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Classification of Groundwater Response Mechanisms in Provincial Observation Wells Across British Columbia

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EXECUTIVE SUMMARY

Groundwater levels in aquifers vary spatially (by location and depth) and temporally (hourly, daily, seasonally, inter-annually, and at longer time scales). The rise and fall of the groundwater level observed on a well hydrograph reflects the addition of water to storage in the aquifer and the release of water from storage. While seasonal variations in climate are a dominant driver of the groundwater level variations, nearby surface water bodies, such as rivers, can also influence groundwater levels.

A consistent graphical (hysteresis plot) and statistical (cross-correlation) approach was used in this study to classify provincial observation wells according to the dominant response mechanism: recharge-driven, where the groundwater level response leads the streamflow; and streamflow-driven, where the streamflow leads the groundwater level response. Identification of the response mechanism can provide useful insight into the nature of hydrogeologic system and possibly aid in the interpretation of hydraulic connectivity between aquifers and streams. Section 4 of this report describes the data sources and the two diagnostic tools used to classify the wells.

The B.C. Provincial Groundwater Observation Well Network currently (as of November 2020) includes 220 observation wells. A total of 164 wells had nearby streamflow hydrometric stations from the B.C. Federal-Provincial Hydrometric Network and so were analyzed. Wells that did not have a hydrometric station on a stream that flows over or adjacent to the mapped aquifer, in addition to wells that are no longer active, were not analyzed. Of these 164 wells, only 123 are classified as recharge-driven or streamflow-driven. The remaining 26 wells were classified as indeterminant because either (or both) the hysteresis plot or the cross-correlation plot yielded indeterminant results. Wells with a nearby hydrometric station that did not have sufficient overlap between the periods of record of the hydrometric data and groundwater level data were not classified due to lack of data.

Considering the 123 wells across the province that were able to be classified, 66% are streamflow-driven and 34% are recharge-driven. The classification for the remaining 26 wells could not be determined. The dominant response mechanism for different aquifer subtypes was also examined, but the low number of observation wells in certain aquifer subtypes likely gives unrepresentative results. In general, aquifer subtypes 1a, 1b, 1c and 2 (unconfined fluvial or glacio-fluvial sand and gravel aquifers situated along rivers or forming river deltas) are dominantly streamflow-driven. However, only slightly fewer observation wells are classified as recharge-driven in these aquifer subtypes. In contrast, observation wells in bedrock aquifers, including subtypes 5a, 6a, 6b and bedrock, were expected to be dominantly recharge-driven, but most wells in 5a and 6b aquifers are classified as streamflow-driven. No observation wells associated with aquifer subtypes 5b or 6a were classified. Additionally, a majority (53%) of wells in recharge-driven systems are in 4b aquifers.

Most wells in the Interior (snowmelt regime) are classified as streamflow-driven, which reflects the steep mountainous terrain and narrow valleys characteristic of much of the province. Interestingly, most observation wells in the Fraser Valley are also classified as streamflow-driven, despite many wells being located at some distance from a stream. The high specific yield and consequent sluggish response of the water table in the Fraser Valley aquifers may account for streamflow appearing to lead the response.

The classification results can be used for a variety of purposes to support hydrogeological investigations and water allocation decision-making:

1. Understanding what is driving the groundwater level response measured in the observation well is important for interpreting the groundwater level response at an observation well, or for comparing responses from multiple observation wells in the same aquifer or the same aquifer subtypes.

2. Inferring the degree of hydraulic connection between and aquifer and a stream. A high likelihood of hydraulic connectivity is inferred in streamflow-driven systems (assuming the hydrometric station used for the analysis is situated on a stream connected to the aquifer). The degree of synchronicity between the signals is a strong indicator of hydraulic connectivity.
3. Informing whether the groundwater level record for a well is suitable for estimating recharge. The Water Table Fluctuation (WTF) method is premised on the well responding to diffuse recharge by precipitation. If the well is streamflow-driven, then the well is not suitable for recharge analysis.
4. Providing useful insight into how long it might take for a change in groundwater level in a recharge-driven system to propagate to the stream, and vice-versa for the streamflow-driven system. The stronger the correlation and the shorter the lag, the more immediate the response will be.
5. Inferring the response mechanism for aquifers across the province that are unmapped, or that have no observation well or no nearby hydrometric station. When considered alongside the aquifer subtype, this additional information may be useful for understanding potential hydraulic connectivity.

