storativity and hydraulic conductivity cannot be measured directly, they have to be calibrated instead. For example, it is assumed that a limestone formation will behave like a theoretical *Equivalent Porous Medium* if the representative elementary volume is chosen sufficiently large.

In that case the non-laminar flow through fractures, conduits and cavities is assumed to 'average out'. If spatial and temporal groundwater head data is available, then parameters such as hydraulic conductivity can be calibrated (Scanlon, et al., 2003).

To apply the Equivalent Porous Medium method, a numerical model is needed that compliments the structure of the data. The data is available in fixed grids (see next section) therefore a finite difference model seems appropriate which also uses fixed grids. The most popular finite difference model is the Modular Finite-Difference Groundwater Flow model (MODFLOW), developed by the United States Geological Survey. 'Modular' refers to the fact that different modules, such as a recharge module, river module, wells module, etc. can be added to the model when they are needed, making the model very flexible. Most previous Equivalent Porous Medium studies use MODFLOW (Quinn, et al., 2006; Scanlon, et al., 2003).

Given below is a schematisation of MODFLOW (Figure 3) and the analytical equation that is solved in MODFLOW using a numerical finite difference scheme (6). The MODFLOW cell is the numerical equivalent of the representative elementary volume.

MODFLOW is considered a 'quasi-3D' model because flow in the vertical (z) direction is simplified by a leakance term between the horizontal layers, leading to an adapted R, R^* in equation (6). The reason for this simplification is to speed up calculations and because horizontal flows are often of secondary importance in constant-density groundwater flow models (Anderson, et al., 1992).

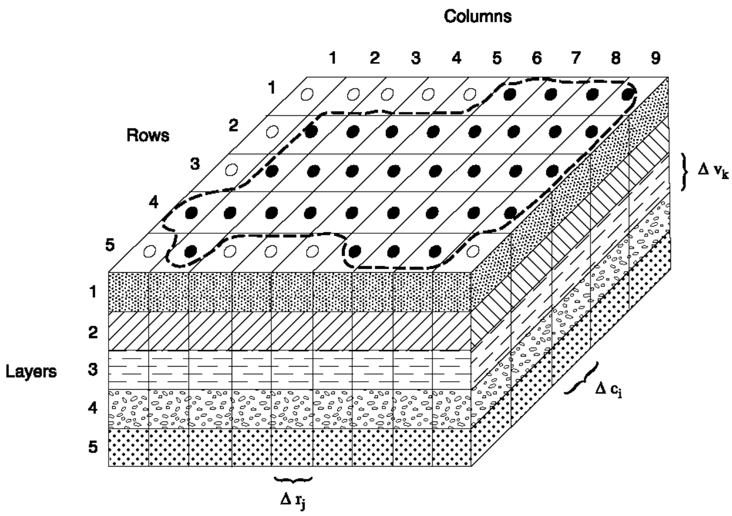

Figure 3 – Schematisation of MODFLOW (Harbaugh, 2005).

$$\frac{\partial h}{\partial t} = \frac{K}{S}\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2}\right) - R^* \qquad (6)$$

To perform the calibration two computer codes can be used: Universal Inverse Modelling Code (UCODE) and Parameter Estimation Code (PEST). Essentially the code changes the value of the parameter(s) being sought, runs the model, and checks if the model results match the measured results using non-linear regression. This is done until an optimum value for the parameter(s) is found. The difference between the codes lies in how they find this optimum (Harbaugh, 2005).

UCODE optimises using a modified version of the Gauss-Newton method (Poeter, et al., 1999). PEST optimises uses the Gauss-Marquardt-Levenberg optimisation algorithm (Liu, et al., 2005). Although much can be written about the strengths and weaknesses of each approach, generally speaking UCODE is slower but better at finding global optima. PEST is faster but gets stuck on a local optimum more easily. In some ways, this makes the codes complimentary and they can be used alongside each other. For example, Scanlon et al used a combination of UCODE and trial-and-error to calibrate their model (Scanlon, et al., 2003).

To complete this review of relevant groundwater modelling theory, dual-porosity media must be discussed as well. Dual porosity media mathematically describe a single medium (e.g. fractured limestone) as if it were two separate media, each with a different porosity. Generally speaking, the lower porosity medium is referred to as the matrix pore system (e.g. solid carbonate rock) and the higher porosity medium is referred to as the fracture pore system (e.g. the fractures in the limestone). Usually, dual porosity models are calibrated using transient data sets (varying the water table with time) or by measuring the porosity of the fracture pore system using a tracer test (Cornation, et al., 2002; Morshed, et al., 2007).

Yet in theory it is also possible to calibrate a dual porosity steady state model if the size of the fracture pore system relative to the matrix pore system is known. This is almost never the case. However it is possible that two real layers are identified that have different porosities but between which there is a lot of interaction (the leakance term has a large value). In that case the geometry of the layers would be known and it would be possible to calibrate a steady state double layered model like a dual porosity model.

Gerke and Van Genuchten describe the relationship between groundwater fluxes: q_{total}, $q_{fracture}$ and q_{matrix} in a dual porosity medium using equation (7), where w is the relative volumetric proportion of the fracture pore system to the matrix pore system, $0 \leq w \leq 1$ (Gerke, et al., 1996).

$$q_{total} = wq_{fracture} + (1-w)q_{matrix} \tag{7}$$

Since the calibration is steady state, it can be re-written by re-introducing Darcy's equation (1) and noting that the water table, h, in both media is equal. This yields equation (8).

$$q_{total} = wK_{fracture}\frac{\partial h}{\partial x} + (1-w)K_{matrix}\frac{\partial h}{\partial x} \tag{8}$$

By definition q_{total} (steady state), $K_{fraction}$ and K_{matrix} (same formation) are constant. The water table, h, is measured and because the geometry of the formations is known, w and x are also known. So in theory this allows the hydraulic conductivity of both media to be calibrated if more than three measurements of the water table are available. This concept is expressed in equation (9) for three theoretical points, 1, 2 and 3, showing how the hydraulic conductivities, K, can be calculated directly.

$$\begin{aligned} 0 &= \left(w_1\frac{\Delta h_1}{\Delta x_1} - w_2\frac{\Delta h_2}{\Delta x_2}\right)K_{fracture} + \left((1-w_1)\frac{\Delta h_1}{\Delta x_1} - (1-w_2)\frac{\Delta h_2}{\Delta x_2}\right)K_{matrix} \\ 0 &= \left(w_1\frac{\Delta h_1}{\Delta x_1} - w_3\frac{\Delta h_3}{\Delta x_3}\right)K_{fracture} + \left((1-w_1)\frac{\Delta h_1}{\Delta x_1} - (1-w_3)\frac{\Delta h_3}{\Delta x_3}\right)K_{matrix} \end{aligned} \tag{9}$$

Note that the implementation of this concept in MODFLOW is different: calibration in

MODFLOW uses the PEST and UCODE optimisation codes. These formulas are simply to confirm that it is possible to perform a steady state dual porosity calibration.

Concluding: MODFLOW, UCODE and PEST provide the tools for groundwater flow model construction by allowing the hydraulic conductivity to be calibrated as an Equivalent Porous Medium using groundwater level data and several other inputs. This entire process will be described in the next sections.

2.3 Data Analysis and Processing

Data and the topic of the next section: model setup, are closely related because they influence each other. Successful models are often parsimonious; they use the data that is available as effectively as possible. Alternatively, data-gathering efforts can also be guided by modelling needs. But that is not the case for the model under consideration which uses existing data. Therefore the available data is analysed first, before choosing the model setup in order to give the reader greater insight into the modelling process.

This section consists of three parts. First, the study area is described to give a general overview of the physical geography, the main geotechnical problems and water quality concerns. Second, the hydrogeological data is processed and analysed. This data will be used to calibrate the hydraulic conductivity in accordance with the Equivalent Porous Medium method. Lastly, a water balance is set up. Data for the model inputs will be derived from this water balance.

2.3.1 Geographic Features of the Study Area

Kuala Lumpur is located in the eastern part of the Klang River basin (total area: 1278 km^2). The Klang, Gombak and Batu rivers originate in the densely forested foothills of the Titiawangsa mountain range, north of Kuala Lumpur and have their confluence near the old city centre, see Figure 4. The Klang river then continues its journey through the relatively flat and heavily urbanised valley floor before discharging into the Melaka Straits at Port Klang (Rustam, et al., 2000).

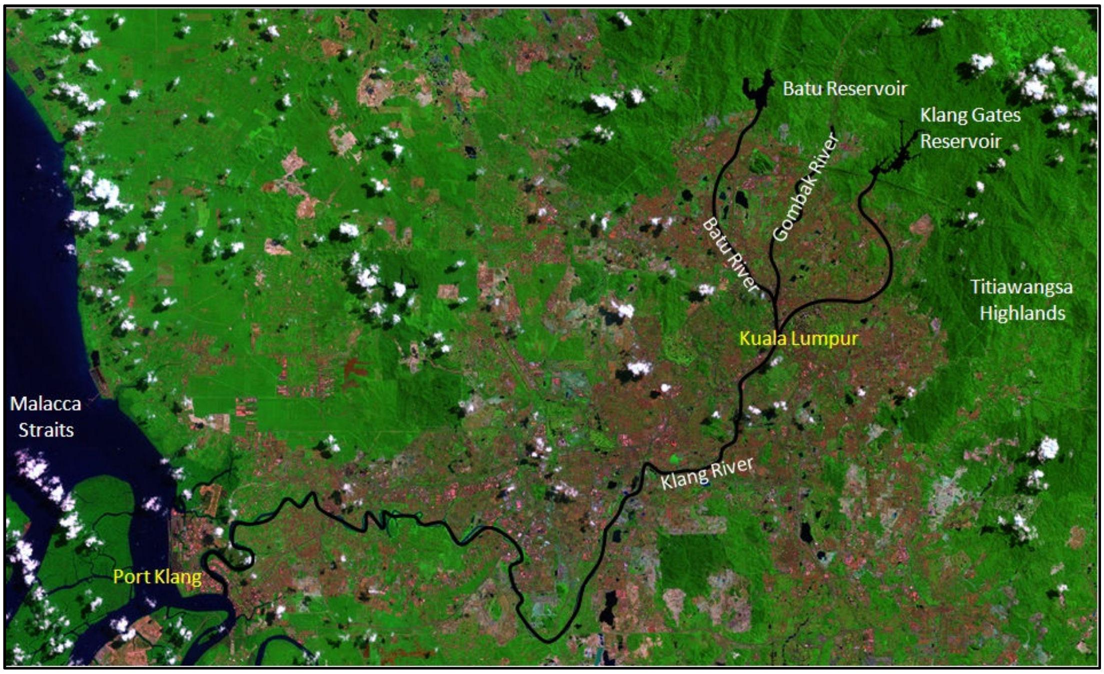

Figure 4 – Colour composite Landsat image of the Klang basin.

The Klang basin has a tropical climate with abundant rainfall of 2700 mm per year. The maximum precipitation occurs in October and November and in April, coinciding with the southeast and southwest monsoon seasons respectively (Rustam, et al., 2000). Rainfall is also the primary source of the basin's two main drinking water reservoirs (Klang Gates reservoir and Batu reservoir).

Tin ponds are one of the most important hydrogeological features in Kuala Lumpur. Limestone, being easily erodible traps mineral deposits (especially tin) in its extensive networks of fractures, conduits and cavities. Tin deposits were mined from the 1850's until the 1980's in open-cast mines. These mines have since been closed and flooded, creating Kuala Lumpur's characteristic tin ponds (Yin, 1986). Because of the high permeability of the limestone, the tin ponds play an important role in regulating Kuala Lumpur's water balance, providing water storage during heavy rains and being a major source of groundwater recharge. The groundwater table in the valley is quite shallow at around 5 m below the surface, making it sensitive to pollution (Binnie dan Rakan, 1980).

The irregular limestone formations also pose geotechnical engineering challenges. If groundwater levels fall and cavities and tunnels are drained, this can lead to sudden catastrophic land subsidence (sinkhole formation) as illustrated in Figure 5. The sudden loss of support provided by the groundwater has caused the collapse of buildings in the past. Often these occurrences were related to the draining of tin mines or major construction projects (Tan, 2006).

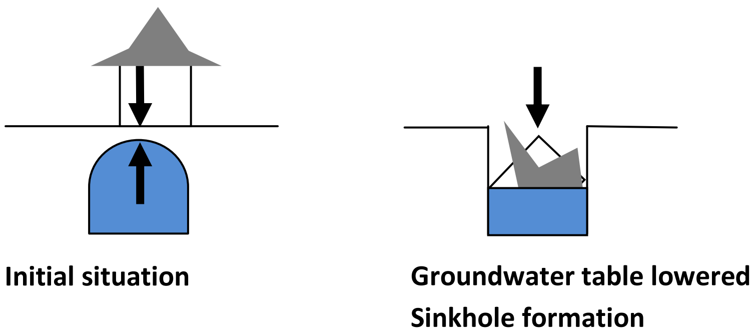

Figure 5 – Simplified illustration of sinkhole formation mechanism.

Other geotechnical challenges are posed by the steep hills that surround most of Kuala Lumpur. Some of these hills have been cleared from natural vegetation to make way for development. Here, heavy rains occasionally induce landslides, some of them involving loss of life (LESTARI, 1997). These landslides are usually caused by inadequate local drainage which causes the soil to become saturated and lose its carrying capacity. However it is a very local problem, whereas sinkholes can be induced by groundwater extractions hundreds of metres away (Tan, 2006; Craig, 1997).

