7 Groundwater Level Trends

7.1 Hydrographs

For discussion, the MPs have been grouped based on similarity of hydrographs. The groups are outlined in Table 7.1 and are discussed in the following sections. The hydrograph grouping is subjective and a number of different groupings would be equally viable. However, the grouping allows ease of discussion, and comparison within and between groups provides an opportunity for insight into the hydrogeological setting.

Figures 7.1–7.8 present the grouped hydrographs together with the ER calculated in Section 2.3. Where possible, the grouped hydrographs have been drawn to the same vertical scale to allow ease of comparison. Where a datum is available, the hydrographs are plotted as metres above ordnance datum, otherwise they are plotted as metres below ground level. Figure 7.9 shows all hydrographs plotted together to show the relative elevation and scale of seasonal trends. To allow comparison of groundwater levels in this figure, an approximate elevation was taken from the appropriate Ordnance Survey Ireland Discovery Series (1:50,000) map for MPs without a datum.

Individual hydrographs for each MP are presented in Appendix D. The hydrographs are plotted against the ER and the captions provide information on geology, subsoil, depth of well, datum and hydrogeological information such as inflow depths from geological logs. Where information on depth to rock was not available, an estimate is made using the subsoil permeability and vulnerability. The ER was calculated as discussed in Section 2.3.

Observations on physical settings have been taken from the appropriate Ordnance Survey Ireland Discovery Series (1:50,000) map. Observations on the aquifer classifications have been made from the National Draft Bedrock Aquifer Map (GSI, 2006).

Table 7.1. Hydrograph grouping.

<table>
<thead>
<tr>
<th>Group</th>
<th>Subgroup</th>
<th>Monitoring point</th>
<th>Relevant report and appendix figure</th>
</tr>
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<tbody>
<tr>
<td>Upper catchment</td>
<td>Barrow Basin</td>
<td>Land Commission 2</td>
<td>Figures 7.1, 7.2 and D.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ardsull DW</td>
<td>Figures 7.1, 7.2 and D.2</td>
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<td></td>
<td>Masterson</td>
<td>Figures 7.1, 7.2 and D.3</td>
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<td></td>
<td>Clomantagh Lower</td>
<td>Figures 7.3 and D.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Woodsgift</td>
<td>Figures 7.3 and D.5</td>
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<tr>
<td>Nore Basin</td>
<td></td>
<td>Tubbrid Lower</td>
<td>Figures 7.3 and D.6</td>
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<td>Discharge-dominated hydrographs</td>
<td>Cullahill</td>
<td>Figures 7.4 and D.7</td>
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<td></td>
<td></td>
<td>Granston Manor</td>
<td>Figures 7.4 and D.8</td>
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<tr>
<td></td>
<td>River-influenced hydrographs</td>
<td>Oldtown</td>
<td>Figures 7.5 and D.9</td>
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<td></td>
<td></td>
<td>Rathduff</td>
<td>Figures 7.5 and D.10</td>
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<td></td>
<td>Knocktopher</td>
<td>Figures 7.5 and D.11</td>
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<td></td>
<td></td>
<td>Ballincurry</td>
<td>Figures 7.6 and D.12</td>
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<tr>
<td></td>
<td>Confined</td>
<td>Boston Co. Co.</td>
<td>Figures 7.7 and D.13</td>
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<td>Abstraction influenced</td>
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<td>Kilmeague</td>
<td>Figures 7.9 and D.14</td>
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<tr>
<td>Gravel hydrographs</td>
<td></td>
<td>Rahilla</td>
<td>Figures 7.9 and D.15</td>
</tr>
</tbody>
</table>
Figure 7.1. Hydrographs of the Barrow Basin group.
Figure 7.2. Hydrographs of the Barrow Basin group between 1972 and 1974.
Subsoil observations have been made from the *Subsoil Map of Ireland* (GSI/Teagasc/EPA, 2006) as well as the *Provisional Subsoil Permeability Map* (GSI, 2008a) and the *Provisional Subsoil Vulnerability Map* (GSI, 2008b). These sources will not be referenced individually in the discussion below.

### 7.1.1 Upper catchment – Barrow Basin (Fig. 7.1)
The Land Commission 2, Ardsull DW and Masterson MPs are located in the Barrow River Basin, to the north-east of the Castlecomer Plateau. The Land Commission 2 MP is located in the Ballyadams Formation, an Rkd karstified aquifer, approximately 70 m down-gradient of where the karstified bedrock is at, or near, the surface. The Ardsull Borehole is located in the Ll Ballysteen Formation. It is located 50 m down-gradient of bedrock being at, or near, the surface. The Masterson MP is located in the Rkd karstified Clogrennan Formation. It is located within 100 m of alluvium of the River Fuer, a tributary of the River Douglas.

The groundwater regime in upper catchment areas can be dominated by recharge as typically the subsoil is relatively thin or absent. A hydrograph dominated by recharge typically shows a large annual variation in groundwater level. The Land Commission 2 and Ardsull MP's are located in areas with thin (0–3 m), moderate permeability till, and are close to areas where bedrock is at, or near, the surface. As may be expected, the annual variation of groundwater levels in these two MP's is large compared with the hydrographs of the other MP's (Fig. 7.1). However, the annual variation observed in the Land Commission 2 MP is exceptionally large (32.5 m on average). This is likely to indicate a particularly low specific yield (see further discussion in Section 7.2.2).

The Masterson MP is located in an area with thicker (3–10 m), moderately permeable till, which may influence its slightly lower annual variation in groundwater levels (Fig. 7.1).

