Ref.	Location	ITM	Date	Approx. distance to Mullenmore	First Arrival Peak Time base	Velocity	Comment 1= high resolution sampling; 2= moderate; 3 = low
Sink 1	Upstream of Ballycarroon gauge Right bank	512024 815893	10.5.17	2300m	N 15h/23h/ 100h S 15h/ 22h/ 75h	145 m/h	Q? <60 l/s but maybe much less? Single peak Mull Q 700 **1**
Sink 2	Upstream side of rapids u/s of Pollgorm Right bank	512254 816174	19.4.17	2200m	N 15.6h/ 20h/122h S 15h/19h/145h	150	Q c.5 l/s Mull Q 875 **1**
Sink 5	Pollgorm, opposite cave 2 Left bank	512322 816178	19.4.17	2000m	N 17h/ 20h/ 42h S 21h/ 30h/ 71h	118	Mull Q 875 **1**
Sink 7	Pollgorm Cave 3 (Cleft) Right bank	512358 816157	25.10.16	2000m	6-14h/?/ c.60h	100-300 m/h	Sink always active Stage 0.31 **2**
Sink 9	150m d/s of Pollgorm caves Right bank	512424 816226	28.11.16	1900m	7-13h/13-20h/ 42h	150-270	Inactive below stage c.0.5 **2**
Sink 12	On outside of bend (Mackey's bend) upstream from Pollnacross Right bank	513148 816570	28.11.16 and 19.4.17	1200m	<7h/7+h /70-77h and N 6.5h/ 7.7h/ 20h S 6.8h/ 7.7h/ 17	>170 m/h /184 m/h	Inactive with stage below c.2.3 Traced twice **1, 1**
Sink 13	Lough Agawna sink		6.9.16	4500m	<4 days/<11 days time base	<100 m/h	Detectors only, so only very approx. values to Mullenmore **3**

Table 7A.5 Summary of Dye Tracing Results to Mullenmore Springs *(continued overleaf)*

Ref.	Location	ITM	Date	Approx. distance to Mullenmore	First Arrival Peak Time base	Velocity	Comment 1= high resolution sampling; 2= moderate; 3 = low
Sink 14	Dye injected into a standpipe inserted into the river bed at the upstream bend at Pollnacross Left bank	513330 816846	17.7.19	900m	40h/ 50-60h/ >100h *	30 m/h	Q c.40 l/sec Multiple peaks ** Mull Q 1,000 **1**
BH 32	Borehole 32 at Pollnacross Right bank	513329 816845	17.7.19	900m	40h/ 50-60h/ >100h *	30 m/h	Multiple peaks ** Mull Q 1,000 **1**
BH 34	Borehole 34 at Pollnacross Right bank	513443 816813	24.7.19	900m	9h/ 14h/ 45h	105 m/h	Mull Q 1,000 **1**
Collapse Doline	Collapse Doline at Pollnacross Right bank	513438 816801	24.7.19	900m	10h/ 19h/ c45h	90 m/h	Mull Q 1,000 **1**

* *Fluorometer not installed at North Spring. The river was dry at this location until c. 6 hours after tracer input and the times given assume no transport of the tracer occurred until the river was flowing. Between c. 50 and 85 hours after input no data are available from the fluorometer at the South Spring so the initial peak concentrations of tracer have to be inferred from the rising and falling limbs.*

** *Multiple peaks are attributed to varying river flows, response to rainfall on 21/22 July and the overlap with the injection of tracer on 24 July 2019.*

Table 7A.5 Summary of Dye Tracing Results to Mullenmore Springs *(continued from previous page)*

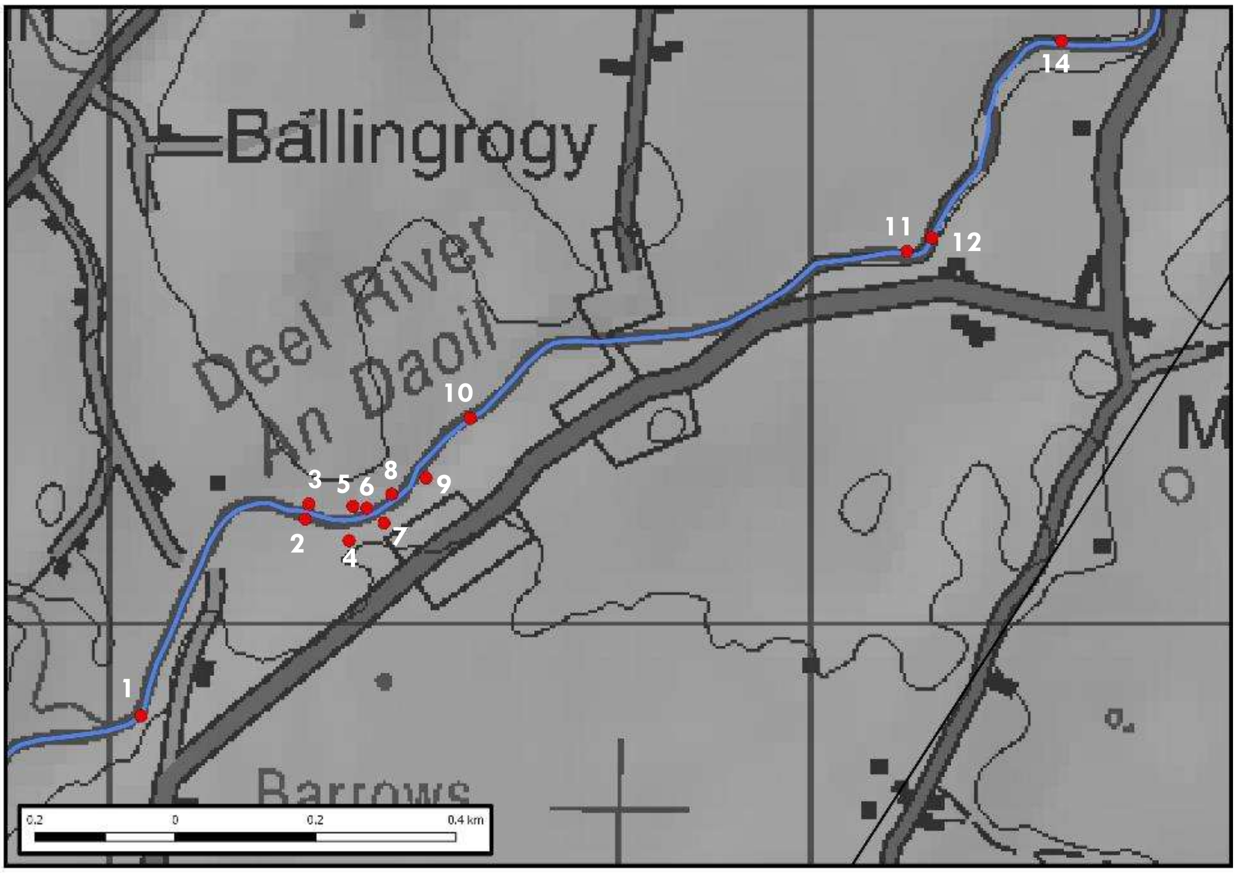


Figure 7A.16 Sinks located along River Deel between Ballycarroon and Crossmolina Town

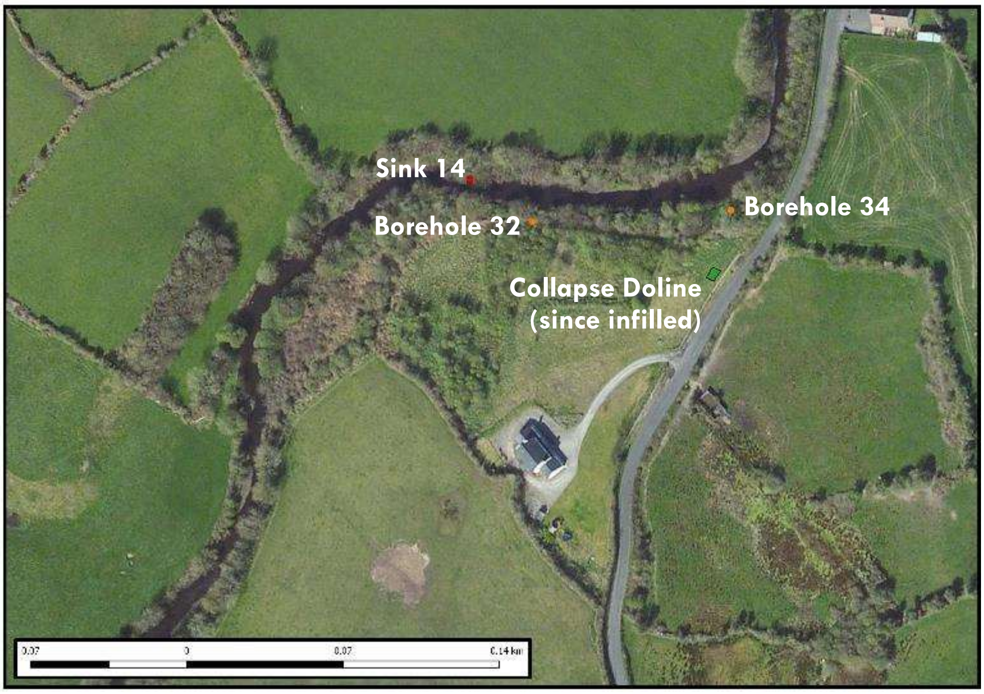


Figure 7A.17 Locations of Tracer Tests carried out at Pollnacross in July 2019

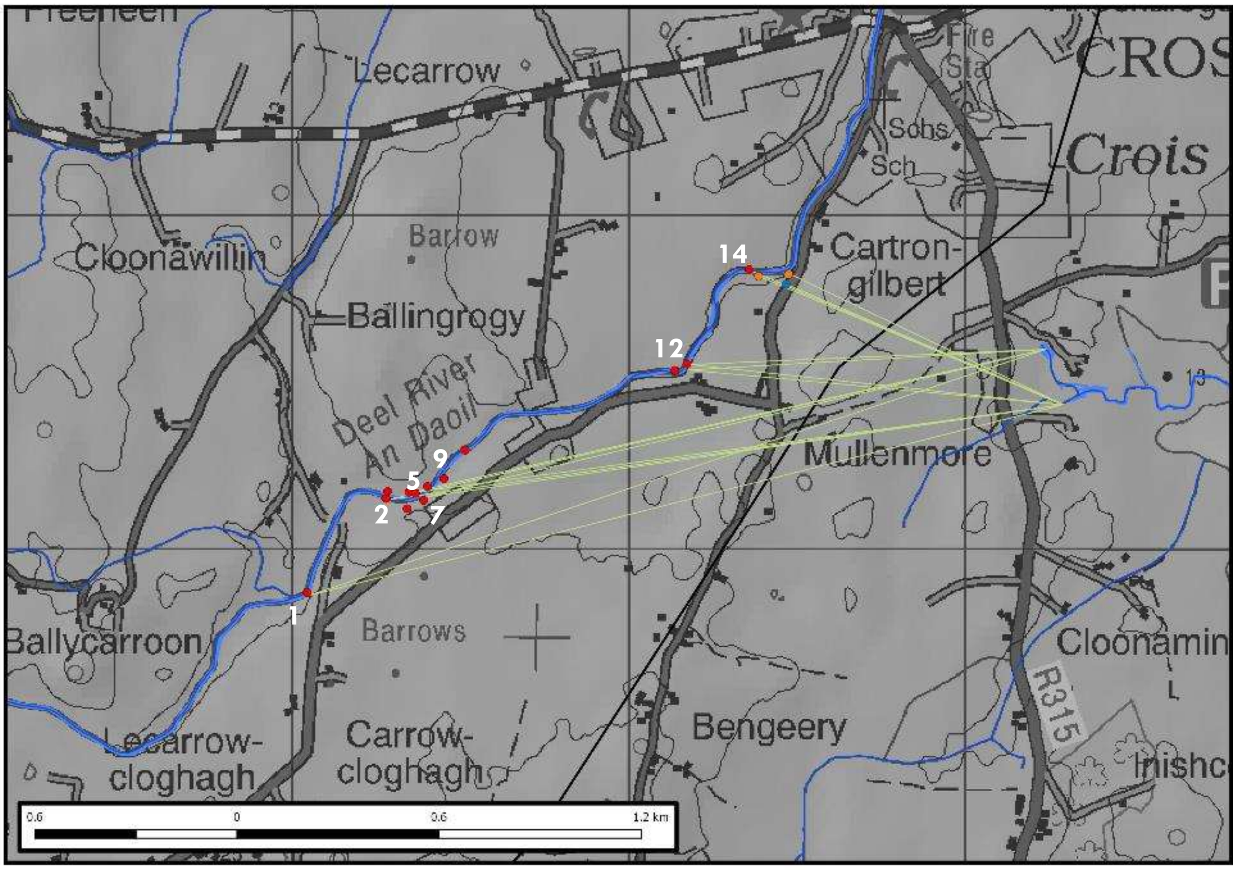


Figure 7A.18 Dye Tracer Lines with Sinks numbered (Lough Agawna Tracer not shown on GSI map viewer)

7A.4.9 Cave Entry Survey

A caving expedition took place on Friday 30/12/16 at Pollgorm.