And then there is groundwater quality. Department of Environment monitoring reports indicate that groundwater quality in Kuala Lumpur is generally good, except near landfill sites where the manganese concentration exceed the Department of Environment benchmark. Manganese is a heavy metal commonly found in batteries and other chemicals. Manganese leaching is a known problem and has been reported at least since the 1980's (Binnie dan Rakan, 1980). Leaching in tropical climates is often more severe than in temperate climates because heavy rainfall generates more effluent from landfills. Some sample groundwater pollutant concentrations are given in Table 1.

Water quality in the tin ponds is not monitored by the Department of Environment, but casual observation suggests that the water quality fairly good because many of the ponds are popular fishing spots used by local residents.

	Department of Environment Benchmark	Sungai Besi Landfill (1979)	Sungai Besi Landfill (2006)	Royal Selangor Golf Course (2006)
Coliform	none	18 MPN[c]/100 ml	2 MPN[c]/100 ml	7 MPN[c]/100 ml
Manganese	0.1 mg/l	0.38 mg/l	0.346 mg/l	0.0037 mg/l
Nitrate	10 mg/l	0.001 mg/l	15 mg/l	3.2 mg/l
Chloride	250 mg/l	9 mg/l	6.9 mg/l	2.1 mg/l

Table 1 – Sample pollutant concentrations in groundwater (JAS, 2007; Binnie dan Rakan, 1980).

2.3.2 Hydrogeology

The primary source of hydrogeological data is the Department of Minerals and Geoscience. At its offices in Shah Alam, the department has a library of borehole records which are mainly collected from site investigation reports produced by private contractors. Location, groundwater depth and bedrock depth data are available for 1305 points in the study area. Most data has been collected after 1980 (see Figure 6). The Department of Minerals and Geoscience also publishes maps that show the approximate boundaries of geological formations, fractures and the local top soils.

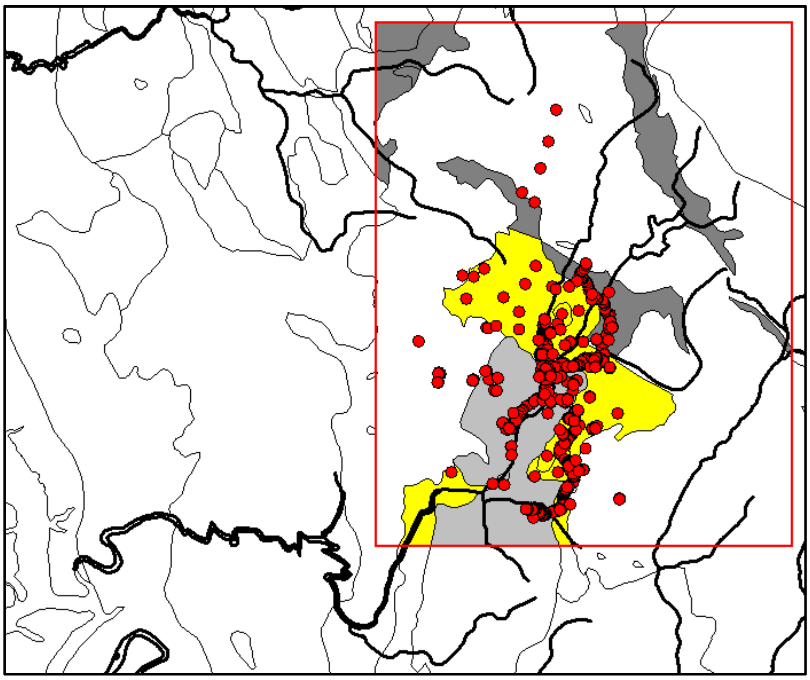

Figure 6 – Measurement points (red dots) and the extent of the study area (red line).

[c] MPN = Most Probable Number, a statistical estimate of the number of bacteria per unit volume.

Detailed digital topographic maps (e.g. the L808 series) are available from the Department of Surveying and Mapping. These are used to identify the location of rivers and lakes. A digital elevation model is obtained from Shuttle Radar Topography Mission data made available on-line by the United States' National Geospatial-Intelligence Agency and National Aeronautics and Space Administration. The digital elevation model is used in the groundwater model instead of the elevation data from the 1305 borehole records because the borehole data does not cover the entire study area.

Almost all of the borehole data is from the valley floor because most construction projects (and therefore most geotechnical investigations) take place there. The borehole data is only representative for a very small area. Given the known large geological variation, errors can easily occur if a single measurement is assumed to be representative for large area, which happens if no other data points are available.

Borehole elevations can diverge by more than 50 m compared to the value assigned to the matching digital elevation model cell. Given that the total elevation range is more than 1000 m, this is an error of about 5%. Nevertheless, 50 m is significant considering that most measurements are taken within the range of 0 to 100 m (Figure 7) and that cell dimensions are about 227 m × 227 m. However, given that there are 1305 borehole points and more than 10,000 cells, it is assumed that the error of the final model and calibration will average out and be smaller.

As mentioned earlier, the borehole data does not cover the entire study area, yet the model does require inputs for the entire study area. Therefore it is necessary to interpolate. There are basically two possibilities: spatial interpolation (e.g. kriging) and interpolation correlating to a variable that is available for the entire study area, in this case: elevation from the digital elevation model.

The spatial correlation of groundwater levels can be tested using a semivariogram (Figure 8). Alternatively, the relationship between groundwater levels and elevation can be plotted (Figure 7). Both graphs show clear results: there is no spatial correlation in the groundwater depth, but there is a clear linear relationship between groundwater levels and elevation.

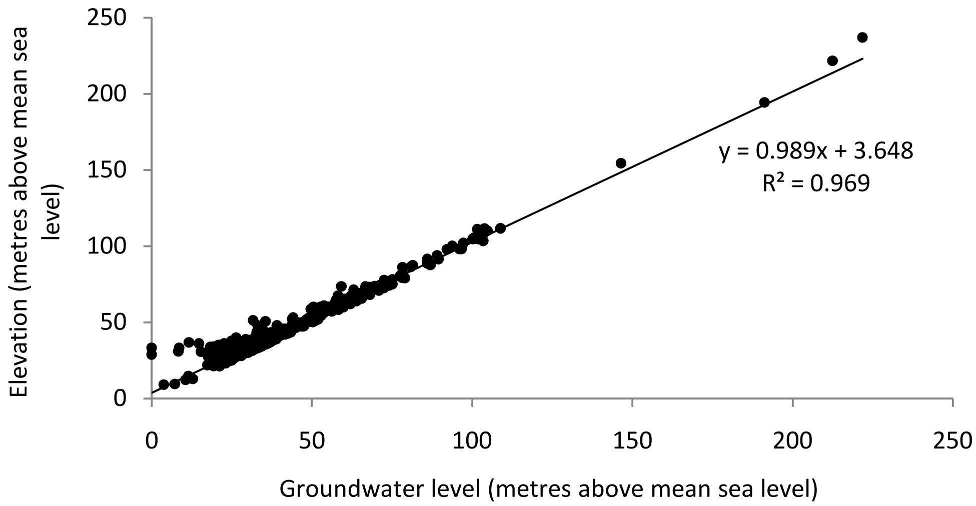

Figure 7 – Plot of Elevation vs. Groundwater Levels for 1305 data points.

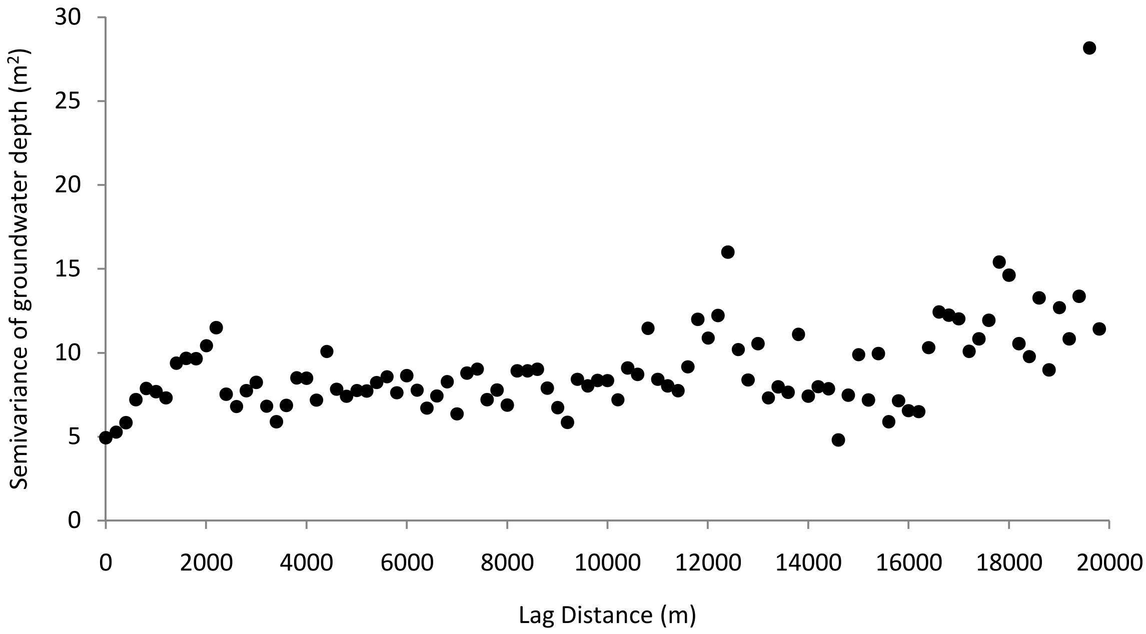

Figure 8 – Semivariogram showing the lack of spatial correlation between groundwater depths.

The lack of spatial correlation between groundwater *depths* can be explained by the highly variable hydrogeology and measurement errors which can distort weak spatial trends. This can make the strong linear relationship between groundwater *levels* and elevations seem surprising. However the relationship between groundwater levels and elevation is offset by 3.65 m, which is essentially the average groundwater *depth*. Hence both conclusions do not conflict.

This still leaves the question of the validity of the linear relationship between groundwater levels and elevation. The relationship is based on data with an elevation of 0 to 250 m above mean sea level, yet this relationship must be extrapolated to elevations of up to 1400 m above sea level, for which no borehole data is available. One would expect the groundwater table to be deeper in the hills (higher elevations) and shallower at the valley floor (lower elevations). The available data does not show this trend.

Additionally, if tin ponds play a significant role in regulating the groundwater table, one would expect this to show in the groundwater data. But even if distance to a tin pond is plotted against groundwater depth, no such relationship is evident (graph not shown).

Nevertheless, the relationship between groundwater levels and elevation is clearly demonstrated at the valley floor. The valley floor is the main focus of the groundwater flow model because the hydrogeological formations that have most groundwater potential are located there. Therefore the groundwater level inputs for the model are generated from the digital elevation model while the comments made in this section must be taken into account when interpreting the model results.

2.3.3 Water Balance

Hydrological data for the water balance is obtained from the Department of Irrigation and Drainage maintains an extensive network of river discharge, reservoir level and rainfall measurement stations. Unfortunately the measurement series of many stations are incomplete and unreliable. Aggregated data about water supply, leakage and consumption are available from the Selangor Water Supply Corporation and the Malaysian Water Association. Evaporation data is obtained from a Landsat image made available by the Global Land Cover Facility of the University of Maryland.

The purpose of setting up the water balance is to generate inputs for the model, to gain insight into the quantity of water flowing through the study area and to fill gaps for which no measurements are possible or available (e.g. infiltration). The water balance is split in three parts: above ground, piped water and groundwater, which are all linked to each other .

These links and relevant assumptions are explained in the next few paragraphs, as well as how model inputs are distilled from the water balance data. The water balance is calculated for the area upstream of the Klang River discharge gauging station at Sulaiman bridge. (Sulaiman bridge is roughly located at the 'Kuala Lumpur' label in Figure 4) The water balance area is 414 km^2.

Water Balance A (Above Ground)

ID	Term	Amount (mm/yr)	Source
A1	Rainfall	+2792.9	Dept. of Irrigation and Drainage
A2	Evapotranspiration	-1200.9	Landsat image
A3	Infiltration (to groundwater, G1)	-138.5	**Calculated** from water balance
A4	River discharge	-1734.4	Dept. of Irrigation and Drainage
A5	Tap water (flowing out from pipes, P2)	+526.5	Malaysian Water Association
A6	Water intake (being put into pipes, P1)	-245.6	Selangor Water Supply Corp.

Water Balance P (Pipes)

ID	Term	Amount (mm/yr)	Source
P1	Water intake (from surface water, A6)	+245.6	See A6
P2	Tap water (to consumers, A5)	-526.5	See A5
P3	Loss (to groundwater, G2)	-164.3	Malaysian Water Association
P4	Net export/import (from outside area)	+445.2	**Calculated** from water balance

Water Balance G (Groundwater)

ID	Term	Amount (mm/yr)	Source
G1	Recharge A (from above ground, A3)	+138.5	See A3
G2	Recharge P (from leaking pipes, P3)	+164.3	See P3
G3	Deep groundwater discharge	-302.8	**Calculated** from water balance

Evapotranspiration[d] (A2) is an important factor in the water balance, in this case being equivalent to 43% of rainfall, the main source of water. Evapotranspiration is calculated from a Landsat image taken over Kuala Lumpur in 2001 (GLCF, 2001) using the Surface Area Balancing algorithm (Bastiaanssen, et al., 1998). This algorithm requires several additional inputs such as emissivity. An atmospheric correction must also be performed (Iqbal, 1983).