The inter-annual groundwater level variations reflect annual variations in ER. There are a number of 'marker' years where similar variation may be seen across all the hydrographs (i.e. not just those in this group). For example, the groundwater maxima in 1976 are notably lower than other years, marking a particularly dry summer and winter; the groundwater minima in 1974 are notably high and the minima in 1984 are notably low, marking a particularly wet winter and dry summer, respectively (Figs 7.1–7.5 and to a lesser extent Figs 7.7 and 7.8).

The hydrograph of the Ardsull DW MP (Ll aquifer) shows a number of short-duration, small-amplitude recharge and recession events superimposed on its annual trend (Figs 7.1 and 7.2). These occur almost exclusively when groundwater levels are elevated in the winter and spring months. By comparison, the hydrographs for the Land Commission 2 and Masterson MP's (both Rkd aquifers) are much smoother with only occasional interruption to the annual trend (Figs 7.1 and 7.2). This difference could be due to relatively low storage of the locally important aquifer compared with the regionally important aquifer. However, as outlined above for the Land Commission 2 MP, it is likely to have a particularly low storage due to its exceptionally large annual variation (see Section 7.2.2). Therefore, the difference is likely to be the ability of the different aquifers to accept potential recharge. Poor and locally important aquifers have an upper limit to the amount of recharge they can accept, after which subsequent recharge will be rejected (see Box 5.2). The short-lived recharge and recession events seen in the Ardsull DW MP's hydrograph are likely to represent the phenomenon of rejected recharge from this Ll aquifer. In contrast, the regionally important aquifer of the Land Commission 2 and Masterson MP's can accept all potential recharge.

### 7.1.2 Upper catchment – Nore Basin (Fig. 7.3)
The Nuenna Catchment MP's are all in the Rkd karstified Ballyadams Formation and are located within 1.5 km of each other. Woodsgift MP is located on the catchment divide for the Nuenna River. Clomantagh Lower is located on the side of a local topographic high (elevated approximately 35 m above the Nuenna River) opposite the Slieveardagh Hills. This MP is located approximately 750 m down-gradient of where karstified bedrock is at, or near, the surface. Six springs are located along the river below the Clomantagh Lower MP. The Tubbrid Lower MP is located close to a spring which forms the head of the Nuenna River; another two springs are located within 100 m of this MP. As outlined in Section 5.2.1, the
Figure 7.3. Hydrographs of the Nore Basin group.
Nuenna Catchment is a karstified area with numerous karst features and evidence of conduit flow.

The annual variations of the three MPs are very variable considering their proximity to each other. The Clomantagh Lower MP has a large annual variation (average of 14.8 m), Woodsgift has a moderate variation (average of 7.7 m) and Tubbrid Lower has a small variation (average of 3.2 m) (Fig. 7.3). The large variation observed in Clomantagh Lower may be due to the MP’s proximity to the area where karstified bedrock is at, or near, the surface and thus its high potential for recharge. Tubbrid Lower’s low annual variation may be due to its local discharge environment. The differences between the hydrographs of these closely clustered MPs highlight the complexity of the karstified system within which they are located.

The inter-annual groundwater level variations are similar to those in the Upper Catchment – Barrow Basin group, as noted by the trends during ‘marker’ years.

The Clomantagh Lower and Woodsgift hydrographs show a number of short-term water-level variations which occur throughout the annual cycle (Figs 7.3, D.4 and D.5). In contrast to the short-term water-level variations attributed to rejected recharge, these variations differ in two ways:

1. They occur throughout the year, during recharge and recession periods; and
2. Their amplitude is of a similar magnitude to the amplitude of the annual variations.

These moderately large amplitude recharge events during the summer months may be the result of either localised summer ER or point recharge, which would allow recharge to bypass the soil zone and thus the soil moisture requirements. Plotting this group of hydrographs against ER calculated for the Tullaroan rainfall station (the rainfall station nearest to the MPs, see Table 2.1), rather than for the Kilkenny synoptic station, indicates that localised summer ER is likely to be the reason for these recharge events.

### 7.1.3 Discharge dominated (Fig. 7.4)

Cullahill and Granston Manor MPs are located to the west of the Castlecomer Plateau, in the LI aquifers of the Durrow and Crosspatrick Formations, respectively. Both MPs are located close to rivers: Cullahill is approximately 20 m west of an unnamed tributary of the River Goul and Granston Manor is within 100 m of an unnamed tributary of the River Erkina. The 1:10,560 (6” to a mile) map for the area shows large marshy areas along the Rivers Goul and Erkina. There are no mapped karst features near the Cullahill or Granston Manor MPs.

The Crosspatrick Formation at the Granston Manor MP is overlain by 1.4 m of sand and then 5.4 m of clay. The subsoils are recorded as moderately permeable and are likely to be hydraulically connected to the underlying aquifer.

The inter-annual groundwater level variations are similar to those in the upper catchment groups, as noted by the trends during ‘marker’ years.

The water levels in these MPs are shallow (winter maxima are frequently less than 1 mbgl) with small annual variations (between 2.0 m and 4.5 m) (Fig. 7.4). These characteristics are likely to reflect that these MPs are located in areas were groundwater is discharging to surface water.

The slightly ‘ragged’ nature of these hydrographs during the winter and spring months may represent the limited ability of the LI aquifers to accept recharge.

### 7.1.4 River influenced (Fig. 7.5)

The regionally important Dinantian karstified, dolomitised aquifers and the Kiltorcan Sandstone Aquifer all discharge into the Callan to Bennettsbridge Lowlands (Section 5.2), where the Rathduff (Kny 27/58) and Knocktopher (Kny 31/72) MPs are located. The Rathduff Borehole is located in the Rkd Waulsortian Formation, which is overlain by 18 m of moderate permeability subsoils, dominated by limestone till. It is approximately 100 m from the King’s River. The Knocktopher Borehole is located in the Rf Kiltorcan Sandstone Aquifer, which is overlain by 5 m of low permeability limestone till. It is approximately 200 m from the Little Arrigal River.
The Oldtown Borehole is located further up the catchment of the King’s River, on the flanks of the Slieveardagh Hills. It is located in the Kilmanagh River gravels approximately 10 m from an unnamed tributary of the King’s River.