Four caves were entered as part of the survey. These are labelled 1A, 2, 3 and 4 in Figure 7A.19. Caves 2 and 3 are connected. The caves were not explored further due to access issues (collapses/ passages dropping below water levels).

Cave 1B was inspected at the surface but found to be clogged with sediment and access was not deemed possible. Plate 7A.7 shows caves 2 and 3 viewed from the opposite river bank. Plate 7A.8 shows the rock overhanging Cave 1B.

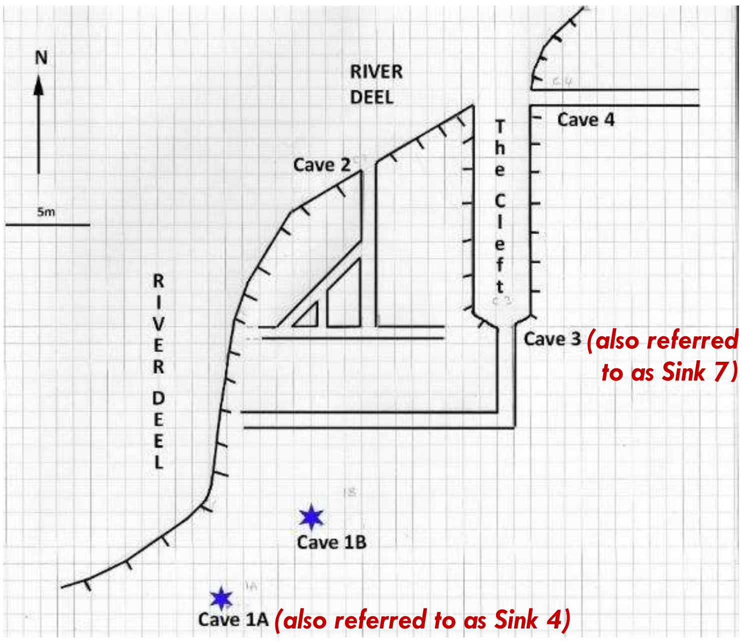


Figure 7A.19 Caves at Pollgorm

These caves form part of the karst drainage conduits that are now utilised only at high water levels (and hence are accessible for exploration) but they are probably representative of the conduits that are always active and which lie at a lower elevation and are therefore always water filled.

As can be seen from Figure 7A.19, the cave conduits (in the limited area surveyed) form a grid network developed along the major joint systems, N-S and E-W.

Plate 7A.7 Caves 2 & 3

Plate 7A.8 Cave 1B

Plate 7A.9 Aerial view of Pollgorm

7A.4.10 Lough Conn Mapping

Inland Fisheries Ireland (IFI) carried out a bathymetric survey on 11, 12 and 17 August 2016 using Lowrance LMS 334 sonar equipment under challenging conditions. The survey indicates that the lake bed drops to c30m below OD. The lake bed levels are shown on Figure 7A.20. The inverts of the Mullenmore Springs are located at 0.37 mOD (Northern Springs) and 3.36 mOD (Southern Spring).

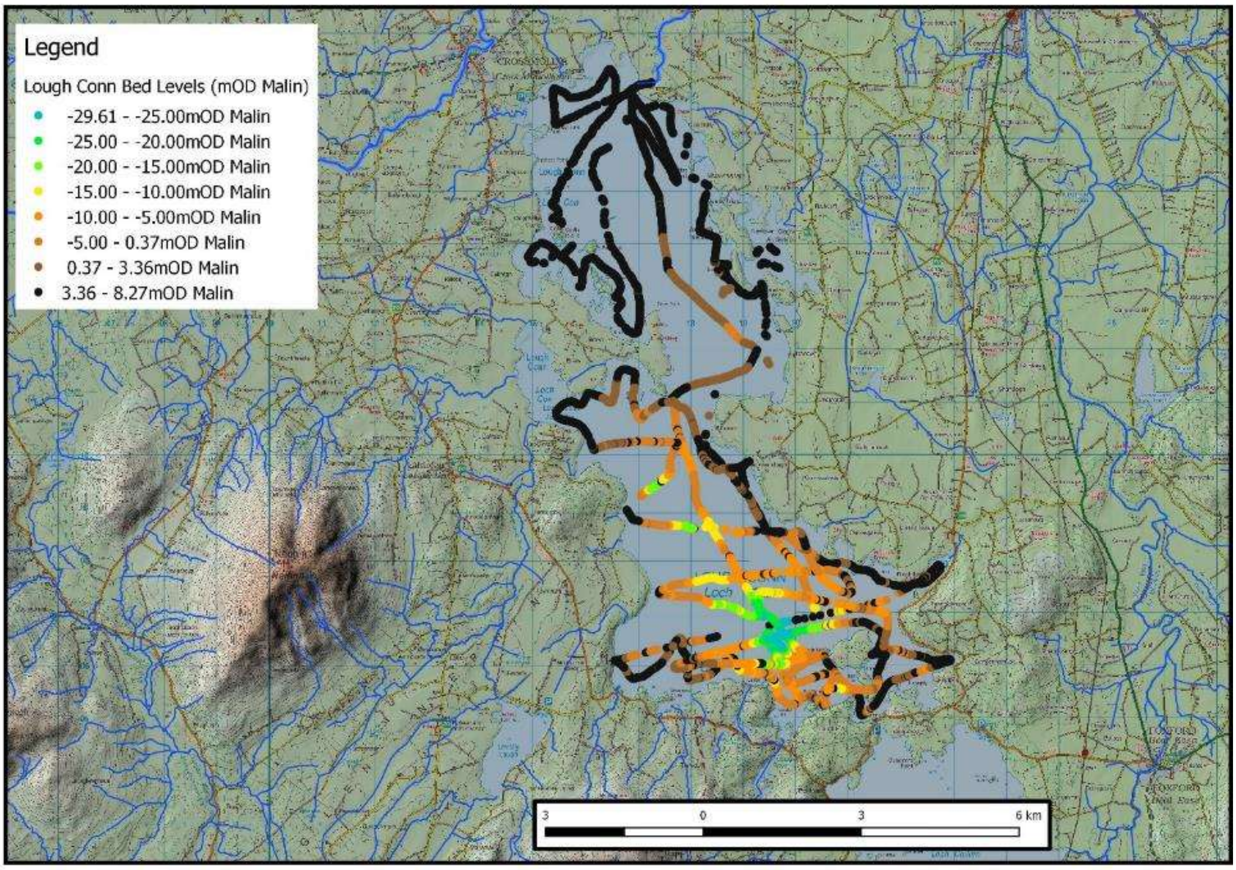


Figure 7A.20 Lough Conn Bathymetry

Thermal imagery for Lough Conn was provided by Trinity College Dublin to inform the Stage 2 Investigation. A desktop assessment of the thermal imagery and radon mapping indicates that the groundwater discharge through the lake bed is likely concentrated in the southern eastern corner of the lake. There is no evidence for groundwater discharge into the lake in the vicinity of the Mullenmore Springs or in the remainder of the NW part of the lake. This reinforces the idea that the Mullenmore Springs are the sole outlet for the water sinking in the River Deel.

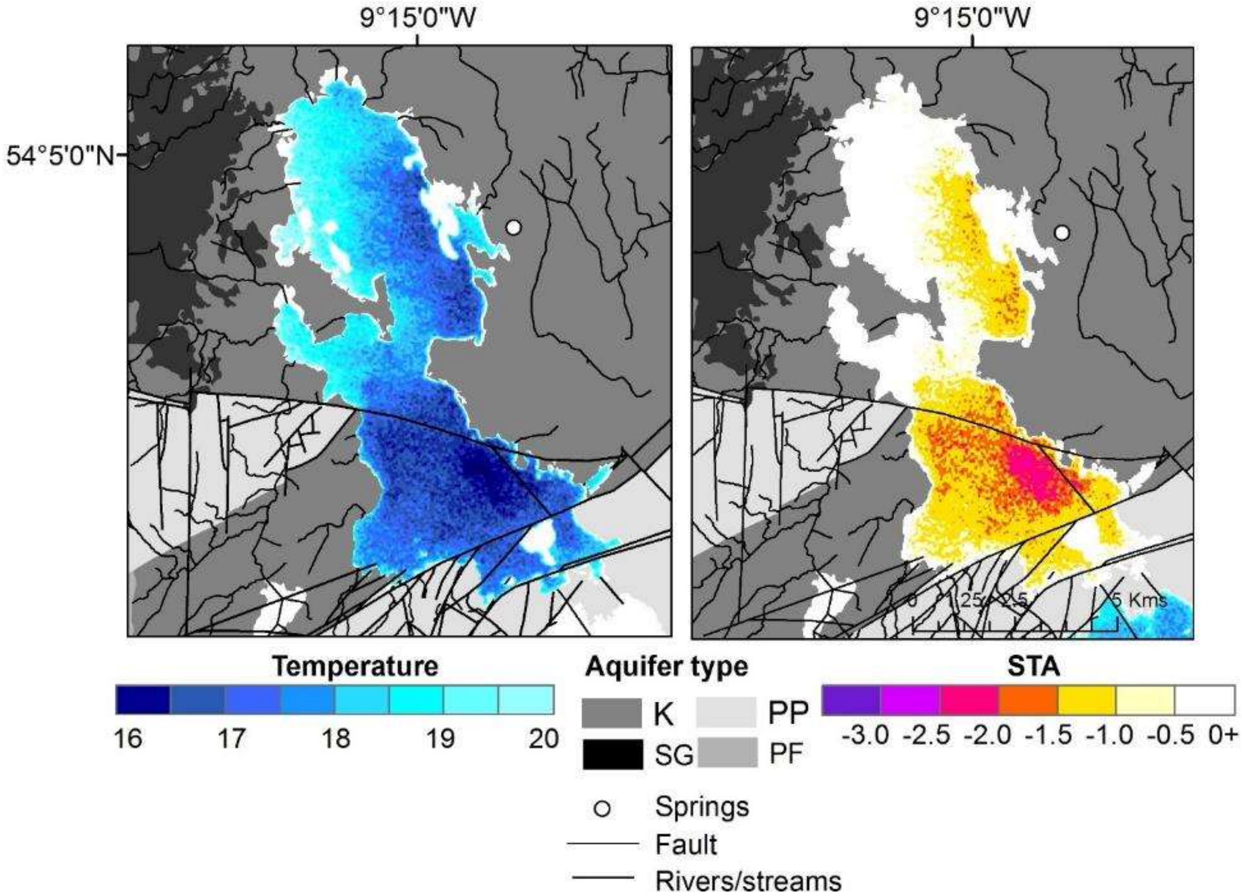


Figure 7A.21 Thermal Imagery and Radon Mapping for Lough Conn (credit Jean Wilson, Trinity College Dublin)

7A.5 Results

The main karst features identified between the River Deel and the Mullenmore Springs are summarised in Figure 7A.22.