Accompanying this report is a spreadsheet listing all available provincial observation wells, some of their characteristics (e.g., what geological unit they are located in, how far away the well is from the nearest and second nearest stream, where the closest hydrometric station and climate station are located) along with how the well has been classified according to dominant response mechanism. As more hydrometric station data and observation well data become available in B.C., the classification can be updated to include wells that could not be analyzed in this study. The classification scheme and diagnostic tools presented in this study can complement methods already used for analyzing observation well data.

The most important limitation of this analysis is the lack of hydrometric stations on streams that intersect the aquifers with the observation wells. In some cases, an alternative hydrometric station at a greater distance from the well was used in the analysis and so may have led to mis-classification. Also, the classification results interpreted from the hysteresis plot was sometimes (9 wells) inconsistent with that interpreted from cross-correlation plot. For such cases, the location, surrounding topography, and aquifer characteristics noted in the aquifer mapping report, such as recharge and groundwater abstraction, were examined to ultimately classify the well. Thus, no single method should be relied upon to determine the classification, and some hydrogeological interpretation may be needed in certain cases.

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1. INTRODUCTION

Groundwater level data are fundamental to most hydrogeological investigations. One of the first tasks a hydrogeologist does when beginning a project in a new study area is to seek groundwater level data. Many countries (or provinces, states or regions) maintain observation well networks. These networks serve a variety of purposes. For example, in British Columbia (B.C.) the Provincial Groundwater Observation Well Network (PGOWN) program provides monitoring of groundwater levels and groundwater chemistry of key aquifers (and basins) across the province to support management, protection and sustainable use of our groundwater resources and associated ecosystems (Government of B.C., 2020a). Many observation wells are used to monitor for trends in groundwater levels that may be associated with changes in groundwater use associated with development, but some wells are strategically located to monitor changes in the natural groundwater conditions that may be associated with climate change for example.

A quick scan of groundwater level records across B.C. highlights their varied characteristics. All show seasonal variations and inter-annual variations, and some show trends; but the particular response exhibited by the groundwater level record depends on a variety of factors. Hydrogeologists and practitioners have a solid understanding of groundwater level responses but often tend to focus on individual well records (or perhaps a few, depending on availability) specific to the purpose of a particular study or area. For this reason, hydrogeologists and practitioners can overlook other attributes of these groundwater level records and how they relate to the groundwater flow system.

Other hydrologic data records may be helpful to understand groundwater flow systems. For example, many groundwater observation wells are located near streamflow hydrometric stations. As these nearby streams are in the same hydroclimatic regime (e.g. rainfall-dominated or snowmelt-dominated), they may have a similar response. Therefore, there may be seasonal and inter-annual relationships between the groundwater level and stream discharge hydrometric datasets that could help infer groundwater response mechanisms. Moreover, many aquifers are hydraulically connected to streams and have direct water exchanges. Therefore, a linked hydraulic response of the aquifer – stream system might be anticipated.

This report provides some background on groundwater level records, and describes the approach used to classify groundwater level responses in PGOWN wells. This classification focuses on identifying the dominant response mechanism (recharge-driven or streamflow-driven) observed in a well by comparing it to nearby streamflow data and other geological information. Accompanying this report is a spreadsheet listing all available provincial observation wells, some of their characteristics (e.g., what geological unit they are located in, how far away the well is from the nearest and second nearest stream, where the closest hydrometric station and climate station are located) along with how the well has been classified according to dominant response mechanism. Understanding the response mechanism can be critical for interpreting the groundwater level response in relation to other environmental factors and can give more meaningful insight into varied processes within the groundwater system[1]. Potential uses of the classification are discussed at the end of the report in Section 5.5.

[1] The term groundwater system includes all water-bearing subsurface materials, whether water can be economically recovered (aquifer) or not (aquitard). In this report, aquifer is used as the default geologic unit when discussing groundwater level data from observation wells.

This report focuses only on the groundwater level data from PGOWN; groundwater chemistry data are not discussed. Neither does this report delve into other characteristics of observation well hydrographs (e.g., trends).