Since no atmospheric data for Kuala Lumpur are easily available, atmospheric data for a clear day from the National University of Singapore observation station is used. Given the geographic proximity of both cities and similar climates and levels of economic development (and air pollution), Singapore data is deemed an acceptable surrogate. Atmospheric data from Singapore

[d] Evapotranspiration: the sum of evaporation and plant transpiration

is made available on-line by the National Aeronautics and Space Administration's Aerosol Robotic Network (AERONET, 2007).

An estimate for emissivity is based on published field work results from a study conducted in African cities. Emissivity mainly depends on the material, temperature and geometry of the object, in this case a city. The city of Dar Es Salaam in Tanzania is most similar to Kuala Lumpur in terms of climate and economic development compared to the other African cities included in the study. The emissivity parameter value used for Dar Es Salaam is 0.8. Emissivity in the heavily built-up and congested city centre and the city's green outskirts is both approximately 0.8 on average, although it varies by about 0.05 throughout the day (Jonsson, et al., 2006).

The calculated evapotranspiration ranges between 0 and 2.72 mm/hour, which is high but not impossible for an instantaneous observation made on a clear and hot day. Average pan evaporation for Kuala Lumpur is 1606 mm/year (4.4 mm/day) (CTI, et al., 2001). Pan evaporation is the maximum possible evaporation. The hourly evaporation is scaled to a daily evaporation that ranges from 0 to 4.4 mm/day.

A single satellite observation is not suitable for calculating average evaporation, but here it is used to estimate relative evaporation between different types of land cover (e.g. urban and vegetation). The scaled average evaporation is 3.29 mm/day (used in the water balance), it is about 1 mm/day in urban areas. The distributed evaporation for the water balance area is given in Figure 9.

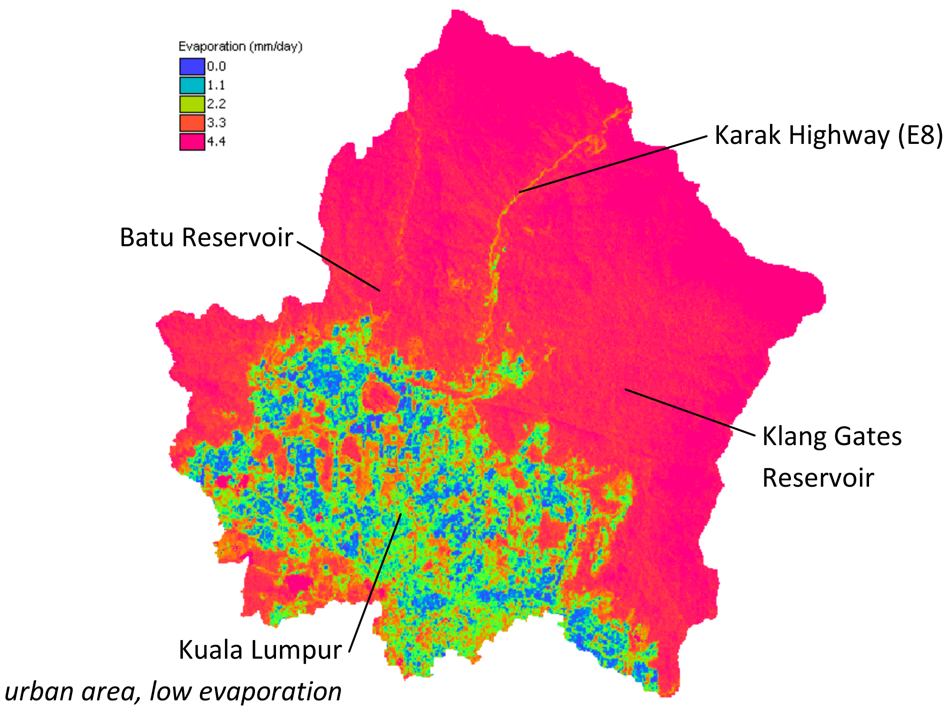

Figure 9 – Evaporation map of water balance area.

Water intake capacities (A6) for the water balance area are displayed on the website of the Selangor Water Supply Corporation. The intake locations included in the water balance (above ground) are Bukit Belacan, Taman TAR, Klang Gates Reservoir and Batu Reservoir (the latter two reservoirs are indicated in Figure 4). It is assumed that water use is broadly constant so that water intake and water intake capacity are similar.

The water consumption (A5) and pipe leakage (P3) data are from the Malaysian Water Association (MWA, 2006). The Malaysian Water Association provides lumped data for all of Kuala Lumpur, Selangor and Putrajaya combined. To estimate consumption and leakage in the water balance area, it is assumed that population correlates closely to consumption and leakage. Although consumption patterns between residential areas and industrial areas differ, within the study area there are both large residential areas (e.g. Wangsa Maju) and industrial areas (e.g. Gombak) and so the assumption is expected to hold. The census districts of Gombak, Selayang, Wangsa Maju, Sentul, Damansara and Kuala Lumpur City Centre are located in the water balance area. According to the 2000 census 1.3 million people live here. This is 26% of the total population of Selangor, Kuala Lumpur and Putrajaya. Agricultural water use in the Klang basin is negligible because the vast majority of the agricultural acreage is used for oil palm plantations, which are not irrigated.

The Malaysian Water Association also provides statistics on non-revenue water. If we assume that the water balance area follows the national average, then 50% of non-revenue water is leaked and the other 50% of non-revenue water is unmetered (Sakura, et al., 2006). Therefore the water consumption in the water balance area is estimated at 218 million m^3/year and total leakage is 68 million m^3/year.

Groundwater recharge (or infiltration, G1 & G2) is an input for the groundwater model and it is calculated using the water balance. Being the remainder of the balance, it includes all infiltration from rainfall and pipe leakage. But there is an additional, secondary source of infiltration which is not accounted for in the water balance: water used by consumers which is not evaporated and does not reach the surface water can infiltrate into the ground, possibly posing a pollution threat. 70% of Kuala Lumpur residents are connected to the central sewerage system so the amount of secondary infiltration is likely to be quite small. Note that wastewater treatment facilities are also small, serving their local surroundings and hence they are located within the water balance area (DBKL, 2000) and thus accounted for in the water balance.

This relatively small secondary source of infiltration is very difficult to measure or calculate and therefore it is ignored at this time. Given that the purpose of the groundwater flow model is to estimate groundwater extraction potential, ignoring secondary infiltration will likely lead to a slight under-estimation of the groundwater potential. This is a prudent course of action because extracting too much groundwater (overestimating the potential) is far more damaging than extracting too little (underestimating the potential).

Based on the water balance, the following model inputs can be defined linked to the local land-use. Infiltration in non-urban areas (67.4% of the water balance area or 279 km^2) is expected to be 108 mm/year, a value calculated for a groundwater study in the neighbouring Langat basin which is mostly rural (CTI, et al., 2001). Infiltration in urban areas (31.1% of the water balance area or 129 km^2) is attributed only to leakage from pipes and is calculated at 528 mm/year. It is assumed that due to pavements, minimal amounts from other sources such as rainfall infiltrate. The remaining infiltration occurs through tin ponds (1.5% of the water balance area or 6.2 km^2)

and is calculated at a rate of 4,369 mm/year, which is deemed realistic as it is just a fraction of the theoretical hydraulic conductivity of the fractured limestone in which the ponds are located.

2.4 Model Setup and Calibration

Following the model selection and data analysis in the previous sections, in this section the model setup and calibration are addressed. To begin, the model schematisation and some important modelling choices are explained along with a description of the parameters and variables. This is followed by the calibration process, calibration results and some general observations about the model performance.

The famous physicist Albert Einstein once remarked that we should "make everything as simple as possible and as complicated as necessary," a point that is very valid in groundwater modelling too. There are four important modelling choices which rely on certain simplifications and assumptions which must be clearly explained if the model and model results are to be fully understood. In the next paragraphs the choice of model boundaries, the assumption of steady-state flow, cell size (model resolution) and the choice between a single layer and a double layer model are all addressed.

The **boundaries** of the groundwater model generally follow the hydrological boundaries because the hydrogeology also follows the direction of hydrological flows and there are no good measurements that allow the definition of other boundaries. The more permeable hydrogeological formations, Kuala Lumpur Limestone and Kenny Hills, are located under the valley floor, while the surrounding hills are underlain by more impermeable formations such as Hawthornden and Granite (Figure 2). These 'hydrological' boundaries are modelled as no-flow boundaries. Where there is an absence of hydrological boundaries, a constant head boundary is imposed based on the interpolated groundwater level data. Most of these constant head boundaries are located on the valley floor, an area for which more data is available.

The model is assumed to be **steady-state** (inflow is equal to outflow at every time-step). This assumption is necessary because it allows the use of groundwater data from different locations and different times. Although desirable, a steady-state model does not require continuous groundwater level monitoring time series, unlike a transient model. Because there are very few artificial groundwater extractions in the study area and mining activities seized in the 1980's the system is probably close to steady state. Casual observations suggest that water levels in the tin ponds are constant. Given their role in regulating the groundwater level, groundwater levels are also assumed to be constant. No measurements are available that can confirm or reject this assumption.

The Equivalent Porous Medium method holds that the **cell-size** should be sufficiently large so that the highly irregular medium behaves like a regular, porous medium when modelled. However, by assigning a single hydraulic conductivity parameter to an entire hydrogeological formation, the model becomes lumped, already satisfying the Equivalent Porous Medium method. Cell-size is instead determined by the calculations speed and the geographic variability of the study area. Large cells speed up calculations, but excessively large cells that aggregate data for large areas distort model characteristics such as elevation and infiltration.

The cell dimensions chosen are 227 m × 227 m, an aggregate of 16 original digital elevation model cells. Trial runs with larger cells of 454 m × 454 m seemed to distort the input data too much. The choice of cell dimensions is a little arbitrary and no efforts at further cell-size optimisation were made once the model calculation time was found to be sufficiently short (around 30 seconds) and the input seemed sufficiently detailed. The model grid consists of 187 rows and 137 columns.

Finally: the decision to construct **a single layer or a double layer** model. At first sight, the data seem to sustain a double layered model because a lower rock formation (limestone, sandstone, granite, schist) can be identified overlaid by an upper layer of weathered rock and alluvial deposits, a layer with a thickness of between 0 and 80 m. To quantify flow between two layers, MODFLOW requires the introduction of a leakance term. There is no data that suggests that an impermeable or less permeable zone separates both layers. Therefore a very high leakance value must be assigned to simulate flow between both layers, effectively making the model a dual porosity medium, a concept discussed in Section 2.2.

Because of calibration difficulties, which are discussed later in this section, only a single layer model is calibrated. The single layer is 300 m thick. This is because the exact depth of the bedrock layers is not known, but it is assumed that 300 m is sufficiently deep for groundwater flows to be minimal so that the hydraulic conductivity calibration can be performed successfully. It must be noted that the calibrated hydraulic conductivity is affected by the layer thickness, but this is not a problem as long as the layer thickness is kept constant during simulations.

The model schematisation is shown in Figure 10 and Figure 11.

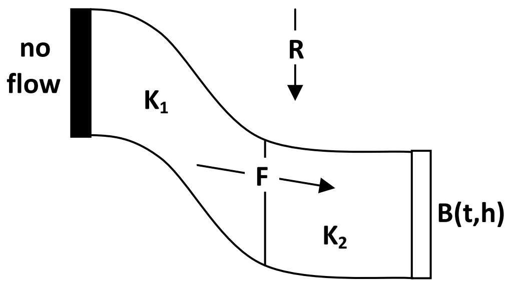

Figure 10 – Model schematization (side view).

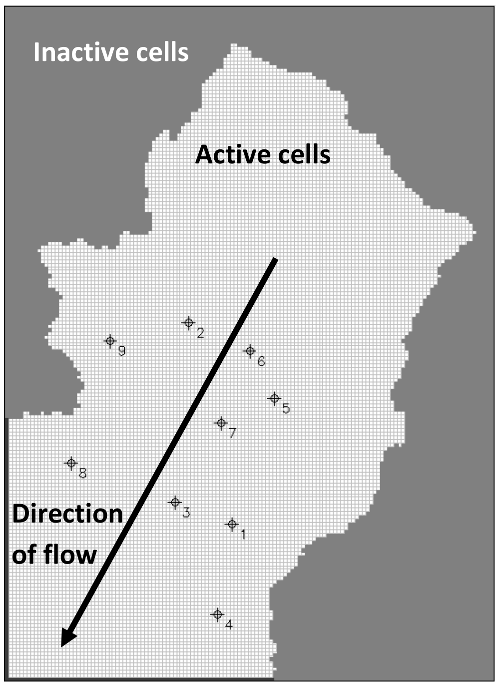

Figure 11 – Model schematisation (top view).

<u>Input</u>
R = Recharge (m/day) – *input*

<u>Parameters</u>
K = Hydraulic conductivity (m/day) – *calibrated*
B = Hydraulic boundary
t = transmissivity (m^2/day) – *estimated*
h = head on boundary (m) – *estimated*
Specific yield and specific storage – *literature values* (Anderson, et al., 1992)

<u>Variables</u>
Groundwater head (m) – *input (initial), then calculated*
F = Horizontal flow (m^3/day) - *calculated*

<u>Output</u>
Deep groundwater discharge (m^3/day) – *calculated*

Setting the hydraulic boundary requires the constant head and the transmissivity to be specified. The transmissivity is not a very sensitive parameter and is set large enough so that it does not form a barrier to the deep groundwater discharge. The constant head is taken from the interpolated groundwater levels. The groundwater model is quite sensitive to the constant head parameter. Recharge is also a very sensitive parameter, which is not surprising, given that it is the input. The hydraulic conductivity of the Kenny Hills and Kuala Lumpur Limestone are also sensitive parameters. This can be explained by the fact that in these areas more recharge takes place, so any changes have a significant impact on the water table.