These hydrographs have low annual groundwater variations compared with the hydrographs of the other MPs (averages between 1.1 m and 2.6 m). The groundwater levels are reasonably shallow throughout the year: Rathduff and Knocktopher are typically less than 7–8 m deep and Oldtown typically less than 2.5 m deep. The hydrographs are ‘peaky’, i.e. they show a rapid response to ER via a number of recharge and recession events within an annual time frame (Figs 7.5, D.9–D.11). The amplitude of these events is the same order of magnitude as the seasonal variations. This ‘peaky’ nature is likely to be due to a high level of groundwater–surface water interaction.

A similar level of evidence of surface water–groundwater interaction has not been obtained for the Rathduff or Knocktopher MPs. Therefore, their grouping with the Oldtown MP is predominantly based on the similarity of hydrographs and comparable physical settings.

The EPA maintains a permanent hydrometric station at Annamult on the King’s River, the details of which are outlined in Table 7.2. The Annamult station is located 4.4 km downstream of the Rathduff MP. The hydrograph of surface water flow at Annamult hydrometric station is similar to the groundwater level hydrograph for Rathduff MP (Fig. 7.10), supporting the
Figure 7.5. Hydrographs of the river-influenced group.
idea of surface water–groundwater interaction at this MP.

A similar surface water hydrometric station is not available for comparison with the Knocktopher hydrograph. The geology of the area around the Knocktopher MP is complicated, with a high degree of folding and faulting. The MP’s location relative to the geological structure allows (but does not prove) a physical connection between the Kiltorcan Sandstone Aquifer unit and the Little Arrigal River.

Misstear and Brown (2008) show that borehole hydrographs, such as these, may be used to calibrate river base-flow separation analyses. In low-storage, rapid-flow situations, borehole hydrographs can provide a means of assessing whether the separation method adequately represents the response to recharge in the aquifer.

### 7.1.5 Confined (Fig. 7.7)

The Ballincurry Borehole is located near the surface water divide for the Nore River Basin in the Westphalian Sandstones of the Slieveardagh Hills. Daly (1980) notes that the borehole was artesian when drilled and that the sandstone units are confined. The subsoil in the area of the borehole is low permeability; as a result there is a high drainage density near the borehole. Bedrock is at, or near, the surface approximately 1.4 km up-gradient from the borehole, which is likely to provide recharge into the sandstone
units. The borehole is located approximately 400 m from the south-eastern extent of the Westphalian Sandstone and the contact with the underlying Pl Namurian Sandstone units. An unnamed tributary to the King’s River passes within 400 m of the borehole.

The annual variation of groundwater level in the Ballincurry MP is moderate at 4.71 m. The hydrograph shows rapid recharge to an elevated groundwater level, which is typically maintained for the winter and spring months, followed by a reasonably rapid groundwater level recession (Fig. 7.6). The elevated groundwater levels are maintained by a number of short-duration, small-amplitude recharge and recession events. The recessions events may represent low, confined storage and possibly subsequent discharge of the sandstone units to the nearby stream.

7.1.6 Abstraction influenced (Fig. 7.8)

The Boston Co. Co. MP is located in the upper Barrow River Basin, in a fault-bounded block (approximately 2.5 km by 3.0 km) of the LI Boston Hill Formation. The subsoil map shows the area to have bedrock at, or near, the surface. It is described as a ‘perched source’ and a ‘poor supply’ in the GSI well records. It is located approximately 75 m to the north-east and downslope of a gravel pit, which is likely to affect the recharge to the limestone in the area. It is not known if the gravel pit was operational in the 1970s–1980s, i.e. the duration of the hydrograph.

The annual groundwater level variation for the Boston Co. Co. (5.95 m) is not as large as might be expected for an aquifer unit which is at, or near, the surface. It is described as a ‘perched source’ for example, the Ardscull DW MP, which is located in the LI Ballysteen Formation (equivalent to the Boston Hill Formation) has an annual variation of 10.88 m (Fig. 7.1). Perhaps the impact of the gravel quarry, the aquifer’s perched or fault-bounded nature restricts the extent of groundwater level movement.

The Boston Co. Co. MP seems to have two distinct groundwater level minima: shallow minima between 10 mbgl and 12 mbgl and deeper minima between 14

Figure 7.7. Hydrographs of the confined group.
mbgl and 16 mbgl (Fig. 7.7). The deeper minima occur in ‘dry’ years, for example the early- and mid-1970s, and may represent a drop below its perched boundary. They also become less deep with time over the duration of the hydrograph. This may be due to a decreasing impact of dewatering from the nearby quarry from the 1970s to the 1980s.

7.1.7 Gravels (Fig. 7.9)

The Rahilla Borehole is located in the regionally important Mid-Kildare Gravel Aquifer whereas the Kilmeague Borehole is located in a “high dry sandy area which rises steeply from the extensive, wet flats and bogs which dominate this part of Kildare” (GSI well records) approximately 13 km to the north-east.

Until approximately 1974, the Rahilla Borehole was used as a source of supply and the groundwater level was measured by listening for a dropping weight to hit the water; after 1974, an electronic dipper was used (Ward, 1993). These two factors account for the ‘ragged’ appearance of the Rahilla hydrograph prior to 1974. It is likely that the method of monitoring at Kilmeague was changed at a similar date.