2. BACKGROUND

2.1 Groundwater Levels in Aquifers – An Overview

2.1.1 Groundwater Level Hydrographs

Groundwater levels in aquifers vary spatially (by location and depth) and temporally (hourly, daily, seasonally, inter-annually, and at longer time scales). Observation wells, or groundwater level monitoring wells, are used to monitor groundwater level variations over time, and the data are normally graphed on a well hydrograph as a time series (Figure 1). Groundwater levels can be expressed either as hydraulic head in metres above sea level (masl) or as a depth in metres below ground surface (mbgs) (as in Figure 1). A measured groundwater level represents the hydraulic head that is averaged across the depth interval over which the well is screened (in the case of a well completed in unconsolidated sediments). For observation wells that are screened across an entire aquifer, the head represents the depth-averaged head for the aquifer. Similarly, if the well is completed in bedrock, the open borehole length from the base of the surface casing to the bottom of the well is the averaging depth interval. In cases where the hydraulic head is expected to vary with depth, such as in a recharge area or discharge area, a longer monitoring depth interval will obscure the vertical variations in hydraulic head. Only if flow is dominantly horizontal in the aquifer (or the groundwater system) will a long depth interval represent the presence of a fairly uniform hydraulic head with depth.

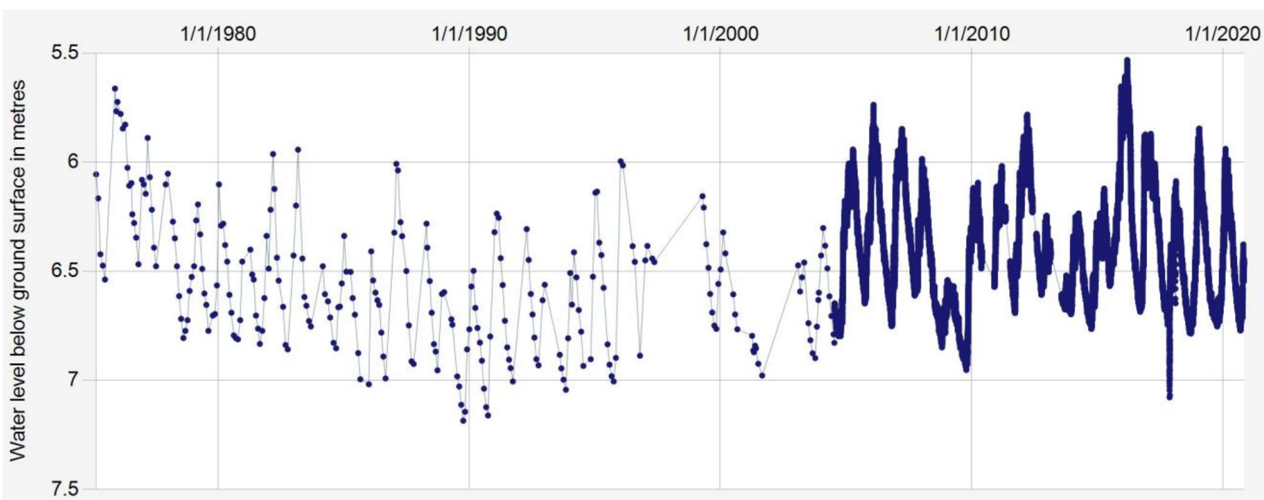

Figure 1: Example of a well hydrograph for B.C. Observation Well 201, Alert Bay (Fir St.) showing seasonal variations in groundwater level, expressed here as a depth in metres below ground surface (mbgs). Measurements prior to 2005 were made manually approximately once per month, while measurements since 2005 have been made hourly. Source: Government of B.C. (2020a).

As illustrated in the well hydrograph shown in Figure 1, groundwater levels vary over time. In this particular aquifer (B.C. Aquifer #858), comprised of silty sand, the annual range in groundwater level is approximately 1 m; however, there is inter-annual variability in the range and the maximum and minimum groundwater levels. Inter-annual variability in the well hydrograph is normally related to inter-annual climate variability. However, changes in local conditions can influence inter-annual variability; for example, groundwater pumping begins at a nearby well(s); irrigation is introduced; land use or land cover has changed; or the discharge environment has been modified. Such “permanent” changes in local conditions often lead to a change in the hydrogeologic regime. Accordingly, the well hydrograph may show evidence of an alteration or a long-term trend. In the example shown in Figure 1, there are no observable positive or negative trends. This record has insufficient data to calculate a statistical trend (Government of B.C., 2020b), despite the relatively long record for this well. Normally, 30 years of data are required to calculate a statistical trend, but in this example, the period from approximately 1995 to 2005 is incomplete.