The calibration is done through a mix of UCODE, PEST and trial-and-error to find a set of hydraulic conductivity parameters which are within the range of expected literature values (Anderson, et al., 1992; Scanlon, et al., 2003), which have appropriate values relative to each other (e.g. granite should be less permeable than sandstone, etc.) and which ensure a closed water balance, a pre-requisite for any steady-state calibration. Obtaining such a set is not very easy as there are many optima which satisfy at least some of these conditions. The optimisation codes try to minimise the discrepancy between the measured and simulated water table for 9 calibration points and this does not necessarily coincide with a closed water balance or realistic values.

It could be argued that 9 calibration points are too few, especially considering there are more than 1305 data points available. However these 9 points have elevations that closely match the digital elevation model (error less than 1 m), making them very reliable. In addition, they have a good spatial distribution. Calibrations with more calibration points were also attempted, but these often created one or two 'trash calibration points' which had exceptionally large errors and still produced unrealistic calibration results. This leads to the decision to calibrate with 9 well distributed, high quality points only.

The reason for the calibration problems are probably the interdependence of the parameters. To improve the calibration, the granite and schist formations are lumped together because their hydraulic conductivities, specific yield and specific storage are very similar. This reduces the degrees of freedom in the calibration. This is also the reason why only a single layered model is calibrated and not a double-layered one. So the hydraulic conductivities of just three formations are calibrated: Kuala Lumpur Limestone, Kenny Hills and Granite/Hawthornden. The results are presented in Table 2.

Formation	H.Conductivity (m/day)	Specific Yield*	Specific Storage* (m^{-1})
K.L. Limestone	1167	10^{-3}	0.3
Kenny Hills	200	10^{-4}	0.2
Granite/Hawthornden	1.87	10^{-6}	0.05

Table 2 – Calibration results and literature values* (Anderson, et al., 1992).

It must be noted that the calibration faces the problem of equifinality: there are other solutions that satisfy the calibration conditions. But how significantly do these results differ from the calibration results presented here? This question could be resolved by testing a different set of calibrated hydraulic conductivity parameters and seeing if the model output is very different. Sensitivity analysis suggests that this will not be the case, unless the hydraulic conductivity parameters are changed significantly. In that case they would violate the calibration conditions. Therefore equifinality is not explored further at this time.

The error in the water balance calibration is less than 0.01%. The root mean square error of the calibrated water tables compared to the measured values is 13.4 m. Considering that the total difference in groundwater levels within the study area is 1472 m, this is an error of 0.91%.

These statistics alone do not give a full picture of the calibration results. If simulated points not included in the calibration are compared to the measured and interpolated values there are very large discrepancies. Figure 12 shows that errors in hilly areas (red area) exceed 50 m and in some cases are as large as 250 m. It is interesting to note that the simulated groundwater depth does show clear spatial correlation and lacks a clear relationship between elevation and groundwater levels: the exact opposite of the conclusions drawn from the data in Section 2.3.2.

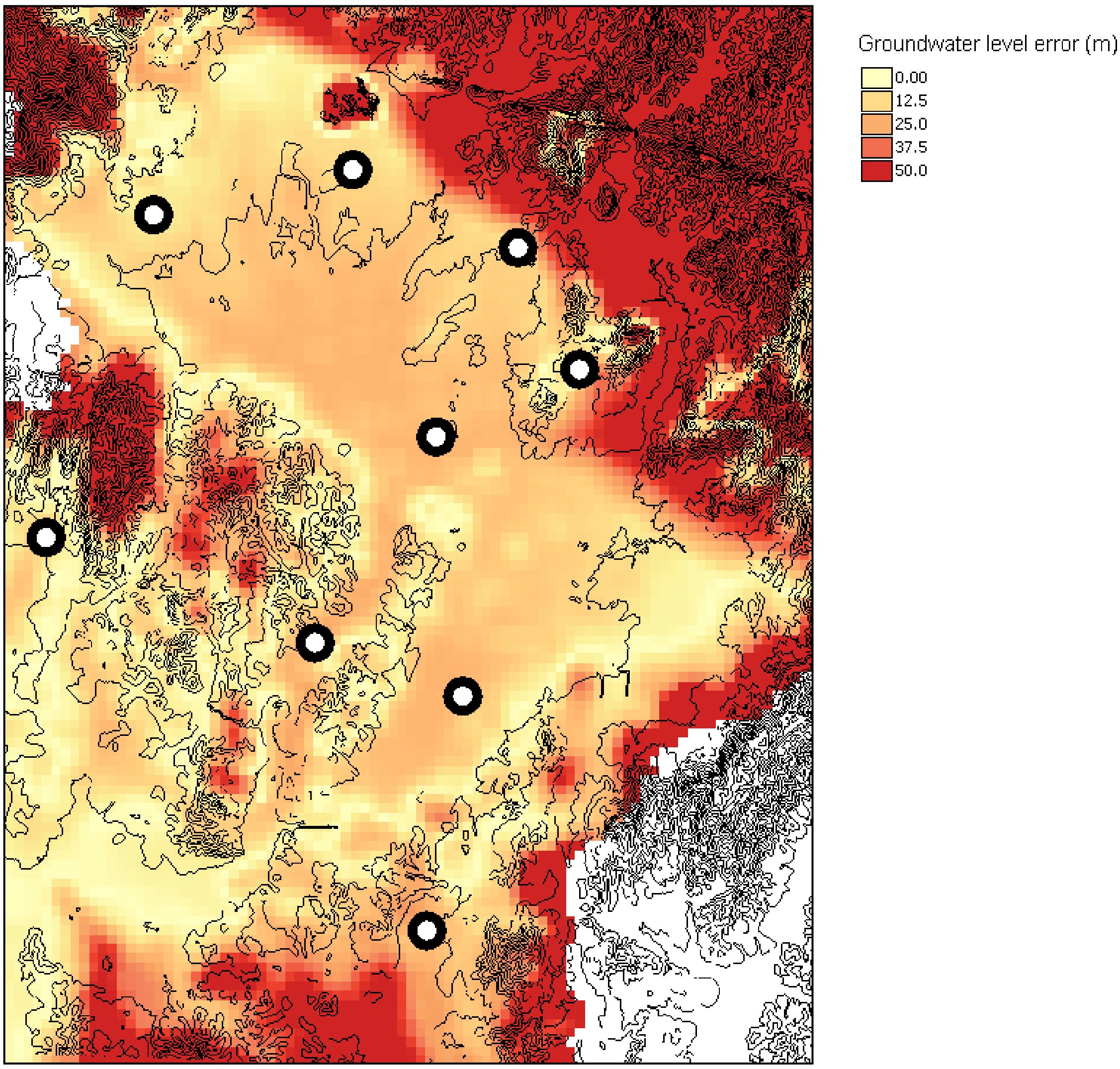

Figure 12 – Groundwater error map.

It must be concluded that the final calibration results are mixed. There is a clear mismatch between the interpolated data and the simulated data. If a choice is made between the two 'possibilities', the simulated data seems most reasonable given that it shows the expected spatial correlation in groundwater depth. Yet this mismatch does introduce a large degree of uncertainty into the model.

However the water balance is calibrated correctly and the calibration error for the groundwater table at the valley floor, the focus of the model, is reasonably small. Note that the specific yield, storativity and recharge (see Section 2.3.3) are conservatively estimated. This slightly underestimates the groundwater potential, which is appropriate as groundwater potential overestimation can be very damaging.

Therefore one can conclude that the calibrated model provides a good estimate of the quantity of groundwater available at the valley floor, but it does not offer any certainty as far as predicting flow directions or specific groundwater levels are concerned.

2.5 Evaluation of Extraction Strategies

Due to model limitations, the range of extraction strategies that can be tested is somewhat limited. For example, the model calibration does not inspire enough confidence to be able to confidently predict the water table and flows at a specific location. Nevertheless, given that the water balance of the model is sound, it is possible to make a rough estimate of the quantity of groundwater that can be extracted. This figure, capturing the potential size of Kuala Lumpur's groundwater resources, is of economic and policy significance.

To evaluate the extraction strategies, relevant criteria need to be determined. Although there is basic knowledge about potential geohazards in Kuala Lumpur, there is little hard data that can be used to quantify these criteria. In this section simple quantitative criteria are used, although the process of setting them is somewhat arbitrary. This is followed by the evaluation of two generic extraction strategies: permanent extraction and temporary extraction. First the effects of a local extraction (single well) is considered. Then the effects of a macro extraction (multiple wells) are simulated.

Common costs of groundwater over-extraction are:

1. Extraction costs such as well drilling, pump installation, maintenance and power. Over-extraction can lower the groundwater level, increasing extraction costs.
2. Over-extraction can lead to a decrease in spring discharge, base flow and lake volume which may adversely affect the natural environment.
3. Groundwater flow patterns can change with potentially detrimental effects to groundwater quality, e.g. infiltration through polluted soil can increase.
4. The decline in pore water pressure may lead to land subsidence, or in fractured limestone areas to sink-hole formation (Custodio, 2002).

Because of the threat from pollution, the groundwater table should remain stable to prevent the induction of pollution flows. Let us assume that a drawdown in excess of 1 m is likely to trigger such flow. If drawdown exceeds a safe limit, environmental remediation is needed to avoid contamination of the aquifer.

Prior to the 1980's when the tin mines still operated, local groundwater drawdown at mines of 20 m or more was not uncommon and therefore this is a kind of benchmark for the Limestone aquifers, where the tin mines (now tin ponds) are located. We assume that there is no threat of sinkhole formation for buildings built before 1980, if there was, they would have already collapsed. We also assume there is no threat for newer buildings: they should have complied with a modern building code. Therefore we assume that a global 5 m drawdown will not trigger any sinkhole formations and is acceptable in the case of an emergency and if adequate environmental protection measures are taken.

In MODFLOW groundwater extraction wells are simulated as a 'sink term' or 'loss term' from a cell. It is suggested that 8,000 m^3/day is a reasonable pumping capacity for wells in the limestone aquifer (LESTARI, 1997), so hence a well field in a cell with an area of 5 ha may well contain 10 wells and thus a total well field capacity of 10 x 8,000 = 80,000 m^3/day.

These wells can be used to extract water permanently or temporarily, say during a period of 100 days (approximately three months) during a drought followed by a period of 1000 days (approximately three years) during which the groundwater table can recover. During a short period of extraction, presumably more groundwater can be extracted. Additionally, extractions from a single well field are likely to have a smaller impact than extractions from an entire well field. This leads us to four scenarios, see Table 3.

Scenario	Extraction per well field (m^3/day)	Number of well fields	Duration
P1	800 / 8,000 / 80,000	1	Permanent
T1	80,000	1	100 days
P2	8,000	12	Permanent
T2	80,000	12	100 days

Table 3 – Extraction scenarios.

The purpose of Scenario P1 is to see which permanent extraction is feasible, considering 80,000 m^3/day is the maximum possible extraction. The purpose of Scenario T1 is to see how rapidly the groundwater table recovers. The results from both scenarios are given in Figure 13. Scenario P1 confirms 8,000 m^3/day as an appropriate permanent extraction amount, causing a permanent drawdown of 0.4 m. Scenario T1 demonstrates that the water table recovers within the 1000 day period.

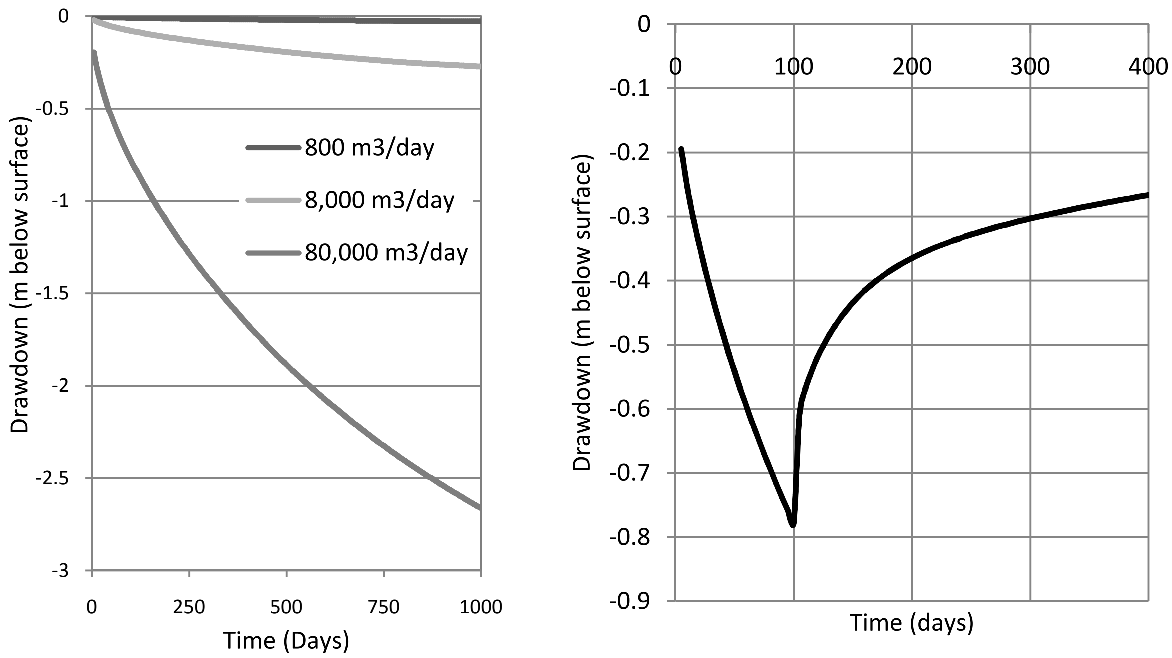

Figure 13 – Scenario P1 (single well permanent extraction, left) and Scenario T1 (single well 100 day extraction, right).