The hydrographs for the Rahilla and Kilmeague MPs are similar. Where the monitoring frequency is adequate (prior to 1982 and 1985 for Kilmeague and Rahilla, respectively), the hydrographs are smooth, rounded and symmetrical. They have low annual variation and show relatively gradual recharge periods over the autumn months and equally gradual recessions over the spring months. The water levels are deep, generally between 30 m and 36 m deep at Rahilla and between 21 m and 25 m deep at Kilmeague. Relative to their low annual range, the hydrographs show a large variation in annual minima and maxima over a number of years. For example, in the Kilmeague MP the difference in groundwater level maxima is approximately 3 m, approximately twice that of the average annual variation (Fig. 7.9). These characteristics are likely to be due to large intergranular storage available in sand and gravel aquifers as well as to the thick unsaturated zones.

The range in annual minima and maxima reflects medium-term rainfall trends, with low water levels in the early- and mid-1970s and higher than normal

7.2 Short-Term and Seasonal Groundwater Level Trends

7.2.1 Groundwater level statistics

Each hydrograph was interrogated to obtain a list of the timing and elevation of each annual groundwater level minimum and maximum. These values were used to generate simple statistics for each MP, such as minimum, maximum and mean groundwater levels, average annual groundwater level variation and duration of recession events. For this analysis, only constrained minima and maxima were included, i.e. only turning points with supporting data points before and after the turning point, within a reasonable time frame, were included. Table 7.3 outlines the minimum, maximum and mean groundwater levels and the average annual variation for each MP.

The following observations may be made:

- Monitoring points with both shallow mean water levels (<7.0 mbgl) and low average annual variations (<4.5 m) are those associated with surface water or discharge points;
- Gravel MPs (selected for this report) have low average annual variation (<2.1 m) but deep minimum, maximum and mean water levels; and
- Monitoring points with reasonably deep mean water levels (>7.0 mbgl but <21 mbgl) and large average annual variation (>4.5 m) are those associated with recharge zones.

Table 7.4 outlines an analysis of the timing of groundwater level minima and maxima for each MP. For the analysis of the duration of recession periods, the recession period is taken to be the length of time from the maximum groundwater level in 1 year to the minimum groundwater level in the subsequent year. For most hydrographs, this method is appropriate;
however, for a few hydrographs it may overestimate the recession period. The Ballincurry hydrograph, for example, has a prolonged recharge period during winter and spring, and the maximum groundwater level may not represent the start of the recession. Similarly, the river-influenced hydrographs, such as Oldtown, have a number of recharge and recession periods within the annual cycle and the annual minima or maxima may not represent the onset of seasonal recession or recharge.

The analysis shows that the groundwater levels in bedrock aquifers typically reach their maximum between November and February and their minimum between September and November. The average recession period length for these hydrographs is between 7.5 months and almost 9 months. It may be seen from Table 7.4 that there is wide variation in the duration of any single recession period, from 2 months to 12 months. These estimates of recession durations are slightly longer than those suggested by Daly (1990), who estimated the groundwater recession ranges from 3 to 7 months and averages of about 5 months in the south-east of Ireland.

The gravel aquifers (Rahilla and Kilmeague MPs) reach their maxima and minima slightly later than the bedrock aquifers: April–May and October–December, respectively. This equates to a slightly shorter average recession period of almost 7 months. This inertia, which is observed in the hydrographs as rounded traces, is likely to be due to the large intergranular storage capacity and the effect of recharge occurring through a thick unsaturated zone.

The bedrock hydrographs which have either late groundwater level maxima (February) or late
groundwater level minima (October–November) are typically associated with Rkd aquifers with extreme vulnerability or are near to areas where the karst aquifer is at, or near, the surface. Hydrographs with slightly earlier minima (September) or maxima (November–January) tend to be associated with locally productive aquifers with high vulnerability. The later response of the Rkd aquifers may be due to the relatively increased storage of the karstified and dolomitised limestones compared with the locally important aquifers or may be due to the fact that they continue to recharge beyond the point at which locally important aquifers begin to reject recharge.

### 7.2.2 Specific yields

Healy and Cook (2002) describe the water-table fluctuation method to calculate recharge. The method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. A water-balance equation for a groundwater system may be written as:

$$ R = \left( S_y \frac{\Delta h}{\Delta t} \right) + Q_a + Q_{out} - Q_{in} \quad \text{Eqn 7.1} $$

where $R$ is recharge, $S_y$ is specific yield, $\Delta h$ is change in water-table elevation, $Q_a$ is groundwater abstraction, and $Q_{out}$ and $Q_{in}$ are any other lateral subsurface outflows and inflows, respectively. If it is assumed that the outflows are equal to the inflows, that abstractions are negligible and that water arriving at the water tables goes immediately into storage, then the water-balance equation may be simplified to:

$$ R = S_y \frac{\Delta h}{\Delta t} \quad \text{Eqn 7.2} $$

This equation was inverted to calculate estimates of specific yields for a number of aquifers. The recharge component of the equation was estimated using the methodology of Misstear et al. (2008) for making initial estimates of groundwater recharge from groundwater vulnerability mapping.