Inter-annual variability in groundwater levels can be assessed statistically. The Province of B.C. maintains a data portal, Groundwater Level Interactive Map (Province of B.C., 2020a), which provides easy access to observation well data for active wells with real-time monitoring, active wells without real-time data, and inactive wells. One of the products is a groundwater level statistics chart (e.g. Figure 2, placed further below) showing the historical daily median groundwater level and the minimum and maximum groundwater level (bottom and top of blue zone) for the previous 10 years of available data prior to the current Water Year (October through September) for those wells with at least two years of data, and raw and approved data for the current year. As illustrated in Figure 2, groundwater level data for Water Year 2020-2021 fall within the historical range of water levels (i.e., the blue band).

2.1.2 Why Do Groundwater Levels Rise and Fall?

The rise and fall of the groundwater level observed on a well hydrograph simply reflects the addition of water to storage in the aquifer and the release of water from storage. It is important to remember that groundwater is constantly flowing in the aquifer - what goes in (recharges) drains out (discharges), although the rates of recharge and discharge vary. If the water level is rising, this means that the rate of recharge is greater than the rate of discharge. So, during seasonal recharge periods we observe a rise in the groundwater level. When recharge is reduced or stops, we observe a groundwater level decline (recession). Groundwater level hydrographs can be used to estimate the rate of recharge using the water table fluctuation (WTF) method by multiplying the specific yield (Sy) of the aquifer by rate of rise in head, and importantly, adding the net drainage rate estimated from a period when there is no precipitation (Cuthbert, 2010). If the net drainage rate is not added, recharge will be underestimated.

The dynamic range (the difference between the maximum and minimum groundwater levels) observed on a well hydrograph depends on many factors. The hydroclimatic regime is a dominant control, as discussed in Section 2.1.3. However, for the same hydroclimatic conditions, the amplitude of the signal in any particular well depends on the aquifer diffusivity, defined as the transmissivity (T) divided by the storativity (S)[2]. Assuming the same hydraulic gradient, an aquifer with a high K value drains rapidly, so as the aquifer is recharged the water level does not rise significantly. Aquifers with high storage capacity also show smaller rises in water level because they can accommodate more water in storage without observing a head increase. Thus, when comparing responses across different aquifers, even if the aquifers have the same climate conditions, the amplitudes will differ.

In B.C., aquifers have been classified by aquifer subtype (Table 1) according to whether the aquifer is unconfined or confined, comprised of unconsolidated deposits or bedrock, and the type of aquifer material, such as fluvial/glaciofluvial, alluvium/colluvium, limestone, crystalline rock, etc. (Wei et al., 2007; Government of B.C. 2020c). Each aquifer subtype can be expected to respond somewhat differently. However, for the same aquifer, the hydraulic properties can generally be assumed to remain

[2] or equivalently, hydraulic conductivity (K) divided by the specific storage (Ss) for confined aquifers, or T divided by Sy for unconfined aquifers.

constant for most purposes.[3] Therefore, it is possible to examine well hydrographs for individual wells to gain insight into hydrologic controls of aquifers that vary from year to year or persist from year to year.

Table 1: Aquifer Subtype Code Description. From B.C. Government (2020c).

Aquifer Subtype Code	Description
1a	Predominantly unconfined fluvial or glacio-fluvial sand and gravel aquifers found along major rivers of higher stream order with the potential to be hydraulically influenced by the river.
1b	Predominantly unconfined fluvial or glacio-fluvial sand and gravel aquifers found along rivers of moderate stream order with the potential to be hydraulically influenced by the river.
1c	Predominantly unconfined fluvial or glacio-fluvial sand and gravel aquifers found along lower order (< 3-4) streams in confined valleys with relatively undeveloped floodplains, where aquifer thickness and lateral extent are more limited.
2	Predominantly unconfined deltaic sand and gravel aquifers are commonly found in deltas where a stream or smaller river flows into a standing body of water.
3	Alluvial or colluvial fan sand and gravel aquifers typically occur at or near the base of mountain slopes, either along the side of valley bottoms, or if formed during the last period of glaciation, raised above the valley bottoms.
4a	Unconfined glacio-fluvial outwash or ice contact sand and gravel aquifers generally formed near or at the end of the last period of glaciation.
4b	Confined Glacio-fluvial sand and gravel aquifers underneath till, in between till layers, or underlying glacio-lacustrine deposits.
4c	Confined sand and gravel aquifer associated with glacio-marine environments near the coast.
5a	Fractured sedimentary rock aquifers primarily found in association with old sedimentary basins.
5b	Karstic limestone aquifers
6a	Crystalline bedrock aquifers associated with flat-lying to gently-dipping volcanic flows.
6b	Fractured crystalline (igneous intrusive or metamorphic, meta-sedimentary, meta-volcanic, volcanic) rock aquifers
UNK	Unknown