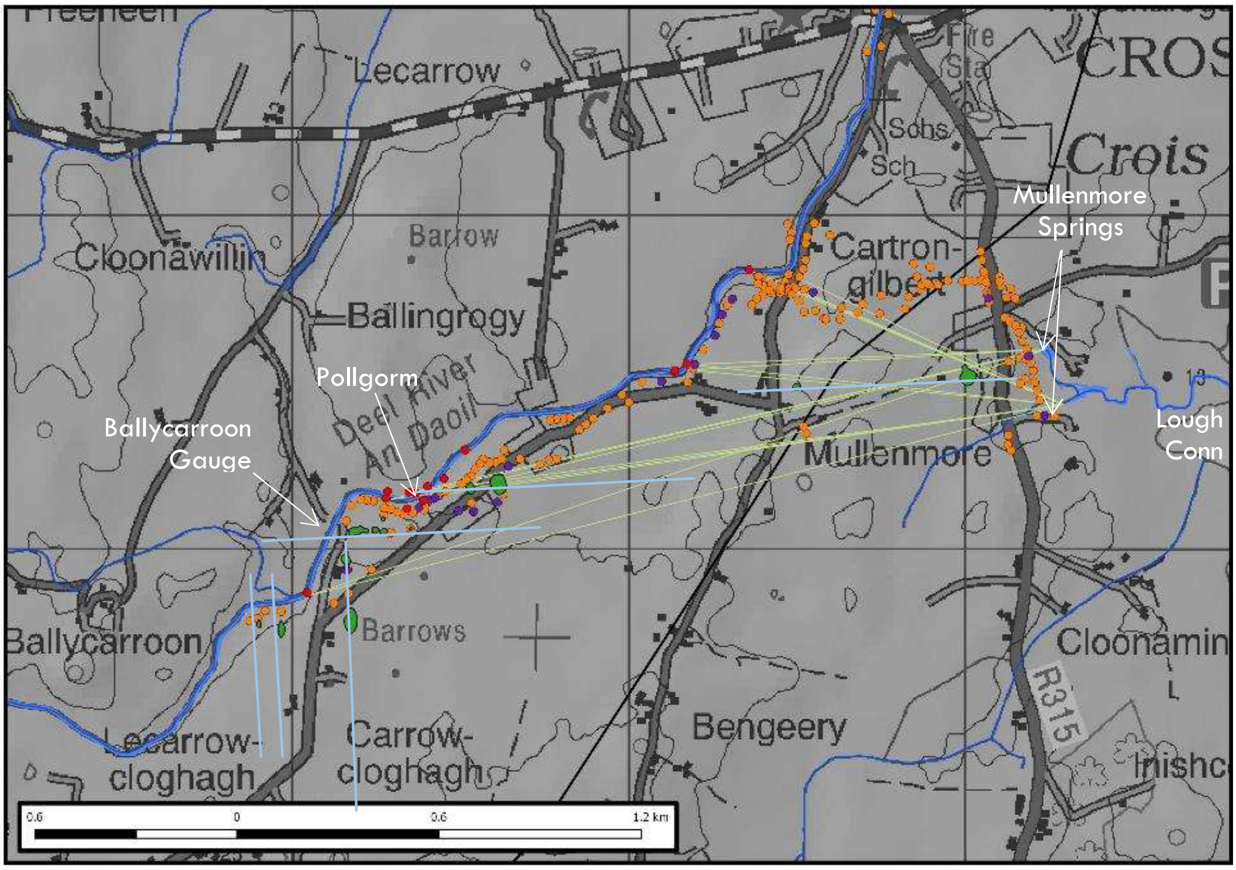


Figure 7A.22: Summary of Karst Features and Investigation Results

Notes on Figure 7A.16:

- Geotechnical investigation points shown in **orange**
- Geotechnical investigation points shown in **purple** where voids were encountered
- Dolines shown in **green**
- Sinks along River Deel shown in **red**
- Dye tracer lines shown in **light green**
- N-s & E-W axes of dolines shown in **light blue**

Stage 2 concluded following the investigation into the collapse doline at Pollnacross in September 2019 with the following outcome:

7A.5.1 Groundwater Systems

Two groundwater systems are present in the area to the South of Crossmolina:

1. A superficial part of the aquifer in the poorly/moderately sorted sand and gravel deposits that overlie bedrock to a depth of <25m and extend over the greater part of the lower Deel catchment. Recharge is diffuse and south of the Deel the few known discharge sites are via small and medium-sized springs such as that at Tobernagowna. To the south-west an area of maximum 4km^2 of sand and gravel terrain probably drains directly to the Mullenmore Springs with the contribution to spring outflow becoming particularly significant at low flow levels.
2. A karstified bedrock part of the aquifer in the Carboniferous limestone which is recharged via swallow holes in the River Deel channel and the sinking stream draining Lough Agawna. The only known outlet for these waters is the springs at Mullenmore.

Both groundwater systems operate within the same aquifer and are interconnected. They are described separately above only to distinguish their distinctly different hydrogeological characteristics. Based on available data, the water table is observed to lie permanently in the sand and gravel aquifer.

7A.5.2 Swallow Holes

Four groups of swallow holes have been located in the Deel channel:

1. On average some 300 l/s sinks at the most upstream known sink (c. 150m upstream of the Ballycarroon gauge), c. 25% of the total loss of groundwater when all the sinks in the Deel are operative.
2. Between chainages 200-700 downstream of Ballycarroon gauge and dominantly in the area known as Pollgorm. Most swallow holes are on the right bank of the river but some are located on the left bank. Some 60% of the total water lost to groundwater sinks in this reach (c. 450-700 l/s on average).
3. In the vicinity of chainage 1200, south of Pollnacross a single swallow-hole engulfs c.12% of total sinking water (on average c. 150 l/s).
4. At Pollnacross, a swallow hole discovered in 2019 within the riverbed at the outside of a bend on the left bank of the river engulfs c. 40 l/s.

As flow in the River Deel declines so the sinks become progressively dry upstream. Under very low water conditions only a small quantity of water sinks at Pollgorm and probably only the sink up stream of Ballycarroon gauge is perennial.

Flow velocities from sinks to the Mullenmore Springs are within the range 100-200 m/h, comparable to velocities recorded at many other karstic systems in lowland western Ireland.

The relatively short time base for tracer (the underground residence time of the tagged water) for all tracings is short and clearly defined, implying that the karst flow system is efficient with little attenuation occurring.

7A.5.3 Mullenmore Springs:

There are 2 springs at Mullenmore but prior to local drainage it is likely that there was just one large water body incorporating two or more groundwater discharge zones. Overall outflow averages c. 960 l/s with an apparent maximum discharge of c.1100 l/s., <150l/s more than the inflow from the Deel sinks.

The more northerly spring contributes c.35% of total spring outflow and the more southerly spring, 200m distant, c.65%. In terms of conductivity the two spring waters seem very similar and most probably derive their water from a single conduit or group of conduits. The southern spring pool is 8.5m deep and the northern spring has been plumbed to a depth of 12.5m – almost datum. No discrete groundwater inflows to the spring pools have been detected suggesting that the bedrock conduits are partly blocked with transported sediment (sands) at the downstream end of the groundwater flow system.

7A.5.4 Doline landforms

Enclosed hollows <15m, <40m in diameter, in depth and typically steep-sided) occur on the south and east side of the River Deel.

The most actively developing (subsiding) dolines have a close association with the known swallow holes and are commonly in lines orientated either north-south or east-west. Further away from the river, dolines are less evident except in the area immediately to the west of the Mullenmore Springs. The most developed doline lines are apparently not directly associated with known active swallow holes.

Collapse dolines have been known to form in the general area based on anecdotal information, however they are often filled in by landowners soon after forming. One such doline which developed in Q4 2018 at Pollnacross, demonstrates that there is potential for re-activation of dormant underground conduits in the karstified limestone within the study area.

7A.5.5 The Main Karstic Groundwater Flow System:

The highly karstified groundwater flow system is localised and comprises the 2,200m reach of the Deel channel containing swallow holes and the area to the east and north-east focussing on the Mullenmore Springs. Groundwater flow is probably concentrated in conduits developed along the strike of the limestone strata, as this would offer the most efficient route from sink to spring.

Data from stage in the River Deel and at Mullenmore springs suggests that the conduit system is probably completely water filled over at least half of its length.

There is no evidence for the existence of a single large karst conduit feeding the springs, but rather a set of small conduits originating at each swallow hole and uniting close to the springs. A total conduit cross sectional area of <2m^2, however derived, is probably sufficient to conduct the observed groundwater flows.

No evidence has been found that water sinking in the Deel discharges at any location (e.g. the bed of Lough Conn) other than the Mullenmore Springs and it is likely that in the past the Mullenmore Springs, located at the eastern margin of the sand and gravel subsoils, emerged on what was then the western shoreline of Lough Conn.

The groundwater flow system is constricted adjacent to the Mullenmore Springs presumably due to sediments mobilised by the rapidly moving groundwater periodically and/or partially blocking the lower end of the bedrock conduits.

7A.5.6 Hydrogeological Impacts of a Diversion Channel:

The proposed routes for the diversion channel are located to the north and east of the zone of concentrated groundwater flow between the Deel sinks and Mullenmore Springs.

A diversion channel located north of Pollnacross is unlikely to encounter the main karst flow system but will probably interact with groundwater in the sand and gravel and possibly the upper bedrock.

The River Deel may have originally pursued a course to the east from the Pollnacross area, directly to Lough Conn via a route which is now partly obscured by glacial deposits.

7A.6 Recommendations

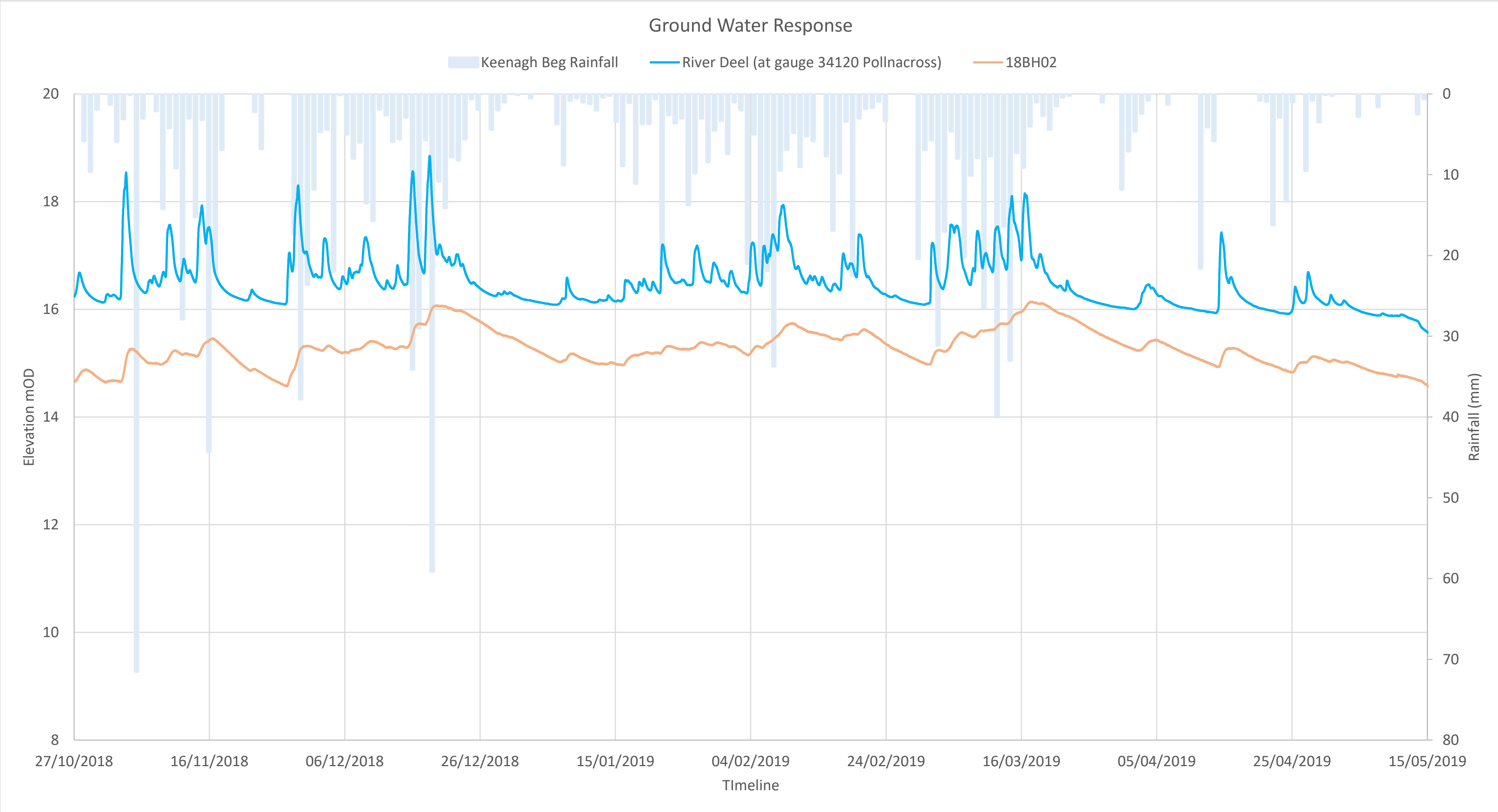
Following conclusion of the Stage 2 assessment, the following is proposed:

- Observation boreholes have been installed adjacent to the channel route and also near the springs with sensors to continuously monitor groundwater conductivity and stage as set out above. This will allow OPW to determine the local hydrogeology of the subsoils and bedrock and the possible impacts of a channel on the hydrogeology to be estimated. It is recommended that where these monitoring points are within the channel footprint, new monitoring points be established in advance of construction works so that data collection can continue during and subsequent to channel construction, with installation of new standpipes as required to replace standpipes disturbed or removed in the course of constructing the scheme.
- The size and location of the direct contribution area to the Mullenmore Springs should be determined particularly in relation to the course of the overflow channel.
- Care should be taken if excavations take place close to the Mullenmore Springs in case the outlets are enlarged/unblocked thereby potentially allowing more water to flow through from the Deel.
- Similarly, care should be taken where excavations take place close to the River Deel in the Pollnacross area.