To test the impact of large scale extractions (12 well fields), scenarios P2 and T2 are simulated. Scenario P2, with a total permanent extraction of 96,000 m^3/day reaches a stable drawdown of 1 m after 1500 days of simulation. Scenario T2, with a total temporary extraction of 960,000 m^3/day reaches a maximum drawdown of 5 m and is almost fully recovered within the 1000 day period. The evolution of the groundwater table in Scenario T2 is shown in Figure 14.

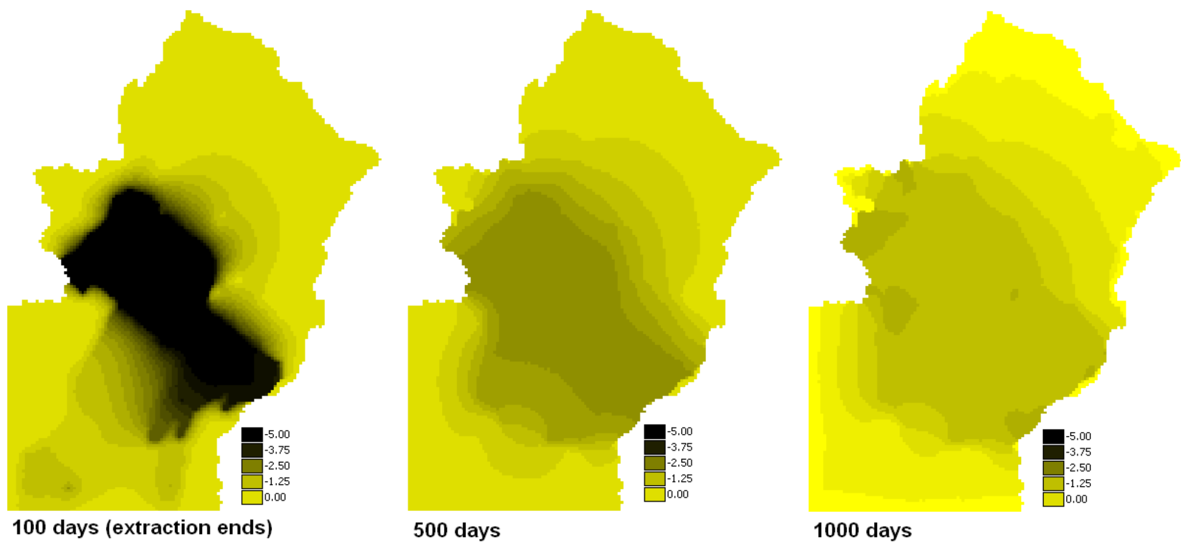

Figure 14 – Scenario T2 with large scale temporary extraction.

Both large scale extraction strategies that were simulated (scenarios P2 and T2) met the simple quantitative criteria that were set. This basically suggests that there are two extraction strategies possible: permanent extraction of 96,000 m^3/day and a temporary extraction of 960,000 m^3/day continuously during 100 days.

These conclusions are tentative because there are some problems with the model calibrations as explained in the previous section that must be appreciated. Definitive conclusions about the appropriate extraction strategy can only be drawn once a more thorough groundwater study has been conducted and certain important model assumptions, such as the model's steady state condition and the groundwater table in hilly areas, are verified.

Nevertheless, the scenarios provide the best possible answer to the research question: *What are the physical effects of groundwater extraction?* and thus a clear indication of the extraction strategies that are possible, information that forms the basis of groundwater development strategies that are the subject of Chapter 4.

3 Governance of Groundwater Resources

3.1 Introduction

Former United Nations Secretary General Boutros Boutros-Ghali once said that “the best way to deal with bureaucrats is with stealth and sudden violence.” It seems Boutros-Ghali held a rather glum view of bureaucracies, yet he would probably agree that we should first do an institutional analysis (‘stealth’), so that we know how to use ‘sudden violence’ to implement a sound groundwater policy, in doing so answering the research question: *What is the current institutional setting with respect to groundwater resource management and how can it be changed to enable groundwater extraction?*

An understanding of the institutional setting is important, especially in the field of integrated water management where problems are often complex and poorly defined because knowledge is incomplete and policy actors can have different problem-perceptions and competing interests. By ignoring the institutional feasibility, one risks developing an irrelevant (technical) solution that simply will not be implemented.

Having established the purpose and necessity of an institutional analysis, this brings us to selecting a framework for performing the institutional analysis. But which analytical framework is suitable for evaluating the institutional setting? And, more importantly, how can this framework lead to useful conclusions and recommendations? Given that governance has strong local characteristics, the framework must be able to perform under different water management regimes in different countries.

Bressers et al have developed an institutional analysis framework for comparing water resource management regimes in different countries and identified *Policy Coherence* as the key criterion for successful and sustainable water management based on an extensive review of European and American literature on natural resource governance. Furthermore, Bressers et al successfully applied their method in six European countries including France, Spain, the Netherlands and Switzerland which all have very different histories and systems of governance (Bressers, et al., 2003).

Although the Policy Coherence framework was developed for and applied in six continental European countries, the ideas on which it is based find wide application elsewhere, including in the United States and the United Kingdom. Given that the Malaysian government and legal system are modelled on that of the United Kingdom, it is reasonable to assume that the Policy Coherence framework can also be applied to groundwater management in Kuala Lumpur.

In this chapter, the Policy Coherence framework is explained (Section 3.2) and then applied by performing the institutional analysis (Section 3.3) and identifying conditions for policy coherence (Section 3.4). Based on this analysis, some institutional changes are explored that might enable groundwater extraction (Section 3.5).

3.2 Analytical Framework

Bressers maintains that policy coherence between all relevant policy actors is absolutely necessary to manage water sustainably. This is because it entails policy actors adapting to each other, stabilising the water management regime and ensuring the commitment and cooperation necessary to carry out sustainable water policies. Policy coherence cannot be imposed because there is no policy actor that has full control. Even a powerful government agency will need to respect property rights, legal jurisdictions and prevailing interests (Bressers, et al., 2003).

Bressers also observes that there are several key barriers to making groundwater policy that leads to a win-win situation or profitable trade-offs between policy actors. Uncertainty, along with the problem's complexity, the long-term time-scale of groundwater changes and pluralism (i.e. the presence of multiple policy actors) can prevent effective decision-making (Bressers, et al., 2003). And while the previous chapter attempted to reduce uncertainty through modelling, this chapter focuses on how cooperation between multiple policy actors can be stimulated.

The other plank of Bressers' research concerns water use rights. However this topic is not very relevant to this specific study because the property and use rights of groundwater are very simple. In Kuala Lumpur groundwater use rights are regulated by a single agency and current groundwater use is insignificant.

In analysing policy coherence, Bressers also stresses the need to identify and take into account that decision-making happens at many levels and that these decisions influence each other.

The institutional analysis is conducted by answering a list of questions that cover all the elements of the Policy Coherence framework: levels of governance, policy actors, perceptions and objectives, policy instruments and resources. The conditions for policy coherence identified by Bressers et al are: a tradition of cooperation, joint problems, joint opportunities, the presence of a credible alternative threat and institutional interfaces (Bressers, et al., 2003).

3.3 Institutional Analysis

The institutional analysis is structured along the elements of Bressers' governance model (policy instruments and resources are combined under a single heading). Detailed questions for each element are given in Appendix A.

Levels and Scales of Governance

Malaysia is a federation in which state governments have significant autonomy. Under article 73 of the federal constitution, state governments have jurisdiction over water and land resources, whereas the federal government can legislate on interstate issues such as pollution control, mining and public health (Perunding Zaaba, 1999). A complete listing of all organisations involved in Kuala Lumpur's groundwater management is given in Table 4.

Selangor state has created a single agency, the Selangor Waters Management Authority, to manage its key responsibilities in the fields of water resources and water supply. In Selangor and Kuala Lumpur the water supply system is operated by the Selangor Water Supply Corporation, a private company which has a concession granted by the Selangor state government and which is part-owned by the Selangor State Investment Company: Kumpulan Darul Ehsan Berhad.

The Selangor Waters Management Authority relies on expertise from the federal government's Department of Minerals and Geoscience and the Department of Environment to carry out its duties. At the state level, the Selangor Waters Management Authority interacts with the Department of Irrigation and Drainage and the Public Works Department. These two agencies are involved in the design and construction of physical infrastructure. The Town and Country

Planning Department is responsible for land-use planning at the national and state levels, which includes gazetting sensitive riparian areas and groundwater recharge zones.

Federal Agencies	Ministry of Natural Resources and Environment • Department of Environment • Department of Minerals and Geoscience • National Hydraulic Research Institute Malaysia Ministry of Federal Territories • Kuala Lumpur City Hall Ministry of Energy, Water and Communications • National Water Services Commission Treasury (Ministry of Finance) • Water Asset Holding Company Ministry of Health
Federal and State Agencies	Ministry of Natural Resources and Environment • Department of Irrigation and Drainage Ministry of Housing and Local Government • Town and Country Planning Department Ministry of Public Works • Department of Public Works
Selangor State Agencies	Selangor Waters Management Authority Kumpulan Darul Ehsan Berhad (Selangor State Investment Company) Local Authorities of Selangor State such as Ampang Jaya Municipal Council, Petaling Jaya City Council, etc.
Private Companies	Selangor Water Supply Corporation

Table 4 – Overview of organisations dealing with groundwater in Kuala Lumpur.

The Selangor Water Supply Corporation, being a private water utility, is regulated by the federal government's National Water Services Commission. The Commission regulates water prices, piped water quality and water delivery. The Selangor Water Supply Corporation buys water from water treatment plants which are operated by other companies. Some of these plants are privately owned, others are owned by the state government or the federal government's Water Asset Holding Company. Because the Selangor Water Supply Corporation supplies drinking water, it is also supervised by the Ministry of Health which operates small-scale water supply projects in some rural areas, but not in Kuala Lumpur.

The Department of Irrigation and Drainage, the Department of Public Works and the Department of Town and Country Planning are federal departments but the state governments hold significant powers over their state-level operations. The Department of Environment and the Department of Minerals and Geoscience are pure federal agencies who assist state governments but are not controlled by them.

Local authorities such as Kuala Lumpur City Hall are required to monitor development in Environmentally Sensitive Areas and withhold building permits if it is deemed prudent to do so. (LESTARI, 1997) Local authorities fall under the control of the state government (there are no local elections), and in the case of Kuala Lumpur, which is a federal territory, under the Ministry of Federal Territories.

It is important to note that the Selangor Waters Management Authority faces several 'holes' in its jurisdiction, notably Kuala Lumpur. In Kuala Lumpur, the Selangor state government is required to supply water (a duty carried out by the Selangor Waters Supply Corporation) but it has no jurisdiction over the city's water resources.

Research on water management issues is conducted by the National Hydraulic Research Institute Malaysia, an institute of the Ministry of Natural Resources and Environment. An overview of the abovementioned agencies is given in Table 4.

The Malaysian government is legalistic and hierarchical. This can prevent cooperation between different levels of government. This legalistic nature of the government is evident from the following example about groundwater monitoring activities. The Department of Environment monitors groundwater quality as part of its tasks to control pollution under the Environmental Quality Act (1974). The Department of Minerals and Geoscience monitors groundwater levels because it has to study hydrogeology as instructed by the Geological Survey Act (1974). This leads to the peculiar situation where both departments operate completely separate groundwater monitoring networks. At Department of Environment wells only groundwater quality is measured. At Department of Minerals and Geoscience wells only groundwater levels are measured. However both departments fall under the same Ministry of Natural Resources and Environment.

In terms of hierarchy, federal ministers and state chief ministers have roughly the same level of authority. So for a comprehensive groundwater policy to be initiated in Kuala Lumpur, the chief minister of Selangor and eight federal ministers must reach agreement. This fragmentation of authority makes regulation of water resources in Malaysia ineffective (Zakaria, 2001; Madsen, et al., 2003; Mutadir, 2006; BERNAMA, 2007).

Only the Prime Minister, backed by the federal parliament and the treasury, has a higher standing than the federal ministers and the chief ministers. The Economic Planning Unit of the Prime Minister's department establishes 5-year plans which direct policy for all ministries and state governments. The current 5-year plan (2006-2010) is the Ninth Malaysia Plan.

Historically, the federal government and the state governments have been controlled by politicians from the National Front coalition. However following the 2008 general elections the National Front lost power in Selangor to the People's Front coalition. Therefore the position of the Prime Minister in relation to the Chief Ministers is likely to change in future.

Actors in the Policy Network

Under the Ninth Malaysia Plan increased groundwater extraction is seen as one way of expanding Kuala Lumpur's water supply, in addition to water conservation and an inter basin water transfer scheme. The relevant government agencies have already been mentioned in the previous sector. In this section their roles with respect to groundwater management are further specified and other relevant actors are introduced.

Hydrogeological studies should be carried out by the Department of Minerals and Geoscience under the Geological Survey Act (1974). The Department of Environment can also be expected to play a role in assessing the broader environmental impacts of groundwater extraction. Responsibility for water supply lies with the state governments, in the case of Selangor with the Waters Management Authority and the Water Supply Corporation. Therefore one would expect the Minister for Natural Resources and Environment and the Selangor Chief Minister to take the lead in making groundwater extraction policy.