2.1.3 Seasonal Variations in Groundwater Levels and Hydroclimatic Regime

Climate is the primary driver for seasonal variations in groundwater level. As noted above, a Water Year (WY) is a common period for reporting and describing hydrologic data. The WY (or hydrological year as defined in the United Kingdom) has been adopted by many countries. North America and Europe have adopted the period October 1 to September 30. A WY differs from the calendar year because the bulk of annual precipitation falls in late autumn and winter recharging aquifers and streams, with accumulated snow not draining until snowmelt occurs in the following spring or early summer, setting up water availability for the drier summer months.

The statistical well hydrograph for Observation Well 406 is shown in Figure 2. This well is located in the Lower Fraser Valley in Chilliwack and is completed in an unconfined sand and gravel - alluvial or colluvial fan (B.C. Aquifer #8). The hydrograph shows a relatively steep rise in groundwater level beginning in October (consider the historical daily median groundwater level, shown as the green line). The groundwater level begins to peak around December, remains high until mid-February, and then declines

[3] Compaction, for example, can lead to changes in specific storage (and hydraulic conductivity) in a groundwater system.

steadily until mid-September. The general timing of the rise and fall of this well hydrograph reflects the rainfall-dominated hydroclimatic regime.

In contrast, Figure 3 shows the statistical well hydrograph for Observation Well 409. This well is located in Spallumcheen and is completed in an unconfined aquifer (B.C. Aquifer #103) comprised of sand and gravel - late glacial outwash. The hydrograph has a noticeably different shape. Groundwater levels remain low from October through to January, rising gradually from January until March. Then, groundwater level increases rapidly, peaking in June. The groundwater level begins to decline in late June, reaching a minimum around late August. This well is located in a snowmelt-dominated hydrologic regime.

Based on these two examples, it is clear (and unsurprising) that the hydroclimatic regime exercises a high-level control on the overall response of an aquifer.

Finally, consider the well hydrograph for Observation Well 217 in Grand Forks (Figure 4). This well is also located in a snowmelt-dominated hydrologic regime and is completed in an unconfined aquifer (B.C. Aquifer #158) comprised of sand and gravel - fluvial or glaciofluvial. The groundwater level is low from October through to March, with a minimum level reached in January-February. The groundwater level begins rising in March and historically peaked over a short time period before gradually declining. Thus, the response is very similar to Obs. Well #409, perhaps with the notable exception that the peak groundwater levels were historically quite high in some years (during major flooding in nearby rivers).