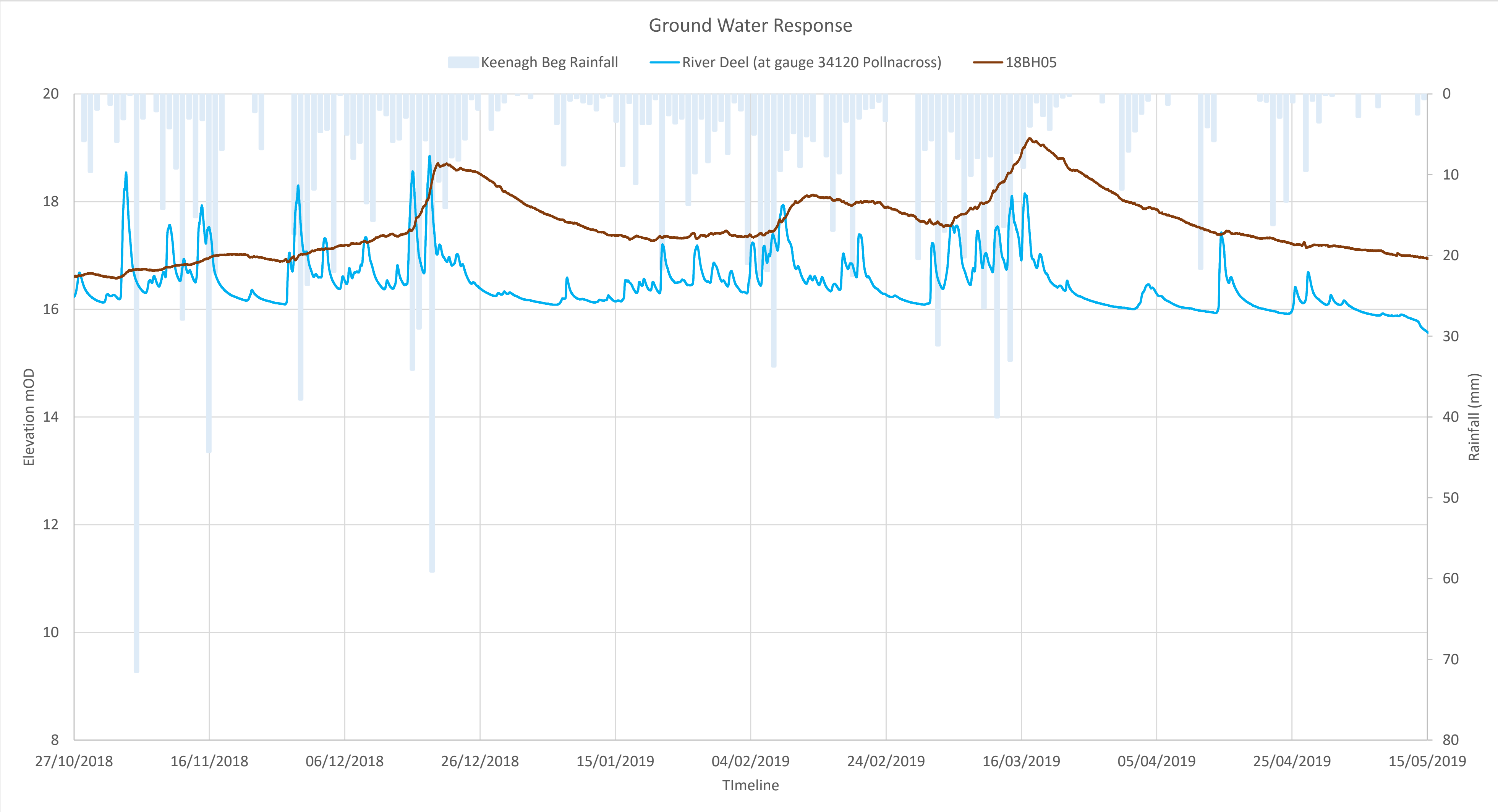
KARST HYDROGEOLOGY ASSESSMENT

APPENDIX 7A (I)

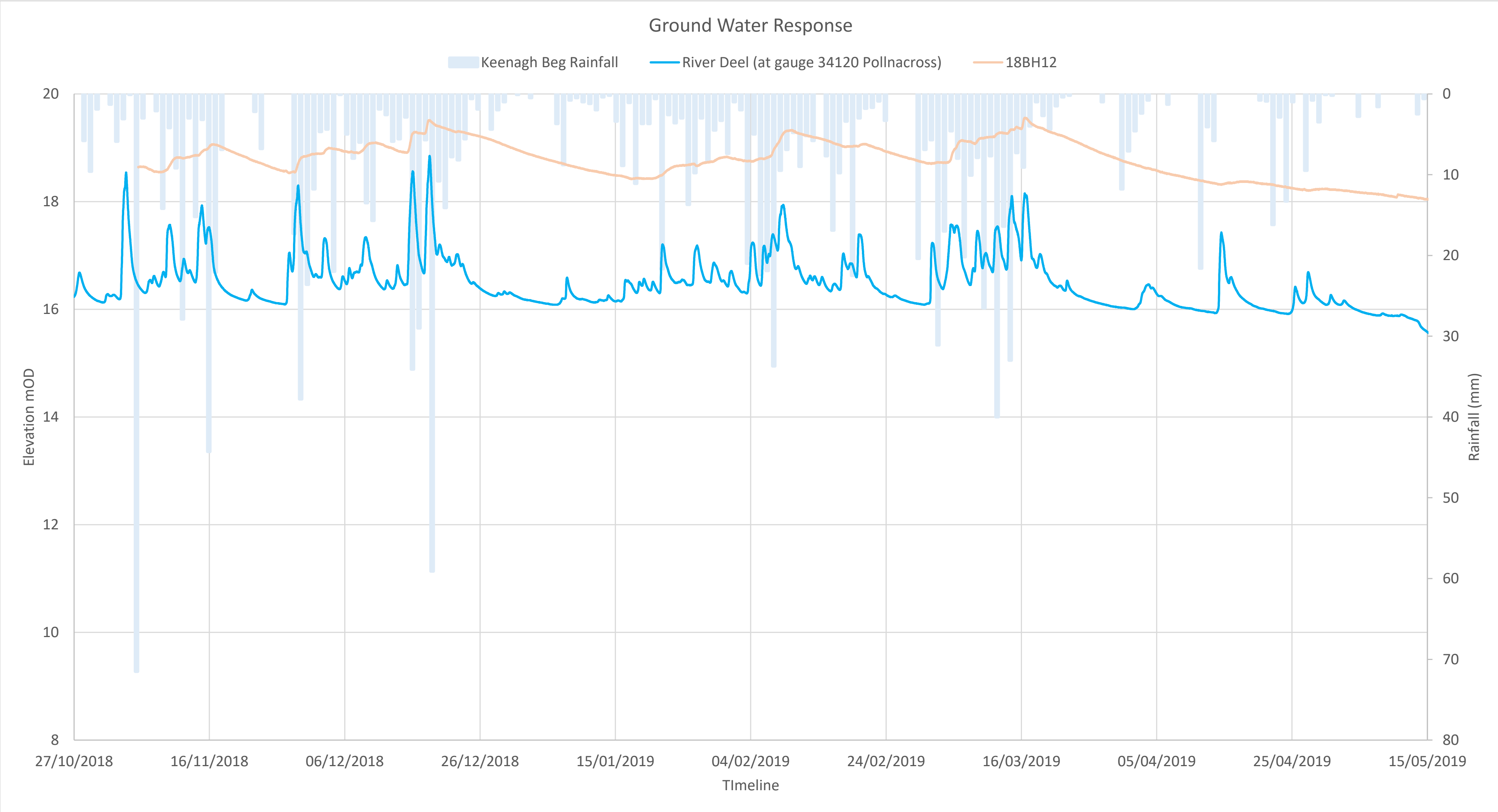
(GROUND)WATER LEVEL AND CONDUCTIVITY GRAPHS

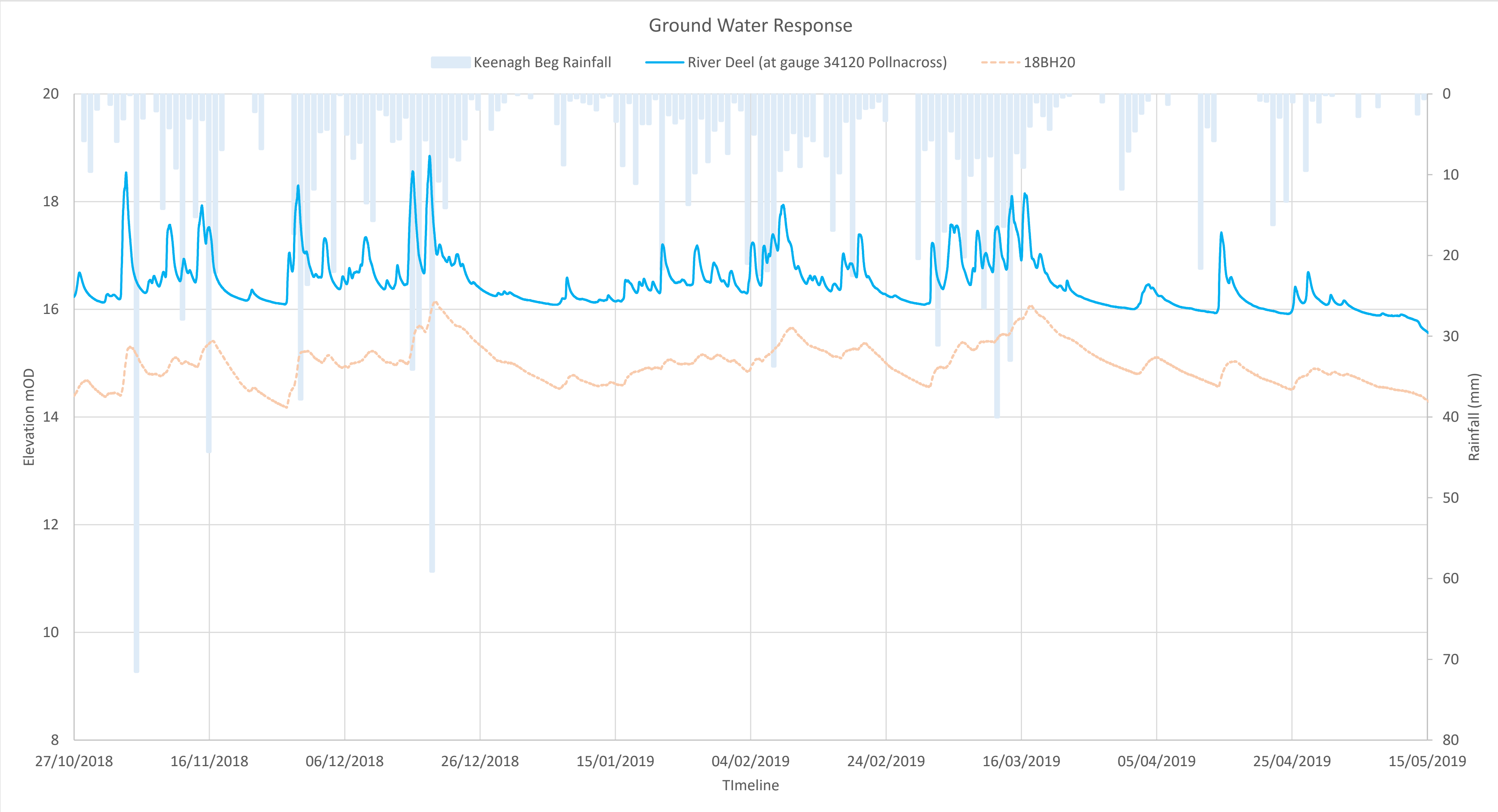


Ground Water Response
Keenagh Beg Rainfall
River Deel (at gauge 34120 Pollnacross)
18BH02
Elevation mOD
Rainfall (mm)
20
18
16
14
12
10
8
0
10
20
30
40
50
60
70
80
27/10/2018
16/11/2018
06/12/2018
26/12/2018
15/01/2019
04/02/2019
24/02/2019
16/03/2019
05/04/2019
25/04/2019
15/05/2019
TImeline