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**Table 7.3. Minima, maxima, mean and average annual variation in groundwater levels.**

<table>
<thead>
<tr>
<th>Monitoring point</th>
<th>Maximum water level (mbgl)</th>
<th>Minimum water level (mbgl)</th>
<th>Mean dip (mbgl)</th>
<th>Average annual variation (m)</th>
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<tbody>
<tr>
<td>Oldtown</td>
<td>0.81</td>
<td>3.43</td>
<td>2.02</td>
<td>1.18</td>
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<tr>
<td>Granston Manor</td>
<td>0.00</td>
<td>4.20</td>
<td>2.05</td>
<td>2.09</td>
</tr>
<tr>
<td>Tubbrid Lower</td>
<td>0.62</td>
<td>4.91</td>
<td>2.37</td>
<td>3.18</td>
</tr>
<tr>
<td>Cullahill</td>
<td>0.31</td>
<td>6.60</td>
<td>3.32</td>
<td>4.36</td>
</tr>
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<td>Ballincurry</td>
<td>3.05</td>
<td>8.62</td>
<td>6.75</td>
<td>4.71</td>
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<td>Rathduff</td>
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<td>8.07</td>
<td>6.79</td>
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<td>Knocktopher</td>
<td>5.34</td>
<td>7.80</td>
<td>7.00</td>
<td>1.94</td>
</tr>
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<td>Masterson</td>
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<td>16.08</td>
<td>9.90</td>
<td>5.95</td>
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<td>Ardsull DW</td>
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<td>20.03</td>
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</tr>
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<td>Land Commission 2</td>
<td>1.05</td>
<td>42.06</td>
<td>20.36</td>
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<tr>
<td>Kilmeague</td>
<td>20.90</td>
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<td>Rahilla</td>
<td>30.45</td>
<td>35.52</td>
<td>33.64</td>
<td>2.06</td>
</tr>
</tbody>
</table>

mbgl, metres below ground level.
Recharge to an aquifer is estimated by multiplying the ER by a recharge coefficient. The recharge coefficient indicates the proportion of the ER that contributes to groundwater recharge. It is determined mainly by the permeability and thickness of overlying subsoils. The recharge coefficients are classed into three groupings:

1. High (70–90%);
2. Intermediate (30–70%); and
3. Low (5–30%).

Scanlon et al. (2002) state that the water-table method is best applied to short time periods in regions having shallow water tables that display sharp rises and declines in water levels. However, it may be applied over longer time intervals (seasonal or annual) to estimate ‘net’ recharge. For the majority of the historic MPs, data resolution is not sufficient to interrogate individual recharge events. Therefore, the method was applied over an annual time period.

Healy and Cook (2002) point out that in fractured rock systems, short-term variations in groundwater levels are significantly attenuated due to the well’s relatively large permeability and storage compared with the aquifer, particularly where the well radius is large (up to 0.5 m). They also state that longer-term variation in aquifer water levels (such as annual cycles) is less attenuated.

It should be noted that while the water-table fluctuation method is widely used in sedimentary (porous media) aquifers, it remains unclear if the method is valid at all in fractured rock systems due to the complexity of such systems (Healy and Cook, 2002).

Therefore, with caution, the $S_y$ calculations were carried out using the annual groundwater level variation outlined in Section 7.2.1. The specific yield was estimated using the following equation:

Table 7.4. Typical timing of groundwater level minima and maxima.

<table>
<thead>
<tr>
<th>Monitoring point</th>
<th>Aquifer type¹</th>
<th>Typical month of maximum groundwater level</th>
<th>Typical month of minimum groundwater level</th>
<th>Range of recession duration (months)</th>
<th>Typical duration of recession (months)</th>
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<tr>
<td>Oldtown</td>
<td>Rg</td>
<td>Nov</td>
<td>Sep</td>
<td>4–12</td>
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<td>Ballincurry</td>
<td>Lm</td>
<td>Dec</td>
<td>Sep</td>
<td>7–10</td>
<td>8.5</td>
</tr>
<tr>
<td>Cullahill</td>
<td>LI</td>
<td>Jan</td>
<td>Sep</td>
<td>6–11</td>
<td>7.9</td>
</tr>
<tr>
<td>Boston Co. Co.</td>
<td>LI</td>
<td>Jan</td>
<td>Sep</td>
<td>4–12</td>
<td>8.8</td>
</tr>
<tr>
<td>Granston Manor</td>
<td>LI</td>
<td>Jan</td>
<td>Sep</td>
<td>6–11</td>
<td>7.9</td>
</tr>
<tr>
<td>Rathduff</td>
<td>Rkd</td>
<td>Jan</td>
<td>Sep</td>
<td>3–11</td>
<td>8.3</td>
</tr>
<tr>
<td>Knocktopher</td>
<td>Rf</td>
<td>Jan</td>
<td>Sep/Oct</td>
<td>2–12</td>
<td>7.5</td>
</tr>
<tr>
<td>Arscull DW</td>
<td>LI</td>
<td>Jan</td>
<td>Oct</td>
<td>6–10</td>
<td>8.1</td>
</tr>
<tr>
<td>Woodsgift</td>
<td>Rkd</td>
<td>Jan</td>
<td>Oct</td>
<td>7–11</td>
<td>8.2</td>
</tr>
<tr>
<td>Tubbrid Lower</td>
<td>Rkd</td>
<td>Jan</td>
<td>Oct</td>
<td>6–12</td>
<td>8.8</td>
</tr>
<tr>
<td>Clomantagh Lower</td>
<td>Rkd</td>
<td>Feb</td>
<td>Sep</td>
<td>6–10</td>
<td>7.9</td>
</tr>
<tr>
<td>Land Commission 2</td>
<td>Rkd</td>
<td>Feb</td>
<td>Oct</td>
<td>7–9</td>
<td>8.1</td>
</tr>
<tr>
<td>Masterson</td>
<td>Rkd</td>
<td>Feb</td>
<td>Oct/Nov</td>
<td>6–10</td>
<td>8.1</td>
</tr>
<tr>
<td>Rahilla</td>
<td>Rg</td>
<td>Apr</td>
<td>Oct/Nov/Dec</td>
<td>4–10</td>
<td>6.8</td>
</tr>
<tr>
<td>Kilmeague</td>
<td>Lm</td>
<td>Apr/May</td>
<td>Nov/Dec</td>
<td>5–10</td>
<td>6.8</td>
</tr>
</tbody>
</table>

¹ For aquifer type codes, please refer to Box 5.1.
The analysis considers recharge as a result of vertical infiltration in the vicinity of the borehole. Therefore, a number of MPs were unsuitable for analysis and have been omitted. They comprise MPs where lateral throughflow from up-gradient is likely to dominate recharge (confined Ballincurry and discharge-dominated hydrographs Tubbrid Lower, Cullahill, Granston Manor, Oldtown, Rathduff and Knocktopher).