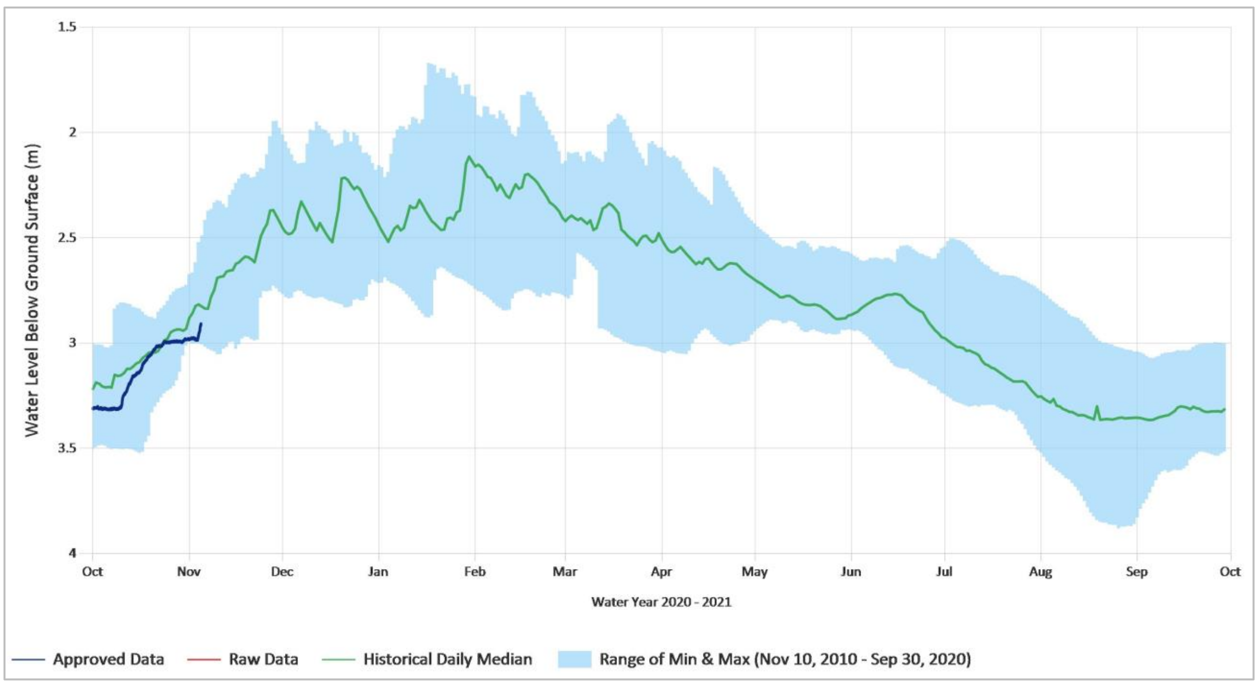

Figure 2: Example groundwater level statistics chart (or statistical well hydrograph) for B.C. Observation Well 406, Chilliwack (Mountview Park). Source: Government of B.C. (2020a).