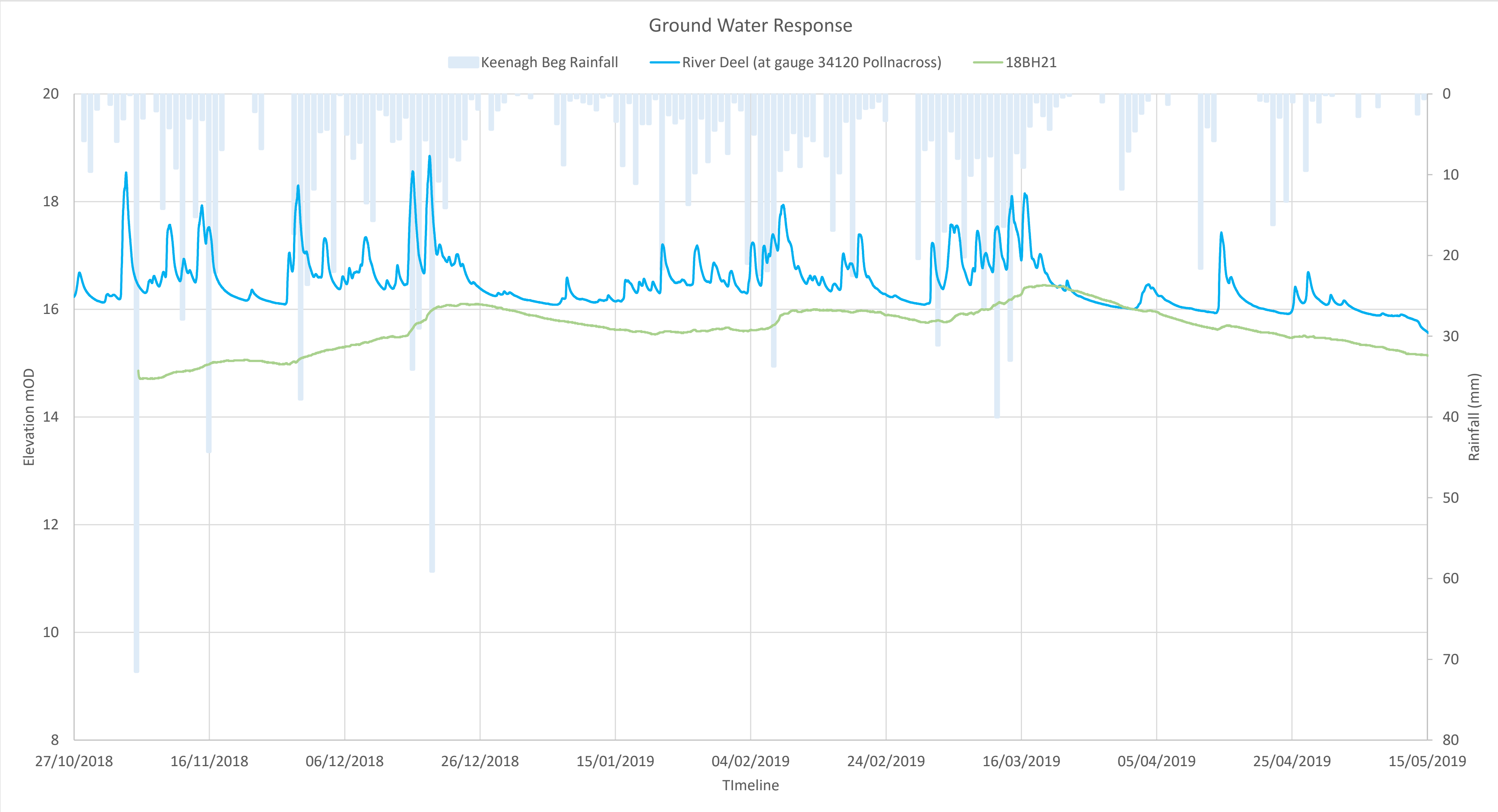


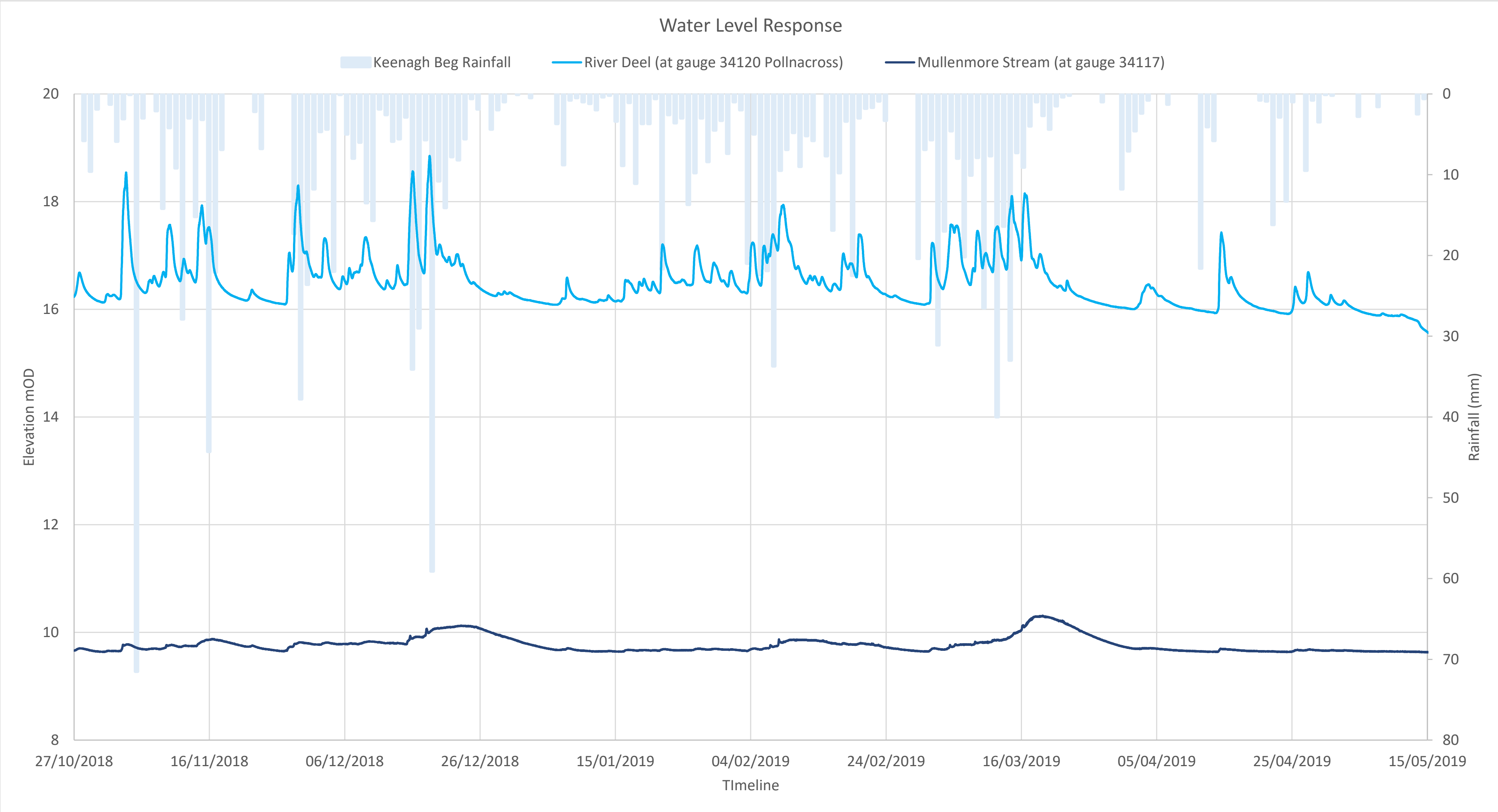
Ground Water Response
Keenagh Beg Rainfall
River Deel (at gauge 34120 Pollnacross)
18BH05
Elevation mOD
Rainfall (mm)
20
18
16
14
12
10
8
0
10
20
30
40
50
60
70
80
27/10/2018
16/11/2018
06/12/2018
26/12/2018
15/01/2019
04/02/2019
24/02/2019
16/03/2019
05/04/2019
25/04/2019
15/05/2019
TImeline


Ground Water Response
Keenagh Beg Rainfall
River Deel (at gauge 34120 Pollnacross)
18BH12
Elevation mOD
20
18
16
14
12
10
8
Rainfall (mm)
0
10
20
30
40
50
60
70
80
27/10/2018
16/11/2018
06/12/2018
26/12/2018
15/01/2019
04/02/2019
24/02/2019
16/03/2019
05/04/2019
25/04/2019
15/05/2019
TImeline

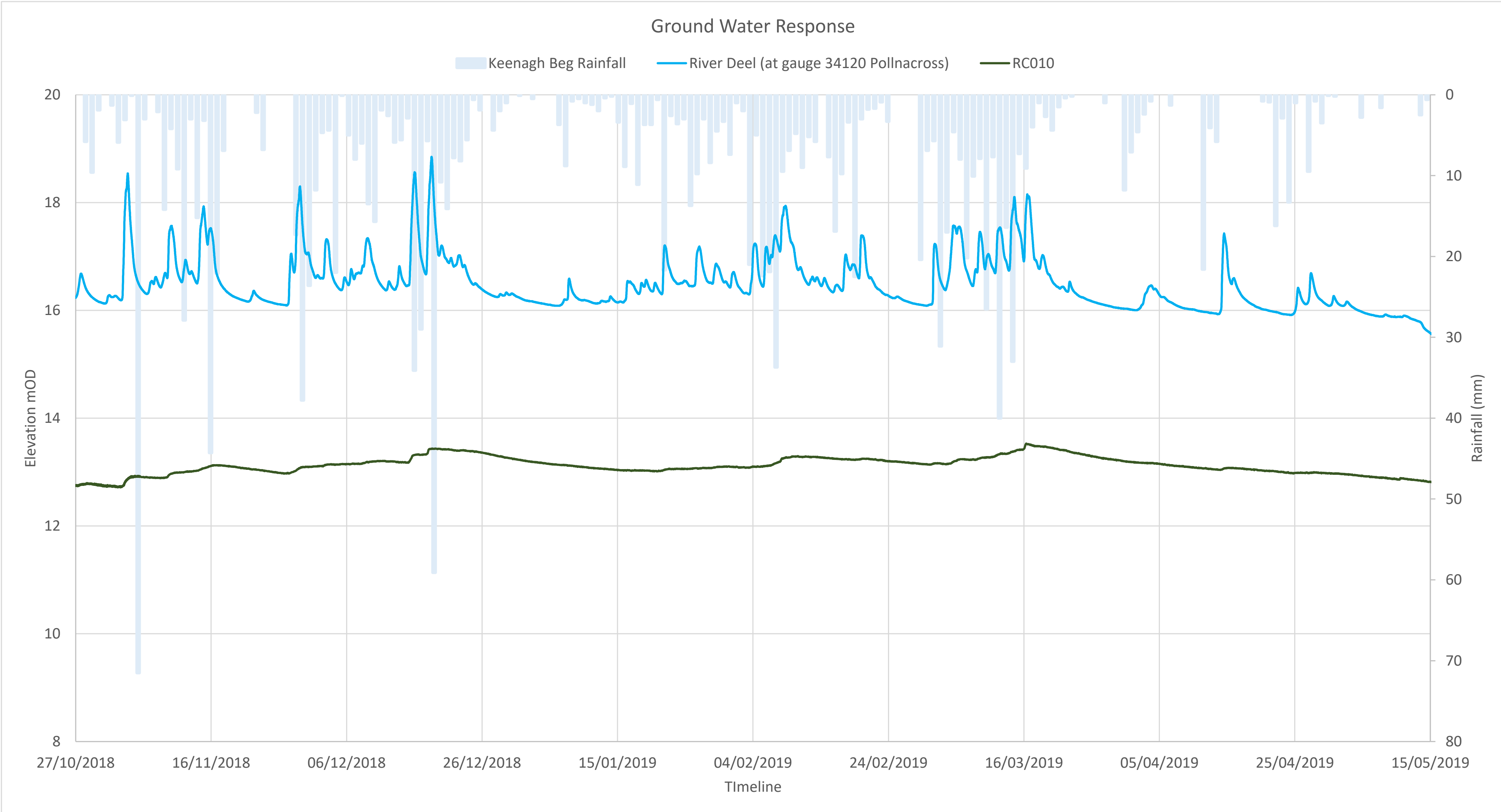


Ground Water Response
Keenagh Beg Rainfall
River Deel (at gauge 34120 Pollnacross)
18BH20
Elevation mOD
Rainfall (mm)
20
18
16
14
12
10
8
0
10
20
30
40
50
60
70
80
27/10/2018
16/11/2018
06/12/2018
26/12/2018
15/01/2019
04/02/2019
24/02/2019
16/03/2019
05/04/2019
25/04/2019
15/05/2019
TImeline