The rainfall used is the annual average rainfall for the rainfall station nearest to the MP (see Table 2.1); the AE is an average taken from the AE calculated for the Callan to Bennettsbridge Lowlands in the Misstear and Brown (2008) study. The recharge classes are chosen based on the subsoil permeability and thickness. Where the MP is proximal to significantly different subsoil (typically down-gradient of bedrock at, or near, the surface), the $S_y$ range over two recharge classes is calculated. The results of the analysis are presented in Table 7.5.

For these calculations the value of $\Delta h$ was calculated as the difference between the annual groundwater level maximum and the antecedent minimum. In contrast, Healy and Cook (2002) state that to calculate the ‘net’ recharge, $\Delta h$ should be calculated as the difference between “the peak of the rise and the low point of the extrapolated antecedent recession curve at the time of the peak”. On an annual time frame, this would translate into the difference between the annual groundwater level maximum and the extrapolated antecedent recession curve at the time of the groundwater maximum. This latter version of $\Delta h$ will be

$$S_y [-] = \frac{\text{Effective rainfall [m] \times Recharge coefficient [-]}}{\text{Average annual groundwater level variation [m]}}$$

Eqn 7.3

<table>
<thead>
<tr>
<th>Monitoring point</th>
<th>Aquifer category</th>
<th>Average groundwater level variation (mm/annum)</th>
<th>Rainfall (mm/annum)</th>
<th>Actual evapotranspiration (mm/annum)</th>
<th>Effective rainfall (mm/annum)</th>
<th>Subsoil permeability</th>
<th>Vulnerability</th>
<th>Minimum recharge class</th>
<th>Maximum recharge class</th>
<th>Specific yield range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land Commission 2</td>
<td>Rkd</td>
<td>32.43</td>
<td>974</td>
<td>432</td>
<td>542</td>
<td>0–3 m TLs/ KaRck</td>
<td>M</td>
<td>E h</td>
<td>h</td>
<td>0.01–0.02</td>
</tr>
<tr>
<td>Clomantagh Lower</td>
<td>Rkd</td>
<td>13.34</td>
<td>1083</td>
<td>432</td>
<td>651</td>
<td>3–10 m TLs/ KaRck</td>
<td>M</td>
<td>H i</td>
<td>h</td>
<td>0.01–0.04</td>
</tr>
<tr>
<td>Ardscull DW</td>
<td>LI</td>
<td>10.88</td>
<td>974</td>
<td>432</td>
<td>542</td>
<td>0–3 m TLs/ Rck</td>
<td>M</td>
<td>E h</td>
<td>h</td>
<td>0.03–0.04</td>
</tr>
<tr>
<td>Woodsgift</td>
<td>Rkd</td>
<td>9.08</td>
<td>1083</td>
<td>432</td>
<td>651</td>
<td>0–3 m TLs</td>
<td>M</td>
<td>E h</td>
<td>h</td>
<td>0.05–0.06</td>
</tr>
<tr>
<td>Masterson</td>
<td>Rkd</td>
<td>6.75</td>
<td>974</td>
<td>432</td>
<td>542</td>
<td>3–10 m TLs/ Alluvium</td>
<td>M</td>
<td>H i</td>
<td>i</td>
<td>0.02–0.06</td>
</tr>
<tr>
<td>Boston Co. Co.</td>
<td>LI</td>
<td>5.95</td>
<td>802</td>
<td>432</td>
<td>370</td>
<td>Rck</td>
<td>–</td>
<td>X h</td>
<td>h</td>
<td>0.04–0.06</td>
</tr>
<tr>
<td>Rahilla</td>
<td>Rg</td>
<td>2.06</td>
<td>802</td>
<td>432</td>
<td>370</td>
<td>Till with gravel</td>
<td>H</td>
<td>H h</td>
<td>h</td>
<td>0.13–0.16</td>
</tr>
<tr>
<td>Kilmeague</td>
<td>LI</td>
<td>1.57</td>
<td>802</td>
<td>432</td>
<td>370</td>
<td>Sand &amp; gravel</td>
<td>H</td>
<td>H h</td>
<td>h</td>
<td>0.16–0.21</td>
</tr>
</tbody>
</table>

1For aquifer category codes, please refer to Box 5.1.

H, High; M, Moderate; X, rock near surface or karst; E, Extreme; i, Intermediate.
greater than the version used; therefore, the calculated values of specific yield are likely to be overestimated.

The results of this simple analysis are reasonably similar to the $S_y$ estimates from Daly (1994). The estimates for MPs with small average annual groundwater level variations are slightly higher than expected values but are within an order of magnitude.

The values calculated for the Woodsgift and Clomantagh Lower MPs are significantly different, given their proximity and the similarity of their setting in the Nuenna Catchment. This difference may indicate the complex characteristics typical of karst hydrogeology.