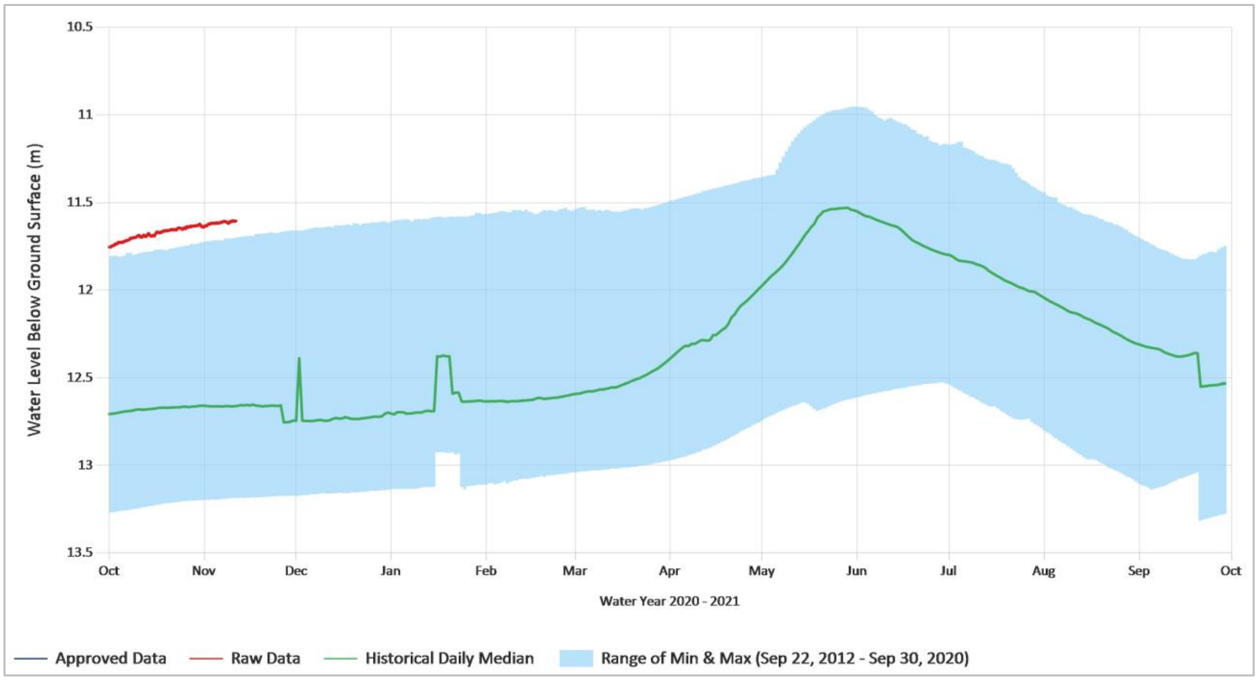

Figure 3: Example of a groundwater level statistics chart (or statistical well hydrograph) for B.C. Observation Well 409, Spallumcheen (Schubert Rd.). Source: Government of B.C. (2020a).

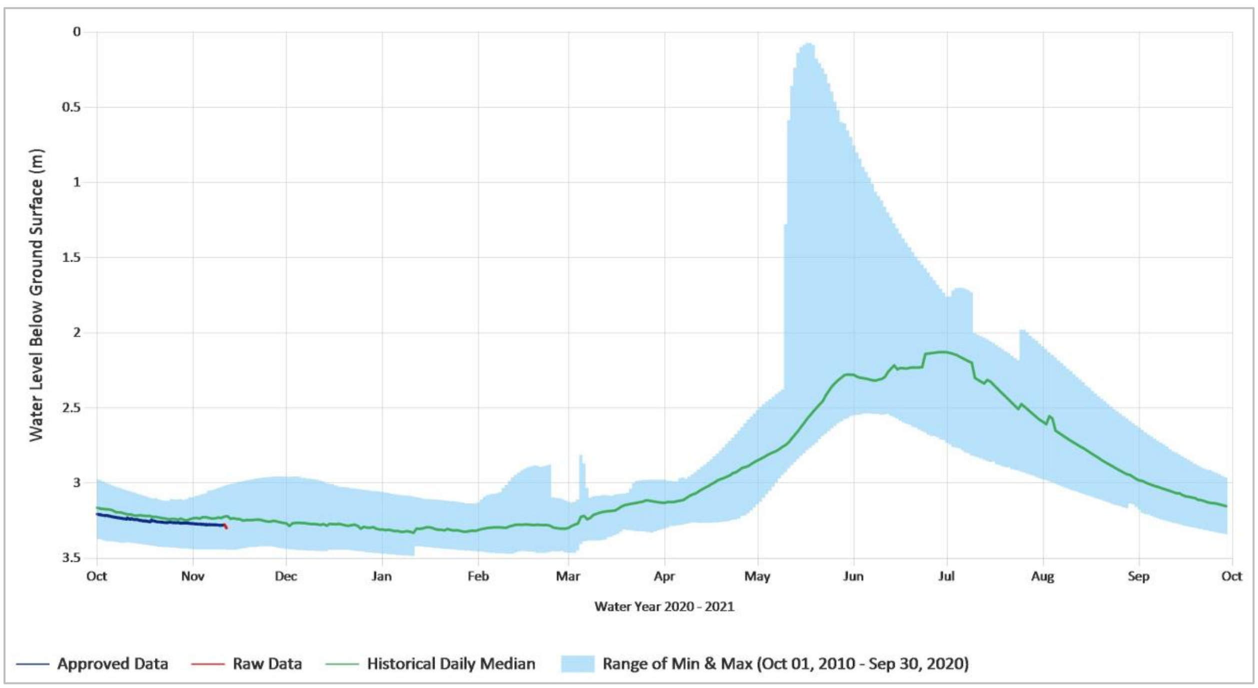

Figure 4: Example of a groundwater level statistics chart (or statistical well hydrograph) for B.C. Observation Well 217, Grand Forks (Richmond Ave.). Source: Government of B.C. (2020a).

2.2 Aquifer - Stream System Type

An important distinguishing feature of Obs. Well 217 (Figure 4) is its proximity to a river. In fact, Obs. Well 217 is located approximately 400 m south of the confluence of the Kettle and Granby rivers. The Grand Forks Aquifer is known to be strongly hydraulically connected to these rivers (Scibek et al., 2007). Figure 5 shows the similar timing in the seasonal rise and fall of the Granby River near Obs. Well 217 in Grand Forks. This strong hydraulic connection suggests that groundwater levels in the aquifer might be influenced by stream levels, at least to some degree, rather than simply to local climate conditions that influence local diffuse recharge.