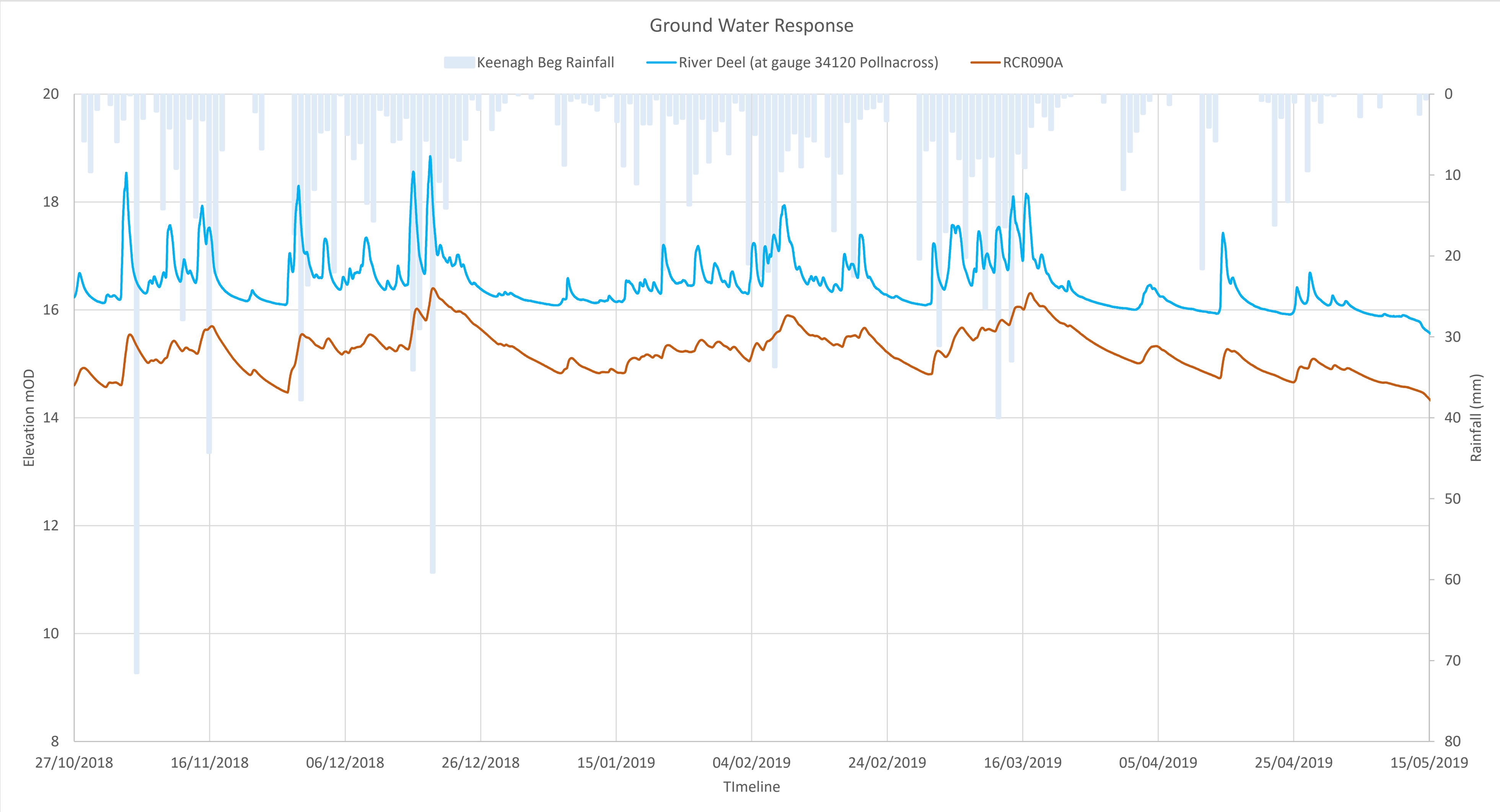

Ground Water Response
Keenagh Beg Rainfall
River Deel (at gauge 34120 Pollnacross)
18BH21
Elevation mOD
Rainfall (mm)
TImeline
20
18
16
14
12
10
8
0
10
20
30
40
50
60
70
80
27/10/2018
16/11/2018
06/12/2018
26/12/2018
15/01/2019
04/02/2019
24/02/2019
16/03/2019
05/04/2019
25/04/2019
15/05/2019

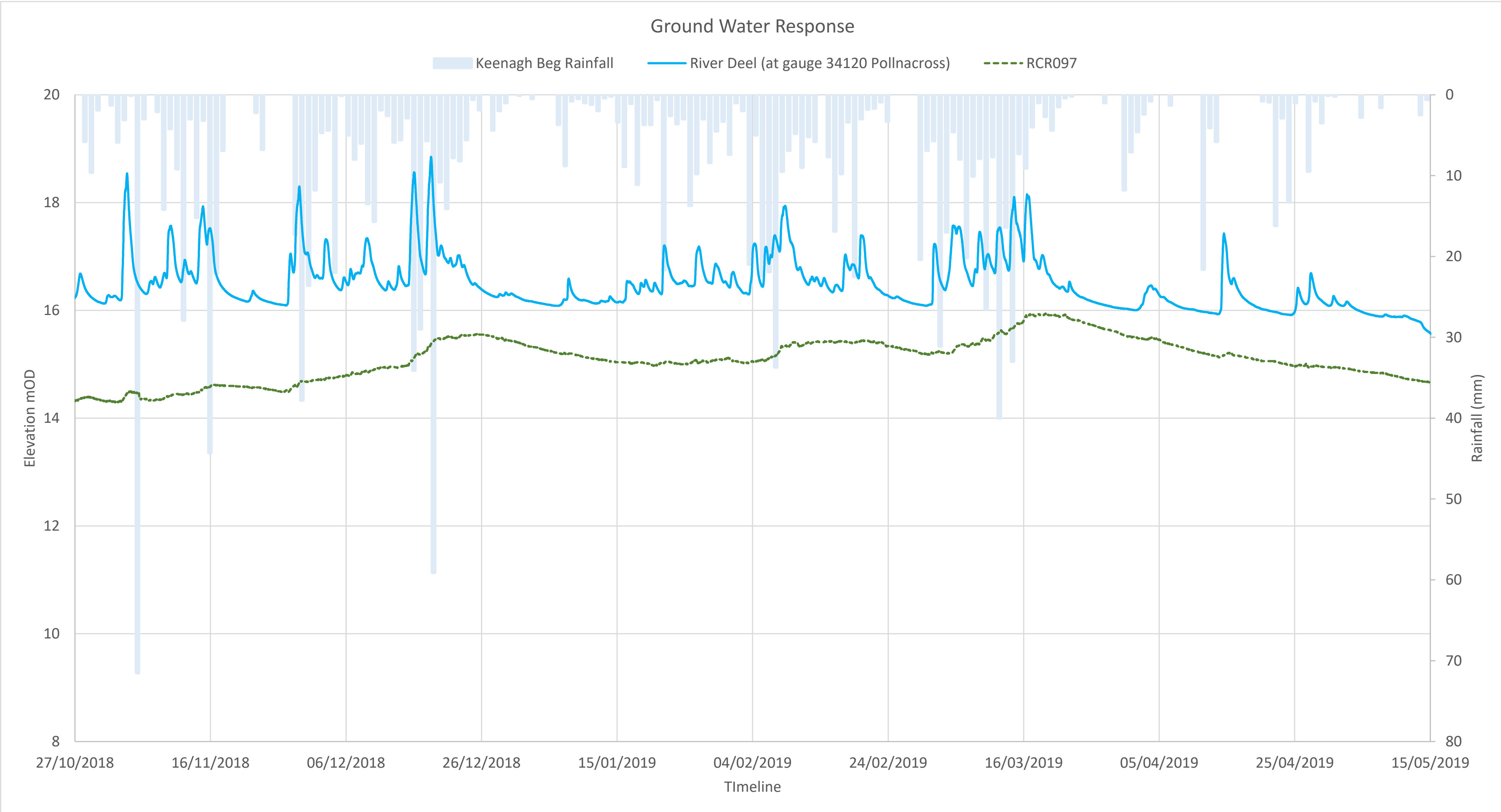


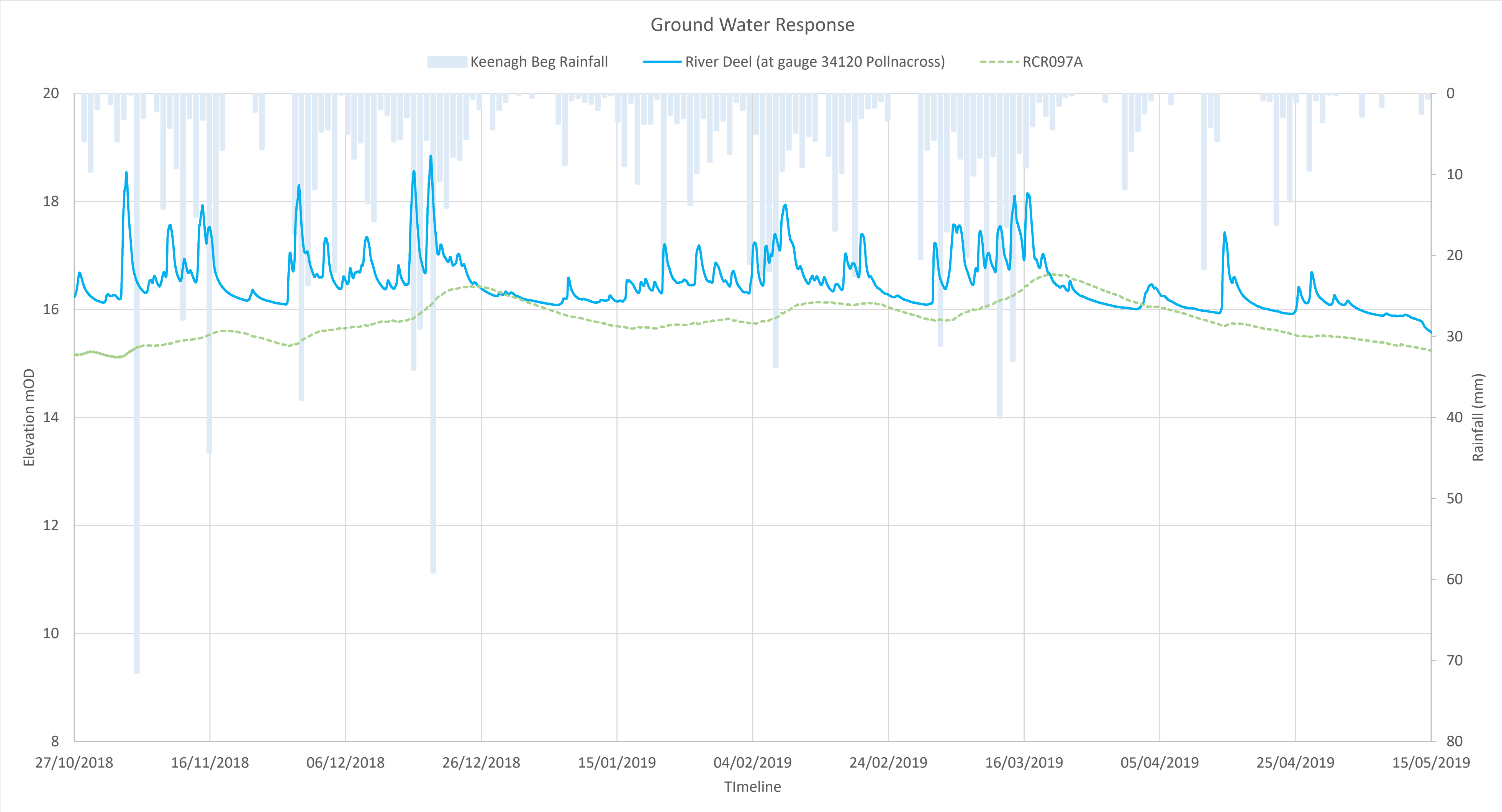
Water Level Response
Keenagh Beg Rainfall
River Deel (at gauge 34120 Pollnacross)
Mullenmore Stream (at gauge 34117)
Elevation mOD
Rainfall (mm)
20
18
16
14
12
10
8
0
10
20
30
40
50
60
70
80
27/10/2018
16/11/2018
06/12/2018
26/12/2018
15/01/2019
04/02/2019
24/02/2019
16/03/2019
05/04/2019
25/04/2019
15/05/2019
TImeline