The reality is very different: Dr. Lim Keng Yaik, Minister for Energy, Water and Communications first proposed in the media that groundwater resources be “fully utilised” to supplement existing sources of water supply (BERNAMA, 2007). He also mentioned that he was briefed by the Selangor Water Supply Corporation and the Selangor State Investment Company about possible groundwater sources (Hamsawi, 2007).

This seems counter-intuitive, because the Minister for Energy, Water and Communications has no formal control over Selangor’s Water Supply Corporation or State Investment Company. However his ministry regulates the Water Supply Corporation through the National Water Services Commission which sets water tariffs, thus exerting significant influence. The Ministry of Energy, Water and Communications also manages the tender process for new water supply infrastructure and the Selangor State Investment Company bids on these projects (The Edge, 2007). Hence one must conclude that the Ministry of Energy, Water and Communications effectively controls the Selangor and Kuala Lumpur water industry.

There are also several non-governmental organisations that are critical of the governments’ current water policy for various reasons. They include the Malaysian Trade Union Congress which opposes privatisation of water utilities and the Malaysian Nature Society, the World Wildlife Fund, the Consumer Association of Penang and local academics such as Prof. Ir. Dr. Zaini Ujang of the University of Technology Malaysia who are concerned about the environmental impact of government policies (Netto, 2005; BERNAMA, 2007; MNS, 2008).

In recent years the influence of public opinion on policy making has increased substantially. This is clearly demonstrated by the defeat of the government’s proposal to build an incinerator at Broga, near Kuala Lumpur, which was vehemently opposed by local residents. Before the plan could be challenged in court, the government withdrew its proposal (BERNAMA, 2007). Almost a decade earlier, following the 1998 water crisis, the government managed to push through the Selangor River Dam with little fuss, which was also highly controversial because of environmental concerns (CAP, 1999).

Lastly, there are the water consumers. The vast majority of water is provided by the Selangor Water Supply Corporation, but it is supplied below cost (ADB, 2004). Domestic consumers in Selangor will receive the first 20 m^3/month of water free from June 1st 2008 onwards. (Singh, 2008) Due to the low cost of piped water and the poor quality of groundwater in Kuala Lumpur (it requires some treatment before it can be used for human consumption), there is very little groundwater extraction by consumers. However, private parties can apply for a license to extract groundwater from the Department of Minerals and Geoscience (in Kuala Lumpur) or the Selangor Waters Management Authority (in Selangor), which is renewable every five years.

Problem Perception and Policy Objectives

At the present juncture, groundwater is primarily regarded as a source of water supply by the government. This is a change from the earlier policy of only using surface water for water supply. At that time, surface water was considered to be abundant and knowledge about Kuala Lumpur’s groundwater resources was (and still is) very limited (LESTARI, 1997).

The largest threat to groundwater development is pollution. Leachate is a known problem near landfills, and given that the groundwater table is shallow at approximately 5 m deep, the entire water system is susceptible to pollution. These findings are published by the Department of

Environment in its annual Environmental Quality Report and may be one of the reasons why the government is hesitant in extracting groundwater in Kuala Lumpur (JAS, 2007).

The protection of groundwater recharge zones is the responsibility of the Department of Town and Country Planning which delineates and classifies Environmentally Sensitive Areas into 3 ranks: rank 1 is the most stringent and absolutely no development is allowed here. Rank 3 generally allows development, but insists it be monitored carefully by local authorities. The upper part of the Klang basin is Rank 1 because it is a part of Peninsular Malaysia's central forest spine and a catchment area for the Klang Gates and Batu reservoirs (JPBD, 2005).

The valley floor on which most of Kuala Lumpur is built is classified as Rank 3. This is due to the limestone subsurface which is prone to sinkhole formation and the threat from pollution, erosion and flooding. Kuala Lumpur City Hall recognises its responsibility in monitoring development, but also states in its Strategic Plan that there is no policy at the moment to deal with these environmental issues (DBKL, 2000; JPBD, 2005).

Under the federal Environmental Quality Act (1974) only 'large scale' developments need to submit an Environmental Impact Assessment to the Department of Environment. 'Small scale' developments such as a shopping centre, 50-storey office towers and apartment buildings do not require an Environmental Impact Assessment, especially if they are constructed as separate projects (Perunding Zaaba, 1999; Neergaard, 2003).

Although new landfills do require an Environmental Impact Assessment, the enforcement of the legislation can be circumvented. Datuk Shahrir Abdul Samad, a senior Malaysian parliamentarian noted that for the Kundang landfill, operated by the Selayang Municipal Council, no preliminary Environmental Impact Assessment report was submitted. Because there is no Environmental Impact Assessment, the Department of Environment has no ground for enforcement (Mutadir, 2006).

On the other hand Kuala Lumpur City Hall, another local authority, recently decommissioned the 15 ha Taman Beringin landfill at a cost of 24 million ringgit. It was turned into a park and facilities to properly deal with leachate were put in place (Sidek Khalid, 2007; Lim, 2008). The decommissioning appears to not have been aimed specifically at groundwater quality concerns, but as a general improvement of environmental quality.

Besides pure environmental concerns, there are other opponents of the governments' groundwater extraction plans. Prof. Ir. Dr. Zaini Ujang, an academic at a local university opposes groundwater extraction for regular water supply, saying that groundwater should only be used during emergencies and not as an alternative to polluted surface water. Zaini also criticised the government for not practicing "Integrated River Basin Management" and said that water regulation in Malaysia was "ineffective" (BERNAMA, 2007).

On the other hand, some non-governmental organisations, such as the Consumer Association of Penang, support increased groundwater extraction as an alternative for the construction of additional reservoirs, which in their view have a far more negative social and environmental impact (CAP, 1999). They also emphasise the need for reducing water wastage, pricing water correctly and reducing pipe leakages. Interestingly, reducing water wastage and leakage and increasing water tariffs to cover costs are also cited in the federal governments' Ninth Malaysia Plan (EPU, 2005).

On the issue of increasing water tariffs, the People's Front coalition which took power in Selangor following recent elections, has decided to reduce water tariffs. This is a part of its election promise to lower petrol, electricity and water prices (Singh, 2008). The National Front coalition, the opposition in Selangor, has endorsed the policy as a part of its new 'inflation fighting agenda' which is aimed specifically at assisting poorer Malaysians. The National Front has controlled the federal government since its creation in 1973.

Instruments and Resources for Implementation

The main instrument of the water supply policy, which is led by the Ministry of Energy, Water and Communications, is financial because water tariffs do not cover costs and the financial resources of the state governments are weak (Lee, 2005). Under the Tenth Schedule of the federal constitution, states can only generate revenue from a limited number of sources such as liquor licenses, entertainment duty, land sales, and mines and forestry developments. However the bulk of tax revenue in Malaysia is from various income taxes.

The fact that water tariffs do not cover the necessary capital investments makes the Selangor state government dependent on the federal government for the financing of new water infrastructure. This dependency is further increased by the fact that the Selangor investment corporation is a major player in the water sector and the Selangor state government depends on the revenues that it generates (BERNAMA, 2008).

With the creation of the National Water Services Commission under the Ministry of Water, Energy and Communications and the Water Asset Holding Company of the federal Treasury, the federal government has greatly expanded its influence in the water sector. The lowering of water tariffs by the Selangor state government will probably increase the federal governments' role.

In the area of water resources, the Selangor state government controls most legal instruments because of its constitutional control of land, mines, forestry and water. Because it also controls local authorities (except Kuala Lumpur) it can block almost any new water supply initiative, should it choose to do so.

The federal government's role in the management of groundwater resources is guided by the Environmental Quality Act (1974) and the Geological Survey Act (1974). In addition, a lot of water resources research and water supply projects are carried out by Japanese companies and funded by grants and loans from the Japanese government (CTI, et al., 2001; The Edge, 2007). Malaysian-Japanese relations are historically strong, especially after Malaysia developed its "Look East" policies during the 1980's, whereby Japan replaced Britain as a model for Malaysian development. Because the loans and grants are a part of the foreign policy between Malaysia and Japan, the federal government has a large say in the allocation of the funds.

Essentially this means that only the federal government has the necessary financial resources to initiate water policy changes. Under the federal constitution state governments have the legal instruments to block such efforts, but they cannot initiate policies independently because they lack the required financial resources, even though they could theoretically raise water tariffs to generate additional revenue.

3.4 Policy Coherence

In the previous section several points of friction concerning coherent policy have already surfaced. Taking a positive approach, conditions for policy coherence can be identified and the obstacles that currently prevent coherence as well. In this section the current level of policy coherence, including any obstacles, are described. In the next section improvements for policy coherence are explored. A full description of the conditions for policy coherence is given in Appendix B. Note that joint problems and joint opportunities have been combined under a single heading.

Tradition of Cooperation

There is a tradition of cooperation between the Selangor Water Management Authority and the Department of Minerals and Geoscience on groundwater issues, whereby the Department provides expertise to the Authority.

Planning bodies, such as the Department of Town and Country Planning and the Economic Planning Unit, liaise with many different departments to assemble their plans. The tradition of 5-year development plans in Malaysia dates back to the First Malayan Five Year Plan (1956-1960) launched a year before Malayan independence in 1957.

The Ministry of Energy, Water and Communications, the federal Treasury, the Selangor Water Supply Corporation and the Selangor state investment agency are working together on expanding water supply. They worked together on the Selangor River Dam project in the 1990's and are now working together on the Selangor-Pahang Interstate Water Transfer scheme.

Joint Problems and Joint Opportunities

A lack of water supply is a problem for the government at both the state and federal levels. Although traditionally a state issue, new water supply infrastructure has been financed by the federal government for many years. This was through loans made to state governments and at present through the Water Asset Holding Company and the National Water Services Commission.

Similarly, environmental problems are a joint problem for the state and the federal government, especially in the minds of the public. The federal government is mostly concerned with strategic decisions and regulation, while the state governments do much of the implementation, sometimes with financial support from the federal government. Because of their weaker financial position, state governments often view natural resources in an economic light, rather than stressing the need for environmental protection.

Joint opportunities also exist between groundwater extraction, gaining knowledge about the groundwater system and protection of the groundwater system. Without adequate knowledge, groundwater extraction could have very negative consequences. Once these consequences are recognised by the public, government departments will be pressured to take action. This would jeopardise the efforts by the National Water Services Commission, Selangor Water Supply Corporation and the Selangor state investment corporation to expand water supply.

Credible Alternative Threat

The Ministry of Energy, Water and Communications in particular and the federal government in general pose a credible alternative threat to the current water management practice because they can, with backing from parliament, step in and take full federal control of the water supply, as nearly happened in 2007 (Netto, 2005).

On the other hand, under current legislation, the Selangor state government can block federal efforts because it carries a constitutional responsibility for water supply and water resources management, even though it lacks the means to meet this responsibility, requiring it to work with the federal government (Jomo, et al., 2003).

Institutional Interfaces
In groundwater monitoring, the Department of Environment and the Department of Minerals and Geoscience effectively operate as competitors, leading to duplication and making both less effective. Similarly, the Department of Environment monitors water quality in rivers whereas the Department of Irrigation and Drainage collects hydrological data. These are all closely related tasks which are managed by separate agencies which run separate measurement programmes housed in separate offices (Madsen, et al., 2003).

Given that eight federal ministries and the Prime Minister's office deal with water resources and water supply in some way, there is little clarity of assigned responsibilities. This greatly limits the effectiveness of policies and regulation (Zakaria, 2001). The geographic discontinuity that Kuala Lumpur's special status poses for the Selangor Waters Management Authority is also a point of concern.

3.5 Improving Policy Coherence

In this section we move to the second part of the research question: *how can the institutional setting be changed to enable groundwater extraction?* or how can policy coherence be improved?

Tradition of Cooperation
Although there is cooperation on many levels and between many parties, there seems to be very little cooperation in the area of research and monitoring. New policies should focus on encouraging this kind of cooperation so that a tradition of cooperation can be established.

Although a long tradition of cooperation exists between the state and federal governments, this relationship is partly due to friendly political relations between the state and federal governments which, until recently were controlled by the same political alliance. Given that there are many possible grounds for state-federal conflicts, especially financial ones (Jomo, et al., 2003), it is important that this tradition of cooperation be maintained and groundwater management not be politicised, regardless of any changes in the political leadership.

Joint Problems and Opportunities
Under the Ninth Malaysia Plan, the federal government is willing to spend several billion ringgits on flooding and water supply projects, which are both important components of water resources management. This suggests that the importance of water resources management in general, groundwater included, is growing, although it may be for purely economic reasons.

The Department of Environment or Department of Minerals and Geoscience could lay claim to the necessary budget to expand their groundwater monitoring and research activities. Similarly, local authorities who manage landfills could apply for funds to carry out programs that protect groundwater resources.

Another possibility is to change the current role of integrated water managers such as the Selangor Waters Management Authority. Now these bodies are coordinators of policy but they could evolve into policy enablers by transferring the necessary authority, knowledge and financial resources to them.

Credible Alternative Threat

A credible alternative threat can be provided in several ways, but the most likely provider of it is the federal government, given its financial strength relative to state governments and previous attempts at reforming the water sector.

One possibility could be for the Ministry of Energy, Water and Communications to implement its own groundwater project, bypassing the Ministry of Natural Resources and its agencies dealing with groundwater. The Malaysian government could request funds from Japan or other countries and let the program be carried out by their contractors. This would not generate much local expertise, but it is in line with current practices in other water supply schemes (The Edge, 2007).

Alternatively, the federal government could start to finance groundwater research through grants and require agencies or alliances of agencies to apply for funding through these schemes to complete projects.