7.2.3 Earthquake fluctuations

A number of GSI MPs registered significant groundwater level fluctuations due to the earthquake on 26 December 2004 off Sumatra (Fig. 7.11) (Wright, 2005). Similar effects were observed in two MPs in Northern Ireland (McConvey, 2005). This discovery prompted a review by Wright (2005) of all charts from these MPs and the responses to over 100 seismic events were discovered.

The Oldtown (Kny 18/92), Rathduff (Kny 27/58) and Knocktopher Manor (Kny 31/72) MPs all registered abrupt groundwater level fluctuations in the early hours of 26 December 2004. The maximum fluctuations observed in each borehole range from 50 mm in Oldtown, to 240 mm in Rathduff to 280 mm in Knocktopher Manor. A fluctuation of 335 mm was recorded in a Roscommon MP (Ros 14/91 at Aghaderry townland).

Water-level fluctuations in response to earthquakes are normally only detectable in confined aquifers, where the very low storage coefficient transforms the minute pressure changes into observable water-level fluctuations. Therefore, it is relatively surprising that water-level fluctuations were recorded in the shallow sand and gravel Oldtown MP (Wright, 2005).

Groundwater level charts since the 1980s were reviewed for the three boreholes in Counties Kilkenny and Roscommon. This revealed responses to earthquakes in the following countries: Indonesia, Philippines, Japan, Canada, United States of America, Siberia, Mexico, Peru, Chile, Colombia, Bolivia, Iceland and other parts of the Mid-Atlantic Ridge, Macquarie Islands, Taiwan, China, Central Asia, Iran, Pakistan, India, Turkey, Greece, Cyprus and Romania. In contrast, the review of three MPs in confined aquifers in County Cork showed no response to earthquakes (Wright, 2005).

These responses were recorded because the wells were monitored using chart recorders (OTT R16 recorders), i.e. a float connected to a pen which

![Image: Knocktopher Manor monitoring point’s groundwater level response to the 2004 tsunami.](image-url)

Figure 7.11. Knocktopher Manor monitoring point’s groundwater level response to the 2004 tsunami.
records variations in water level onto a chart on a rotating drum. Groundwater level monitoring in these boreholes is now recorded using a digital data logger. The loggers record at 15-min intervals and therefore they are very unlikely to record any similar responses in the future. In the Oldtown and Rathduff Boreholes, however, both recording systems operate simultaneously.

7.3 Trends in Long-Term Groundwater Levels

7.3.1 Climate change studies

A number of analyses have been carried out on the impact of climate change on precipitation and hydrology in Ireland (Kiely, 1999; Steele-Dunne et al., 2008; Kiely et al., 2010).

The results of the Steele-Dunne et al. study (2008) suggest an amplification of the seasonal cycle across Ireland, driven by increased winter precipitation, decreased summer precipitation and increased temperature.

Kiely (1999) used observations from eight climate stations and hydrometric stations on four rivers to analyse annual precipitation and the occurrence of extreme precipitation events in Ireland during the second half of the 20th century. He notes a change point evident in the mid-1970s for climate stations on the west coast (Valentia, Belmullet and Malin Head), after which there is increased rainfall. He also notes a change in the seasonal distribution of precipitation — most of the increase in annual precipitation was observed to come in the months of March and October, and an increased storm intensity was also observed in these months.

Kiely (1999) states that on the east side of the country there was almost no increase in the post-1975 precipitation. After the mid-1970s, however, there was a similar change in the seasonal distribution of precipitation as observed in the west, with increased precipitation in March and October, while other months experienced decreased amounts of precipitation. It should be noted that this analysis included data from the Wexford rainfall station but not from the Kilkenny station.

Kiely et al. (2010) repeated the analyses presented by Kiely (1999) with over a decade of additional data. The re-analysis showed evidence that change points in the annual total precipitation occurred for stations near the west coast: Belmullet, Claremorris, Malin Head and Valentia. Of these stations, the change points occurred between 1975 and 1978, with the exception of Belmullet, where the change point was determined to be in 1983. No significant change points were detected for stations in the remainder of the country, or for the Shannon station despite its proximity to the west coast.

An analysis of whether an equivalent change in behaviour is present in groundwater levels may not be possible due to the relatively limited duration of the groundwater level records in Ireland. In the west of the country, where a change in groundwater level behaviour is most likely to be observed, there are unlikely to be MPs with a suitable duration of record. For example, Wright (1994) documents that groundwater level monitoring in County Roscommon did not commence until 1978, County Kerry until the 1980s, County Limerick in the mid-1980s, and County Galway until the 1980s.

In the SERBD, there are a number of MPs which were established prior to the mid-1970s. The Rahilla and Kilmeague MPs were established in the late-1960s; however, up to the mid-1970s their records are ‘ragged’ and are likely to be influenced by pumping (see Section 7.1.7) so are not suitable. Other potentially suitable MPs (Land Commission 2, Tubbrid Lower, Boston Co. Co., Masterson and Ardscull) were established between 1969 and 1971 (see Table 6.1). On visual inspection, there is no obvious change in behaviour before and after the mid-1970s.

The timing of groundwater level minima and maxima were interrogated to investigate if the amplification of the seasonal cycle was evident in the SERBD groundwater level (Fig 7.12A and B). Increased rainfall in October and decreased rainfall in the surrounding months could refine the onset of autumn recharge observed in groundwater levels. Increased rainfall in March could prolong the recharge period and delay the onset of the recessionary period.

The month in which each groundwater level maxima and minima occurred was obtained from the five MPs...
Figure 7.12. Average date of (A) groundwater level maxima and (B) groundwater level minima per decade.
with suitably long records. A comparison of the timing of maxima and minima was made for before and after the mid-1970s. The typical month was defined as the month with most turning points occurring in it; no averaging over months was conducted and only constrained turning points were included.