Ground Water Response
Keenagh Beg Rainfall
River Deel (at gauge 34120 Pollnacross)
RC010
Elevation mOD
Rainfall (mm)
20
18
16
14
12
10
8
0
10
20
30
40
50
60
70
80
27/10/2018
16/11/2018
06/12/2018
26/12/2018
15/01/2019
04/02/2019
24/02/2019
16/03/2019
05/04/2019
25/04/2019
15/05/2019
TImeline


Ground Water Response
Keenagh Beg Rainfall
River Deel (at gauge 34120 Pollnacross)
RCR090A
Elevation mOD
20
18
16
14
12
10
8
Rainfall (mm)
0
10
20
30
40
50
60
70
80
27/10/2018
16/11/2018
06/12/2018
26/12/2018
15/01/2019
04/02/2019
24/02/2019
16/03/2019
05/04/2019
25/04/2019
15/05/2019
TImeline


Ground Water Response
Keenagh Beg Rainfall
River Deel (at gauge 34120 Pollnacross)
RCR097
Elevation mOD
Rainfall (mm)
TImeline
20
18
16
14
12
10
8
0
10
20
30
40
50
60
70
80
27/10/2018
16/11/2018
06/12/2018
26/12/2018
15/01/2019
04/02/2019
24/02/2019
16/03/2019
05/04/2019
25/04/2019
15/05/2019



Ground Water Response
Keenagh Beg Rainfall
River Deel (at gauge 34120 Pollnacross)
RCR097A
Elevation mOD
Rainfall (mm)
TImeline
20
18
16
14
12
10
8
0
10
20
30
40
50
60
70
80
27/10/2018
16/11/2018
06/12/2018
26/12/2018
15/01/2019
04/02/2019
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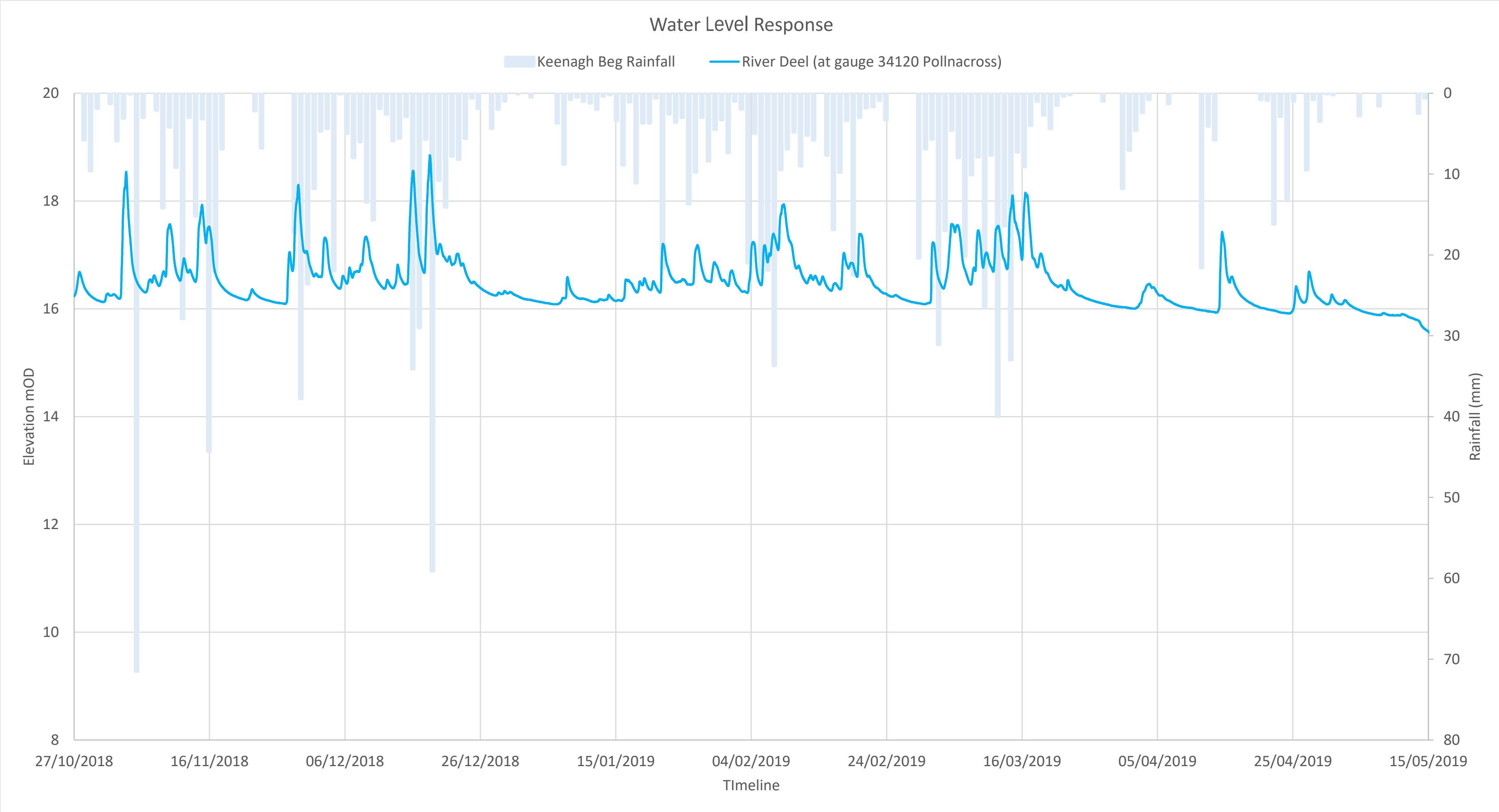
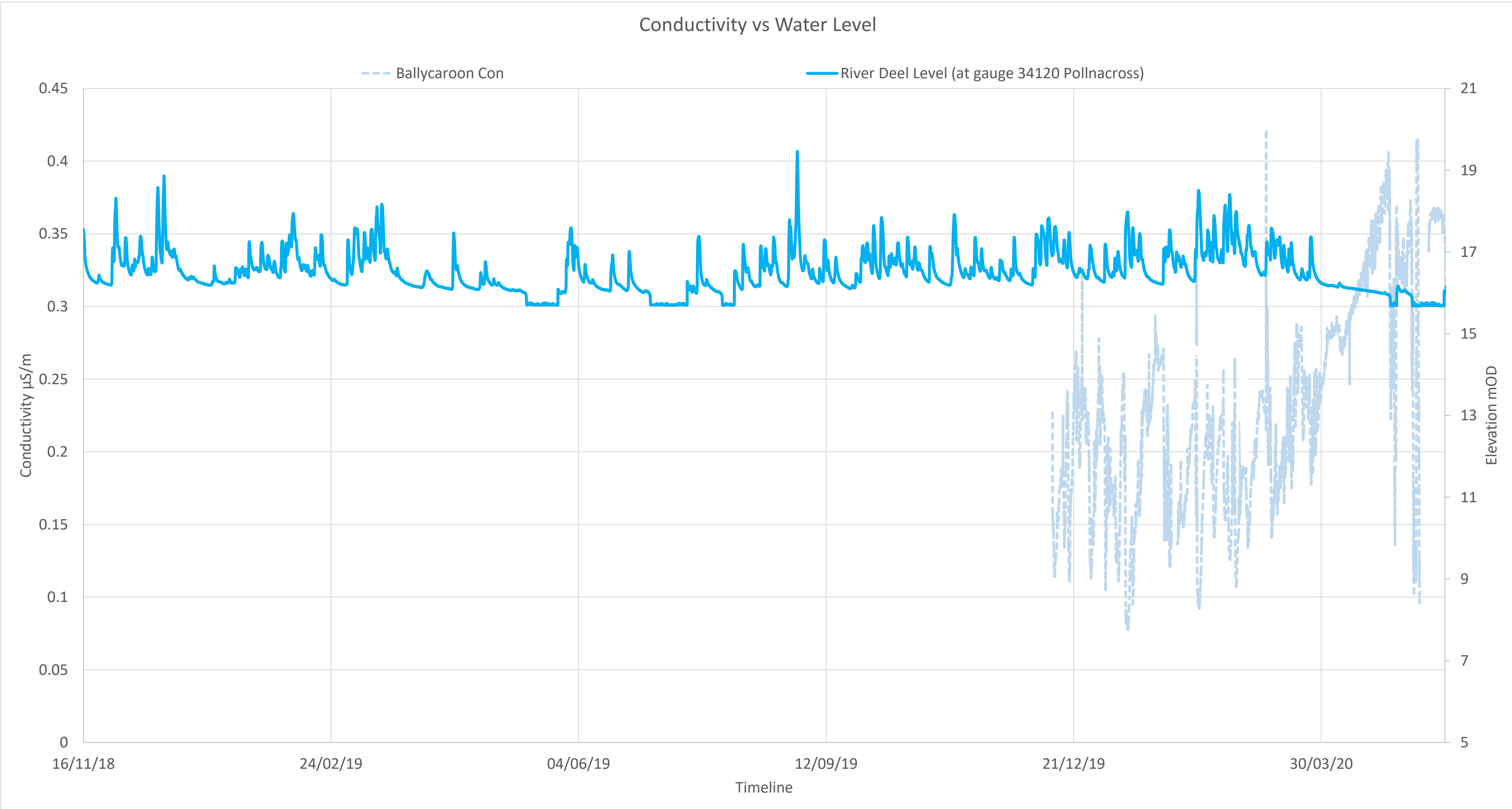
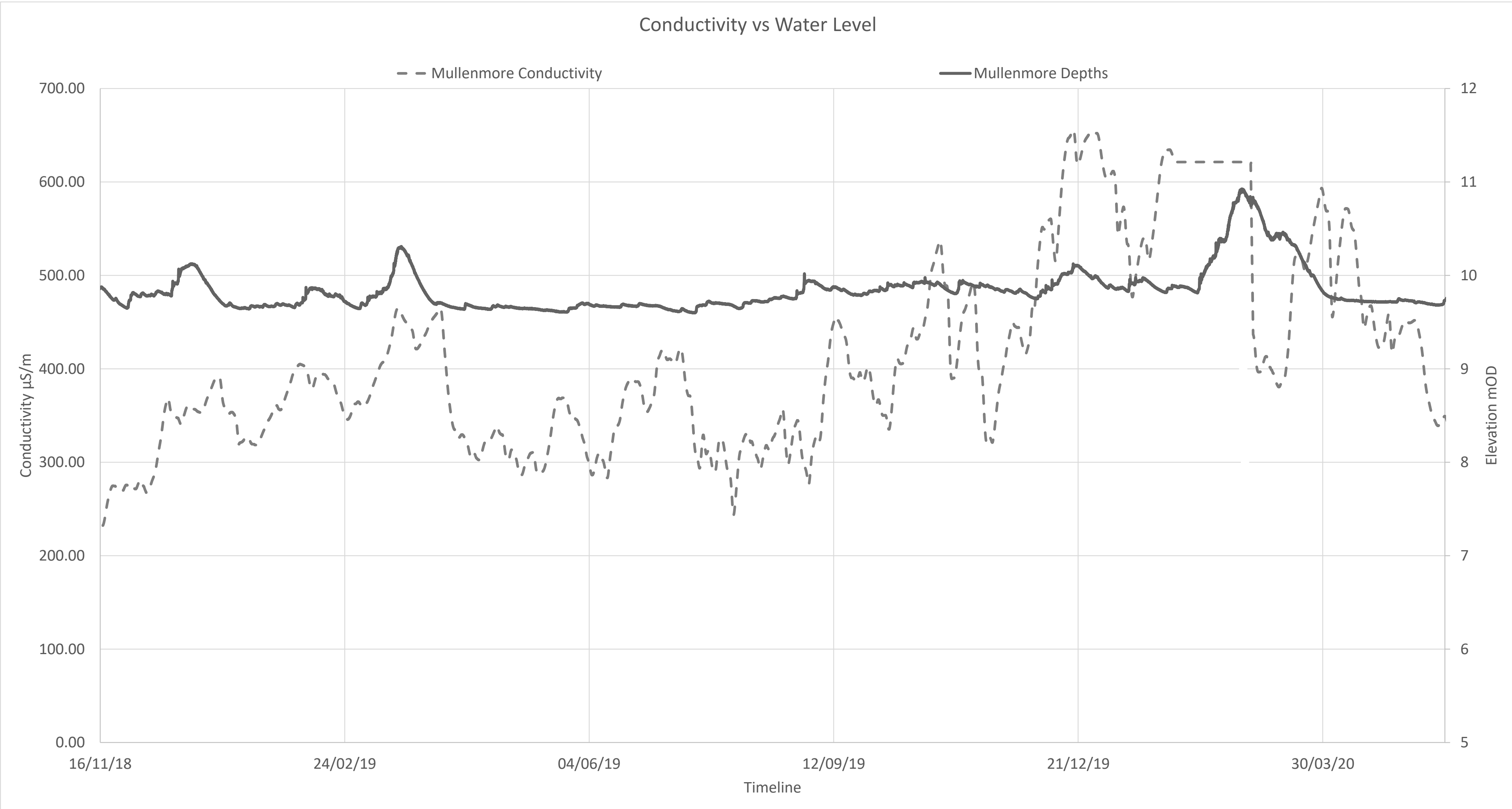
25/04/2019
15/05/2019