If the federal government does not move, the state government or the Selangor Water Supply Corporation could invest in groundwater instead, but this would probably mean an increase in water tariffs to finance the development, which requires federal approval and could be unpopular politically.

Institutional Interfaces

The above analysis has revealed that the responsibilities of the state governments for water resources and water supply are not matched by financial and knowledge resources. This leaves the federal government as a key enabler and may be the cause of political conflicts.

Additionally, in the limited political discourse on groundwater resources that is taking place at the moment, there is a marked disconnect between groundwater extraction for water supply and environmental issues pertaining to issues such as groundwater pollution. This disconnect may be because there are simply too many agencies involved in groundwater resources management, who all focus on a different aspects and are unable or hesitant to make connections between different policy areas. It may also be due to a general lack of knowledge about groundwater resources.

More radical solutions in changing institutional interfaces may be found in merging some of Malaysia's 27 federal ministries to ensure just one or two ministries deal with water resources policy, for example the water supply activities of the Ministry of Public Works and the Ministry of Health could be combined with the irrigation and drainage activities of the Ministry of Natural Resources for more comprehensive planning. Similarly, the Department of Environment, Department of Minerals and Geoscience and the Department of Irrigation and Drainage, all located within the same ministry, have many overlapping responsibilities and could be merged as well.

It must also be noted that Kuala Lumpur is a federal territory governed independently from the surrounding Selangor state by the federal government. But in practice it is almost indistinguishable from Selangor in terms of society, economy and water resources. The federal territory was created in 1974 when Kuala Lumpur was the seat of the federal government. Since then, the federal government, save for the King's palace and parliament, has moved to the new capital at Putrajaya, which is also a federal territory. So why should Kuala Lumpur maintain its status as a federal territory and not be re-absorbed as a city in Selangor, which it is for all practical purposes?

Conclusion

This section in particular and this chapter in general have provided a departure point for discussing the institutional role in groundwater development and how this role can be changed. It is clear that a lack of a clear reason (or threat) for developing groundwater policy, combined with fractured jurisdictions and uncertainty caused by a lack of knowledge all conspire to obstruct the formulation of an effective groundwater policy. In the next chapter the *reasons* for groundwater extraction are addressed. These include the economic reasons and the threats (or stimulants) that could encourage policy actors to establish a sound and *coherent* groundwater policy.

4 Development of Groundwater Resources

4.1 Introduction

The development of groundwater resources is never an end in itself; it is a means to guarantee a reliable water supply. So when addressing the development of groundwater resources we must consider both the end and the means.

The reasons for having a reliable water supply are mainly economic and in that sense it is important to know the economic contribution groundwater extraction can make. Hence, we seek to answer the research question: *What is the economic value of groundwater extraction?* It could be argued that groundwater development also has a social and environmental dimension. However the environmental concerns are already addressed as a technical issue in Chapter 2 and that social dimension, for example the redistributive role water supply can play, is beyond the scope of this study. We assume that an economically competitive and sustainably managed groundwater extraction program always has significant net social benefits. These economic issues are discussed in Section 4.2 and Section 4.3.

Having identified the purposes of groundwater extraction, we then address the means. Based on the ways to stimulate policy coherence described in Chapter 3, three institutional strategies for groundwater extraction are explored in Section 4.4. This is followed by the formulation a groundwater development strategy in Section 4.5 which forms the basis of recommendations made in the final chapter.

4.2 Current and Future Developments

Kuala Lumpur, with a population of 1.4 million (2000), is the heart of the Kuala Lumpur Conurbation (population 4.2 million in 2000), Malaysia's most prosperous and most densely populated region. Kuala Lumpur is a major commercial and industrial centre in Southeast Asia (DBKL, 2000).

Average per capita income in Kuala Lumpur is approximately double the national average (DBKL, 2000). This means that average purchasing power of city residents (25,600 dollars) is comparable to that of developed countries such as Greece (24,000 dollars) and New Zealand (26,200 dollars). Malaysian average purchasing power per capita (12,800 dollars) exceeds that of Bulgaria (10,700 dollars), a member state of the European Union (CIA, 2007).

Kuala Lumpur initially developed as a trading centre in the 1850's to service the nearby tin mining industry. Large rubber and palm oil plantations were established in the vicinity soon after. From the 1950's onwards the city started to industrialise and today all mines and most plantations around Kuala Lumpur have closed. Between 1995 and 2000 average per capita income grew by 6.1% per year. Population growth is projected at 2.2% per year for the period from 2000 to 2020 (DBKL, 2000).

Total water demand in Selangor, Kuala Lumpur and Putrajaya was estimated at 3.74 million m^3/day in 2005 and it is projected to grow by 34% to 5 million m^3/day by 2010. Total water supply capacity for Selangor is expected to reach 5.15 million m^3/day by 2010, just 103% of total demand. All of the population in Selangor, Kuala Lumpur and Putrajaya have access to the public water supply. Non-revenue water stood at 37% in 2005 which is worth more than 1 million ringgit per day in lost revenue. Non-revenue water accounts for the 449.1 million ringgit annual revenue shortfall of the Selangor water system (Lee, 2005). Non-revenue water is targeted to be reduced to 23% by 2010 (EPU, 2005). The Malaysian Water Association defines non-revenue water as water that is treated but lost due to leakages, theft, pipe bursts, meter under-registration, etc.

To put the performance of the Kuala Lumpur water system into perspective, see Table 5. The working ratio, the ratio between operating and maintenance expenditure, and revenue, should be 1 or less to be financially balanced. So in Kuala Lumpur water tariffs are too low and do not cover the full costs of operation, maintenance and capital expenditure. Comparing tariffs and production costs between cities is difficult because of volatile exchange rates and the fact that some cities pay more than others for access to raw water (ADB, 2004). Note that Kuala Lumpur does not have significant agricultural water consumption because plantation crops such as palm oil are not irrigated.

City	Kuala Lumpur	Hong Kong	Ho Chi Minh City	Jakarta
National GDP per capita (2008)	14,400 dollars	42,000 dollars	2,600 dollars	3,400 dollars
Water supply sources:				
Surface Water	100%	100%	58%	100%
Groundwater	0%	0%	43%	0%
Coverage	100%	100%	84%	51%
Water use:	132 l/c/d	187 l/c/d	167 l/c/d	77 l/c/d
Domestic	30%	37%	45%	29%
Non-domestic	32%	38%	17%	20%
Non-revenue (loss)	43%	25%	38%	51%
Average tariff	0.302 dollars/m^3	0.351 dollars/m^3	0.183 dollars/m^3	0.285 dollars/m^3
Production cost	0.229 dollars/m^3	0.845 dollars/m^3	0.128 dollars/m^3	0.112 dollars/m^3
Working ratio	1.34	2.41	1.13	0.80

Table 5 – Overview of water utility and economic statistics for selected Asian cities (ADB, 2004; CIA, 2007).

Kuala Lumpur was hit by a severe water shortage in 1998 caused by an extended period of drought. Due to its dependence on rain-fed reservoirs for its water supply the city may be faced with a similar shortage in future (Hamirdin, et al., 2004). Following the 1998 water shortage, a controversial inter-basin water transfer scheme was constructed to supply water from the Selangor river basin to Kuala Lumpur (Tan, 1999). In 2008 construction will start on another inter-basin transfer scheme from Pahang state valued at 4 billion ringgit. A total of 8 billion ringgit has been allocated for all water supply projects nation-wide under the Ninth Malaysia Plan (EPU, 2005; Barrock, 2007).

To put the water supply and demand numbers into perspective, note that total rainfall over the entire Klang basin is approximately 9.4 million m^3/day on average (Rustam, et al., 2000) which is about 140% of 2005 demand for all of Selangor and the federal territories, evapotranspiration taken into account. So in theory, there is water enough to meet Kuala Lumpur's needs, the question is: can it be captured?

It is clear that Kuala Lumpur is reaching a level of economic development that is comparable to that of developed countries. Yet it also has population and economic growth rates that are usually found in developing countries. On the one hand this growth will put pressure on natural resources, including water. On the other hand Kuala Lumpur has the economic strength to cope with these challenges.

4.3 Economic Value of Groundwater Extraction

Valuing the economic costs and benefits of policy changes is a very complicated task. Ideally, one should be able to quantify the effects and understand the risks that are involved, in order to compare them. It is often a challenge in itself to determine what will happen if no changes are made, the so-called 'baseline condition'. There are also concerns over justice, the timing of costs and benefits and uncertainty that should be addressed (EPA, 2000).

It is beyond the scope of this study to carry out a comprehensive cost-benefit analysis that takes all of the above into account. But it is possible to make some useful observations, based on recent developments and price levels, to gain insight into the economic dimension of groundwater extraction in Kuala Lumpur.

An important measurement in cost-benefit analysis is willingness-to-pay. It is perhaps the clearest signal of the costs a party is willing to bear to carry out a particular policy. In Malaysia, water tariffs are supposed to cover the cost of operating the water supply system, although some water supply systems, notably Selangor's, are loss-making, mainly due to large amounts of non-revenue water. Because of the low profit margins on water supply operations, capital expenditure is insufficient and therefore the federal government has set up the Water Asset Holding Company to temporarily finance new water infrastructure. Under the direction of the National Water Services Commission, water tariffs are to be gradually raised to reach the full cost-recovery level (ADB, 2004; Lee, 2005).

Therefore, new investments in water infrastructure are the best gauges of willingness-to-pay, as opposed to current water tariffs. Under the Ninth Malaysia Plan the Pahang-Selangor Inter State Raw Water Transfer Scheme is expected to supply Kuala Lumpur and Selangor with an additional 2.2 million m^3/day. The project is budgeted at a cost of approximately 9 billion ringgit, which comes down to about 4,000 ringgit per m^3/day of new water supply capacity. Of this amount 1,800 (45%) ringgit is for the dam and pipeline and 2,200 (55%) ringgit is for the construction of water treatment plants (KTAK, 2007).

One should note that the project is financed by a loan from the Japanese government, which may have influenced decision-making and the selection of Japanese contractors. The high cost of the project have been criticised in the Malaysian media (The Edge, 2007). Nevertheless, it is a probably a good indication of the value placed on securing reliable water supply by decision-makers.

In Chapter 2 two extraction options were highlighted: a modest permanent extraction (approximately 100,000 m^3/day) and a large temporary extraction during droughts (approximately 800,000 m^3/day for 3 months once every 10 years, averaged over 10 years this entails an average extraction of 80,000 m^3/day). In both cases we estimate that cost of the construction and pump for a tube-well is 100,000 ringgit (Gomez, 2004) and that each well requires a site of 100 m^2, land which must be bought at a price of 800 ringgit/m^2 (Malaysialand.com, 2008) or 80,000 ringgit per tube-well. Selecting an appropriate site and optimising tube-well locations is quite a complex task (Kavanagh, et al., 2003), but we assume that the need to buy 100 m^2 of land per well is a reasonable estimate. In addition we assume that installing the necessary piping to a water treatment plant will cost 120,000 ringgit per well, bringing the total required capital lay-out per tube-well to 300,000 ringgit.

For the extraction options described in Chapter 2 it is assumed that there are 12 pumping sites with 10 wells each, bringing the total cost to 36 million ringgit. In addition to this there is a need to install monitoring wells. Monitoring wells are simpler than tube-wells used for groundwater extraction, hence we estimate their cost at 100,000 ringgit per well. Assuming we construct 240 monitoring wells (on average 20 monitoring wells per pumping site, a large number) then the total capital lay-out for groundwater infrastructure is 60 million ringgit. This seems like a conservative estimate: real costs may turn out to be somewhat lower.

Based on the above assumptions, a comparison can be made between the government's willingness-to-pay (the water transfer scheme) and the two groundwater extraction options. An overview is given in Table 6. Note that the reason treatment costs for the temporary extraction are 0 ringgit because no additional capacity needs to be constructed: temporary extraction makes up for a shortfall from reservoirs.

Cost of expanding water supply capacity with 1 m^3/day	**Water Transfer Scheme**	**Permanent Extraction** (100,000 m^3/day)	**Temporary Extraction** (80,000 m^3/day on average in 10 years)
Sourcing water (i.e. dam or tube well)	1,800 ringgit	600 ringgit	750 ringgit
Treatment	2,200 ringgit	2,200 ringgit	0 ringgit
Total	4,000 ringgit	2,800 ringgit	750 ringgit
Price relative to Transfer Scheme	same	1,200 ringgit less	3,250 ringgit less

Table 6 – Cost overview of different water supply schemes

The price difference of the groundwater schemes relative to the water transfer scheme is between 120 million ringgit (permanent extraction) and 260 million ringgit (temporary extraction). Given that the Taman Beringin landfill mentioned earlier was decommissioned at a cost of 24 million ringgit (Sidek Khalid, 2007; Lim, 2008), there seems to be room financially for between 5 and 10 of such environmental remediation projects, which could be invested in even before costs reach the level of the water transfer scheme.

One could also argue that such environmental remediation projects should occur anyway, regardless of groundwater extraction plans. In that case the 120 to 260 million ringgit mentioned earlier is pure 'profit'.

In order to estimate the total cost of environmental remediation projects, a detailed hydrogeological study and a good groundwater monitoring network are needed. This will require a significant investment. If we account for the proposed 240 monitoring wells and an additional 6 million ringgit for modelling and additional data gathering, the total monitoring/surveying/investigation layout could be 30 million ringgit or nearly 40% of the total infrastructure investment.

It must be noted that the cost of the groundwater extraction schemes are only compared to the Water Transfer Scheme. There may be other economically viable alternatives such as non-revenue water reduction programs. The comparison here merely serves to put the cost of groundwater extraction schemes into perspective.