The results showed that there has been very little change in the timing of the groundwater level maxima for these MPs. The groundwater level minima tentatively showed a refinement in timing from a range of August to November before 1975 to a smaller range from September (one MP) to October (four of five MPs) after 1975. It should be noted that this is a basic analysis conducted with a limited data set, especially prior to 1975.

A further test was conducted to investigate any change in timing on a finer scale. The date (rather than just the month) of each constrained turning point was assessed for all 15 MPs. An average date was determined for each MP’s minimum and maximum groundwater levels for the duration of the record and for each decade within the record. A consistent change in the timing of either the groundwater level maxima or minima was not observed (Fig. 7.12A and B). The results for the five MPs investigated previously did not show a refinement in the timing of the groundwater level minima. The range in the timing of turning points within one decade was generally much larger than the averaged variation in groundwater levels between decades.

7.4 Interactions between Groundwater and Surface Water

Additional analysis of the Oldtown hydrograph was conducted to investigate the groundwater–surface water interactions at this site. The MP is located in the regionally important Kilmanagh Gravel Aquifer which overlies the Pl Killeshin Siltstone Formation (Namurian Shales), approximately 10 m from an unnamed tributary of the Munster River.

The geological and construction logs for the Oldtown Borehole are presented in Fig. 7.13. These logs are likely to be for the pumping well at Oldtown (Kny 18/93) as the drilling log for the observation well at Oldtown (Kny 18/92) only states “large, medium, fine boulder gravel with coarse, medium sand and occasional traces of silty clay bands” and “no samples as it is just for observation” (GSI well records). It is expected that the geological conditions will be similar between the two boreholes.

The Oldtown hydrograph shows a number of recharge and recession periods within one hydrometric year. On a number of occasions the groundwater level annual minima plunge below the level normally reached in autumn. This is seen in 1984, 1989, 1990, 1995, 1996 and 2002 (Figs 7.5 and D.9). On closer inspection of the hydrographs, it may be seen that the point from which the water level plunges on each of these occasions is at a constant level of 116.2 maOD. This suggests that the plunging groundwater levels have a physical control. The proximity of the river and the nature of the Oldtown hydrograph suggest that this control is likely to be related to the river.

There is a weight of evidence to support the idea that the physical control is the base of the river, and that when the river runs dry the groundwater levels drop rapidly:

- 1984, 1989, 1990 and 1995 were ‘dry’ years with rainfall being much lower than average which could lead to low river flows; 1996 and 2002, however, were ‘wet’ years, where rainfall was higher than average (see Fig. 2.2).

- The EPA has two surface-water hydrometric stations near to the Oldtown MP, the details of which are outlined in Table 7.6. The stations record water level with monthly to quarterly frequency. The Ballyline station shows a number of water levels at 0 m in 1984 and 1989 (on 6 July 1984, 29 August 1984, 31 July 1989 and 28 September 1989). The Kilmanagh station does not record any zero levels but it is likely that if the water level in the larger river at Ballyline is zero then the water level at Kilmanagh is also zero. No zero levels are recorded at either station after 1989, although dry spells may not have been recorded.

- Notes on the groundwater level charts in 1984 (26 July, 19 September and 24 October), 1989 (12 August and 19 October), 1990 (11 October), 1995 (22 August and 13 October) and 1996 (24
September and 22 October) state that the river was dry. There are no similar notes in 2002. On 1 November 1984 a note states “the farmer says river dry at 10 am but there was water in it at 11.00 am”; it also notes that the river was dry “at least 200 yards downstream” of the MP. The water level is seen to increase rapidly after 1 November 1984.

- Measurements taken on 18 June 2009 are shown in Figure 7.13. They show that the river bed is approximately 2 m below the groundwater level datum and therefore at an approximate elevation of 116.4 mAO. These measurements are very rough and therefore could be 20 cm out, thus allowing the river bed to be at an elevation of 116.2 mAO and coincident with the level observed on the hydrograph. The most likely physical control at this level is the river bed.

7.4.1 Future data analysis

7.4.1.1 Groundwater level response to ER

A preliminary investigation into the response times of a number of hydrographs to individual storm events has been carried out. The recent data from the Woodsgift, Oldtown, Rathduff and Knocktopher Manor MPs were used, as these records are at a high resolution and are relatively continuous. The preliminary findings showed
that the response time increased as the permeability of the subsoil decreased. Further investigations are suggested to develop the understanding of water level responses and subsoil properties.

7.4.1.2 Groundwater levels and spring discharges
The EPA is in the final stage of installing flow monitoring systems on 27 springs around the country. In the SERBD, the following springs are included in the network: Kyle, Paulstown, Pollardstown Fen and Hangedman’s Arch (see Table 6.2). Once the data are available from these sites, it will be possible to analyse spring discharge with respect to groundwater levels.

7.4.1.3 Abstraction-influenced MPs
An analysis of groundwater levels influenced by abstraction is suggested. Figure 7.15 presents the groundwater abstractions for drinking water to give an indication of which MPs are likely to be affected.

7.4.1.4 Long-term trend analysis
A visual inspection of all the SERBD historic groundwater levels for any long-term trends generally showed that there are no overall increasing, or decreasing, trends. The exception is the Oldtown hydrograph, which shows a long-term decrease in groundwater level over its duration of record from the 1980s to the present (Figs 7.5 and D.11). Time-series analysis could be conducted on hydrographs with long-term trends. This analysis may involve the use of Box–Jenkins transfer noise modelling, which allows the hydrograph to be split into a number of components related to known causes (e.g. ER, abstraction, etc.) and an unknown noise component (van Geer and Zuur, 1997).
Figure 7.15. Groundwater abstractions for drinking water in the South Eastern River Basin District.