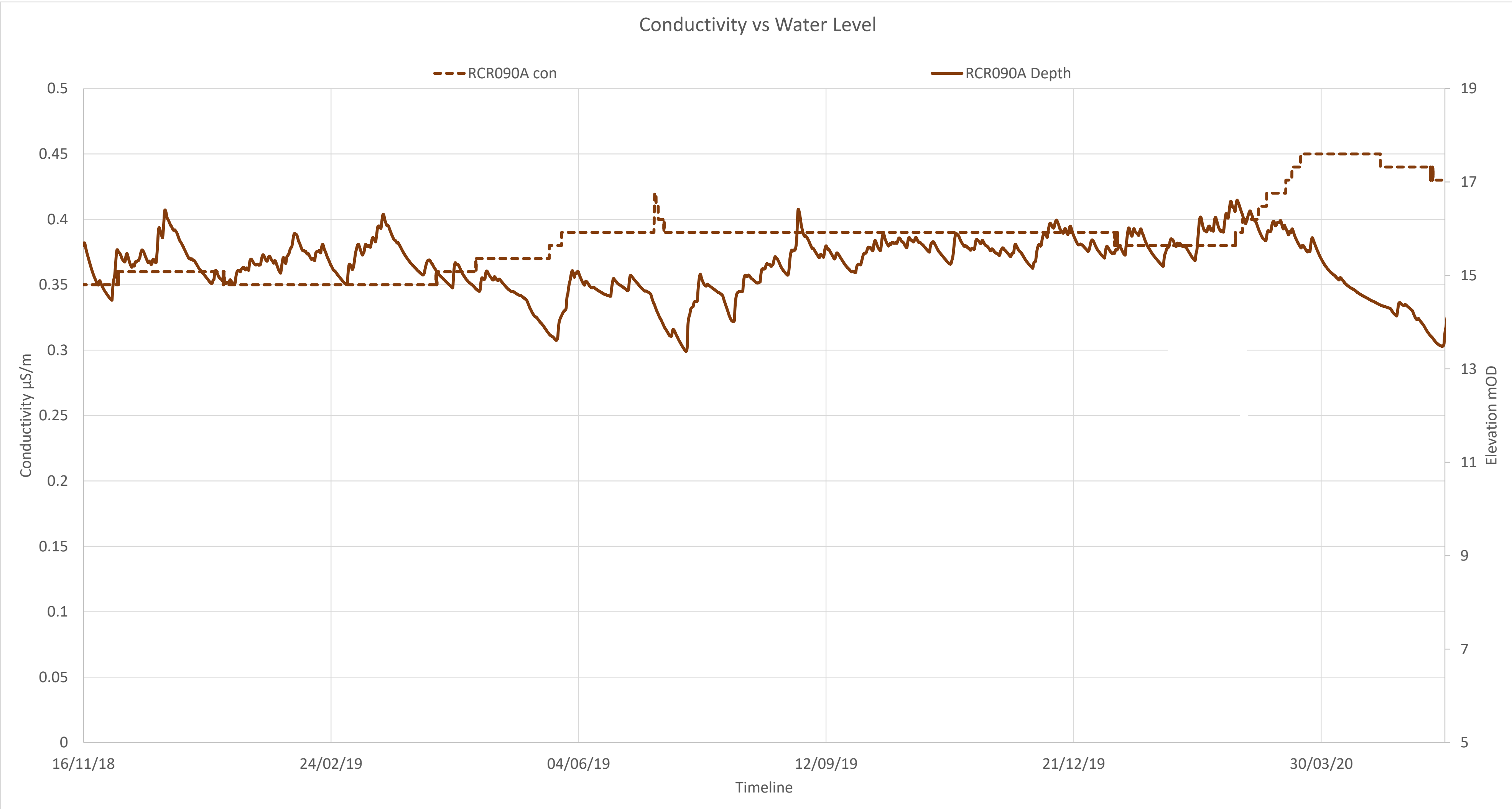
Water Level Response
Keenagh Beg Rainfall
River Deel (at gauge 34120 Pollnacross)
Elevation mOD
Rainfall (mm)
TImeline
20
18
16
14
12
10
8
0
10
20
30
40
50
60
70
80
27/10/2018
16/11/2018
06/12/2018
26/12/2018
15/01/2019
04/02/2019
24/02/2019
16/03/2019
05/04/2019
25/04/2019
15/05/2019


Conductivity vs Water Level
18BH21 con
18BH21 level
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Conductivity µS/m
19
17
15
13
11
9
7
5
Elevation mOD
No Data Avalible after
19/05/2019
16/11/18
24/02/19
04/06/19
12/09/19
21/12/19
30/03/20
Timeline

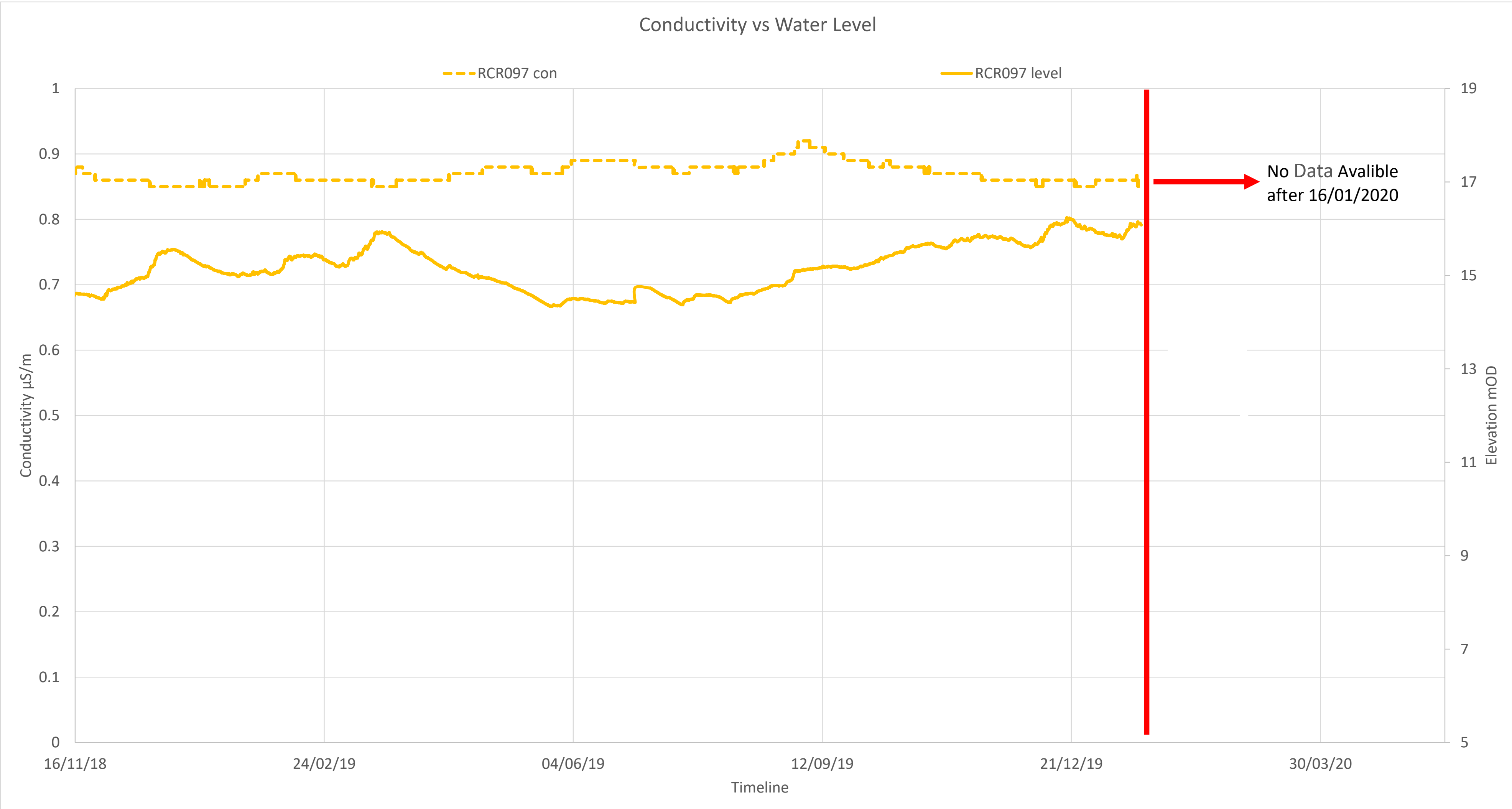

Conductivity vs Water Level
Ballycaroon Con
River Deel Level (at gauge 34120 Pollnacross)
Conductivity µS/m
Elevation mOD
Timeline
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
21
19
17
15
13
11
9
7
5
16/11/18
24/02/19
04/06/19
12/09/19
21/12/19
30/03/20



Conductivity vs Water Level
Mullenmore Conductivity
Mullenmore Depths
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Conductivity µS/m
12
11
10
9
8
7
6
5
Elevation mOD
16/11/18
24/02/19
04/06/19
12/09/19
21/12/19
30/03/20
Timeline



Conductivity vs Water Level
RCR090A con
RCR090A Depth
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Conductivity µS/m
19
17
15
13
11
9
7
5
Elevation mOD
16/11/18
24/02/19
04/06/19
12/09/19
21/12/19
30/03/20
Timeline


Conductivity vs Water Level
RCR097 con
RCR097 level
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Conductivity µS/m
19
17
15
13
11
9
7
5
Elevation mOD
16/11/18
24/02/19
04/06/19
12/09/19
21/12/19
30/03/20
Timeline
No Data Avalible
after 16/01/2020