4.4 Institutional Strategies for Groundwater Extraction

Section 3.5 provides a departure point from which changes to stimulate policy coherence can be conceived. Essentially, the institutional structure itself or the incentives for institutions to act must be changed to enable the establishment of a comprehensive groundwater extraction policy. Although many institutional alternatives are possible, in this section three distinct alternatives are explored. They are the status quo, the creation of a unified water agency and a competitive grant scheme run by the federal government.

Status Quo

The strength and weaknesses of the status-quo have already been outlined in Section 3.4. Similar to the Pahang Selangor Water Transfer Scheme, the Ministry of Energy, Water and Communications could also take the lead in a groundwater development program for Kuala Lumpur.

The Ministry of Energy, Water and Communications could tender out the groundwater study and monitoring program to a private consultant, by-passing agencies from the Ministry of Natural Resources (see Table 4). Funds could be obtained from the Japanese or another foreign government and then carried out by foreign contractors. Once the groundwater network has been created and operating procedures are developed, responsibility for operation and maintenance can be transferred to the Selangor Water Supply Corporation, the Selangor state investment corporation or some other suitable private or government party.

The investment in groundwater extraction and monitoring is estimated at approximately 60 million ringgit (possibly more, considering necessary environmental remediation measures), a relatively small amount compared to total water revenues for Selangor and Kuala Lumpur which amounted to 1.4 billion ringgit in 2005 (MWA, 2006). Therefore Selangor state entities such as the Selangor Water Supply Corporation or the Selangor Waters Management Authority can probably finance a groundwater development programme independently, should they wish to do so.

Unified Water Agency

The Selangor Waters Management Authority is the closest thing to a unified water agency in Malaysia, whose jurisdiction spans the complete spectrum of water resources management from flood control, to water supply to environmental conservation. However the Selangor Waters Management Authority lacks the funds and authority to control the state's water resources independently and needs to coordinate with several state and federal agencies.

An interesting alternative example is provided by Singapore's Public Utilities Board, which not a coordinating body like the Selangor Waters Management Authority, but the 'owner' of the Singapore equivalent of the Department of Irrigation and Drainage, the Selangor Water Supply Corporation, the National Water Services Commission, the Water Assets Holding Company, sewerage treatment companies and parts of agencies such as the Department of Minerals and Geoscience and the Department of Environment.

Although the Public Utilities Board's main priority is water supply, it has a strong interest in water resources management in order to expand the water catchment area and collect more rainwater for water supply. This necessitates high environmental quality standards of Singapore's water resources (PUB, 2004).

Besides being a drastic change to the existing institutional landscape, creating a unified water agency in Malaysia requires careful consideration of the division of responsibilities and resources between state governments and the federal government. If the Selangor Waters Management Authority were to receive similar authority and financial resources as Singapore's Public Utilities Board it would need to receive significant additional funding, probably from the federal government. In addition, the newly created National Water Services Commission should be disbanded and privatised water utilities nationalised.

A federal-level Public Utilities Board would remove states' control over water resources and water supply, probably requiring constitutional changes.

Federal Grants
Instead of creating new agencies, the federal Treasury could instead allocate grants for groundwater development, but leave government agencies or consortia of government and private agencies to come up with a plan. For example, a consortium consisting of the Ministry of Energy, Water and Communications and the Selangor Water Supply Corporation and a Malaysian university or research institute could bid against a consortium consisting of the Department of Environment, the Department of Minerals and Geoscience and the Selangor Waters Management Authority and a reputable Malaysian consultant.

By forcing agencies to work together, enforcement and monitoring activities can be rationalised and expertise combined. The federal Treasury could then appoint a committee of experts to select the best plan. Such procedures are also used by the European Union to disburse nearly 347 billion euro in grants via European Structural Funds and Cohesion Funds to finance infrastructure and socio-economic developments in its 27 member states (EC, 2006).

An essential part of these grants are the ability to measure quality and results. Although groundwater developments are highly complex, the iterative process of data-gathering, decision-making, groundwater extraction and environmental protection has many similarities to industrial quality control. This management system is clearly described in the International Standardisation Organisation international quality management standard (ISO 9001:2000) which can also be applied to groundwater management (Von Storch, 2004). ISO 9001:2000 certification processes in Malaysia are usually conducted by the Standards and Industrial Research Institute of Malaysia (SIRIM), whose procedures are internationally recognised through cooperation with the United Kingdom Accreditation Service (UKAS) (SIRIM, 2007).

The advantage of the grant system is that it leaves the current institutional landscape intact while giving the federal government the ability to direct water policy, without micro-managing it. This is an advantage, considering that the Economic Planning Unit or the Treasury cannot and should not know everything about water management. Although the grant procedures may seem complicated, the necessary quality control standards have already been developed and can be used.

4.5 Formulating a Development Strategy

Taking the economic analysis in Section 4.3 at face value, there appears to be a case for groundwater extraction, and therefore an investment in further groundwater studies is merited. In Section 4.4 we asked which institution could conduct this research or finance it and in this section we analyse the institutional alternatives and propose a groundwater development strategy.

Of the schemes analysed, the grant scheme by the federal government seems the most promising. Although there are ways under the status quo to finance and conduct groundwater research, the fact that it is not happening is in itself significant. The federal grant scheme stimulates cooperation without making any formal institutional changes, it is in line with the groundwater ambitions expressed in the Ninth Malaysia Plan and being a competitive process it should be a-political, reducing the risk of state-federal conflict. The unified water agency requires major reforms of a scale that far exceed the scope of this groundwater resources study. Hence its impact cannot be fully assessed here and it seems like an over-sized "cannon" solution for a modest "mosquito" problem[e].

The grant scheme can also be phased into an exploration phase which seeks to verify some of the assumptions made in this model by making some modest improvements in groundwater monitoring. If these results are positive, a second phase could be followed by a comprehensive study to identify pumping sites, extraction quantities and environmental threats and to estimate the costs and benefits of a full groundwater extraction program. A third phase could then be the implementation and operation of a groundwater extraction program. This gradual decision making is necessary because of uncertainty: new information needs to be re-examined before committing further resources to groundwater extraction.

Because the grant scheme leaves the existing institutional structure intact, it is relatively easy to implement. Even if the decision is taken not to extract groundwater, the grant scheme will have provided a test case for inter agency cooperation and generated new knowledge and experience that can be applied elsewhere. Given its financial strength and current involvement in water resources management, the federal government should initiate the grant scheme, although in a later stage it could be implemented by Selangor state entities.

[e] "Do not use a cannon to kill a mosquito" – Confucius, 551-479 BCE

5 Conclusions and Recommendations

The conclusion is structured around the research questions formulated in Chapter 0 and seeks to provide a comprehensive answer that meets the objective of this study: *to evaluate the feasibility of urban groundwater extraction in Kuala Lumpur as a source of potable water*. This is followed by the recommendations, which are separated into recommendations for engineers, dealing with the technical aspects of groundwater management, and recommendations for decision makers, who wish to use the results of this study to formulate policy.

1. What are the physical effects of groundwater extraction?
The first research question demands an inquiry into the physical effects of groundwater extraction. Analysis presented in Chapter 2 reveals that two extraction strategies are possible: a permanent extraction of approximately 80,000 m^3/day (2.5% of total water demand) or a 3-month temporary extraction of 800,000 m^3/day (25% of total water demand). These conclusions are based on several technical assumptions that are yet to be verified and this is the main weakness of these model results. It is however a best estimate that can be used in making decisions to conduct further groundwater studies.

2. What is the economic value of groundwater extraction?
The second research question addresses the economic value of groundwater extraction. Taking into account the two strategies identified in Chapter 2, economic analysis in Chapter 3 concludes that groundwater extraction compares favourably to other water supply schemes, although not all possibilities are evaluated. This favourable outcome supports a decision to conduct further groundwater studies.

3. What is the current institutional setting with respect to groundwater resource management and how can it be changed to enable groundwater extraction?
The last research question is aimed at discovering why, given the incentives provided by the previous answer, no comprehensive groundwater extraction policy exists. The main reasons for this appear to be a lack of knowledge about groundwater resources and a lack of clear responsibilities and jurisdictions between the more than 10 organisations concerned with some aspect of groundwater extraction for potable water. The most effective incentive for stimulating agencies to pursue a coherent groundwater policy therefore seems to be a competitive grant scheme funded and administered by the federal government.

So is extracting groundwater feasible? Weighing all the evidence presented in this study, one is tempted to say *yes*, however it must be followed by a more cautionary *but*. Extraction of groundwater is feasible under certain conditions. Uncertainty continues to exist in the assumptions on which this conclusion is based. What is a safe level of drawdown? Is the steady state assumption of the model valid? How does the groundwater table behave in the hills surrounding Kuala Lumpur? etc. These questions need to be answered.

If we accept that the groundwater extraction estimates presented here are the best possible estimates, then one must conclude that further, phased groundwater studies should be conducted to explore the full potential of Kuala Lumpur's urban groundwater resources.

5.1 Technical Recommendations for Engineers

A. The model relies on the assumption of a more-or-less constant water table. Because there are no groundwater level monitoring wells in Kuala Lumpur, this assumption cannot be verified. There are groundwater quality monitoring wells in Kuala Lumpur operated by the Department of Environment. These should be used to monitor groundwater levels.

B. The model lacks data from the hills surrounding Kuala Lumpur, therefore priority should be given to gathering data in these areas.

C. Infiltration is a very sensitive factor in the model and should therefore receive priority as well. The infiltration from tin ponds is poorly understood but highly significant. One possible method of identifying sources of infiltration could be by analysing groundwater quality. The main sources of infiltration: piped water and tin ponds have a distinct chemical profile due to the likely presence of metal residues in the tin ponds and the chlorination of potable water to kill bacteria.

5.2 Policy Recommendations for Decision Makers

D. If the model results and economic analysis are accepted, then further groundwater studies are merited.

E. A phased competitive grants scheme may be a good way to finance further studies. It would encourage cooperation between different agencies and improve effectiveness and coherence without making large organisational changes. By phasing the groundwater studies, there are clear moments for re-evaluating new and existing information before taking the decision to commit further resources to groundwater extraction.

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Appendix A

The following is taken from (Bressers, et al., 2003).

A model of governance in five elements

(1) *Levels and scales of governance*
Where? – Multi-level
Which levels of governance dominate policy and the debate on conducting policy, and in which relations? What is the relation with the administrative levels of government? Who decides or influences such issues? How is the interaction between the various administrative levels arranged?
(2) *Actors in the policy network*
Who? – Multi-actor
How open is the policy arena in theory and practice, and to whom? Who is actually involved and with what exactly? What is their position? What is the accepted role for government? Which actors have relevant ownership and use rights or are stakeholders in some other capacity (including policy-implementing organisations)? What is the structural inclination to co-operate among actors in the network? Are their 'coalitions' formed across social positions? Are there actors among them who operate as process brokers or 'policy entrepreneurs'? What is the position of the general public versus experts versus politicians versus implementers?
(3) *Problem perception and policy objectives*
What and why? – Multi-faceted
What are the dominant maps of reality? What is seen as a problem and how serious is this considered to be? What do people see as the causes of the problem? Is the problem considered to be a problem for individuals or a problem for society at large? Why are the previous questions seen that way: what values and other preferences are considered to be at stake? Which functions are allocated to the sector? Is the problem seen as a relatively new and challenging topic or as a 'management' topic without much political 'salience'? To what degree is uncertainty accepted? Where are the recognised points of intervention? What relations with other policy fields are recognised as co-ordination topics? Which policy objectives are accepted? What are levels to which policy makers aspire (ambition) in absolute terms (level of standards) and relative terms (required changes in society)?
(4) *Strategy and instruments*
How? – Multi-instrument
Which instruments belong to the policy strategy? What are the characteristics of these instruments? What are the target groups of the policy and what is the timing of its application? How much flexibility do the instruments provide? To what extent are multiple and indirect routes to action used? Are changes in the ownership and use rights within the sector anticipated? To what extent do they provide incentives to 'learn'? What requirements do they place on the availability of resources for implementation? How are the costs and benefits of the policy distributed?
(5) *Responsibilities and resources for implementation*
With what? – Multi-resource-based
Which actors (including government organisations) are responsible for implementing the policy? What is the repertoire of standard reactions to challenges known to these organisations? What authority and other resources are made available to these actors by the policy? With what restrictions?

Appendix B

The following is taken from (Bressers, et al., 2003).

Conditions for policy coherence

Tradition of co-operation
- a dominant policy ideology that supports integration
- positive examples of integration known by the actors involved
- mutual respect and trust in 'fair play' of the actors involved

Joint problem
- knowledge bases in the form of reports and statements by respected sources on resource deterioration due to fragmentation
- information symmetry between the actors involved on these points
- a sense of responsibility for the future with the actors involved

Joint opportunities
- knowledge bases from respected sources on opportunities stemming from more integration
- information symmetry between the actors involved on these points
- a sense of respect for each others' interests among the actors involved

Credible alternative threat
- sufficient imbalance of power favouring a dominant actor (government?) to enable unilateral action
- information on alternative options to 'solve' the problem from the perspective of the dominant's actor's perspective
- alternative option has more severe consequences for the other stakeholders than the specific form of integration would have

Institutional interfaces (not all indicators below are equally important to all forms of integration)
- clarity of assigned responsibilities (to prevent territorial battles)
- free and alert mass media to induce awareness of challenges to the system
- legal or practical possibilities to protect negotiated compromises from continuous litigation
- actors, independent or within the administration, with solely process objectives (brokers)