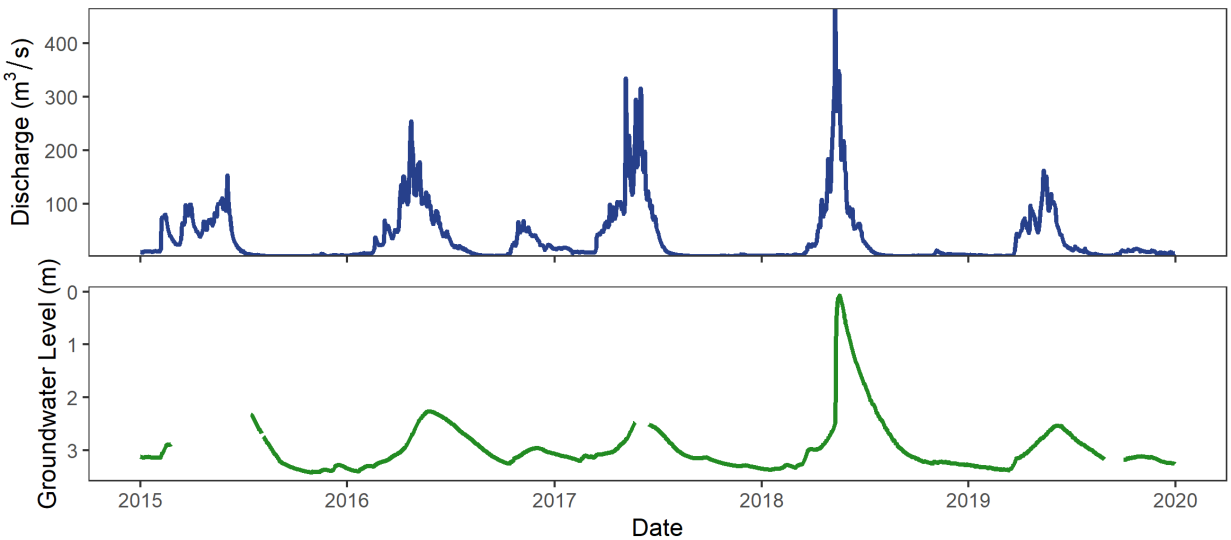

Figure 5: Daily mean discharge for the Granby River (08NN002) (top) and the daily mean groundwater water level for Obs. Well 217 (bottom). The rise and fall of both streamflow discharge and groundwater level follow very similar patterns.

Assuming a homogeneous aquifer, the amplitude and timing of the groundwater level response at a specific well location depends on the proximity and magnitude of various hydroclimatic driving forces. Therefore, it is important to consider the position of the observation well in the aquifer relative to these driving forces (or boundary conditions) which might influence the response. Essentially, the aquifer is responding to different signals, and those signals become superimposed in the observed response. For example, we are all aware that atmospheric pressure variations alter the groundwater level response; hence we correct for atmospheric pressure variations. Essentially, we filter out these typically low amplitude signals to reveal the actual groundwater level signal; although, sometimes, atmospheric pressure variations can overwhelm the signal. Similarly, we filter out tidal variations from hydraulic head data collected during a pumping test so that we can isolate the response of the aquifer due to pumping alone.

Seasonal variations in climate are a dominant signal, as discussed in the previous subsection, but so is the potential hydraulic signal from nearby surface water bodies, such as rivers, particularly when those rivers are allogenic (meaning their source is remote) and as such are influenced by climatic conditions outside the immediate area of the aquifer. For instance, Figures 6 and 7 show groundwater observation well data plotted alongside streamflow discharge from nearby streams. There is a high degree of synchronization between the groundwater level and the stream discharge (both following similar seasonal and inter-annual patterns). However, the timing of groundwater level synchronization with discharge differs between the two observation wells. For Obs. Well 122, the seasonal peaks and lows of groundwater level occur slightly before those of stream discharge peaks and lows (Figure 6). The opposite occurs with Obs. Well 351, where the seasonal peaks and lows of groundwater levels occur afterwards. If hydraulically connected, the relationships between these signals may provide insight into groundwater exchanges with the stream.

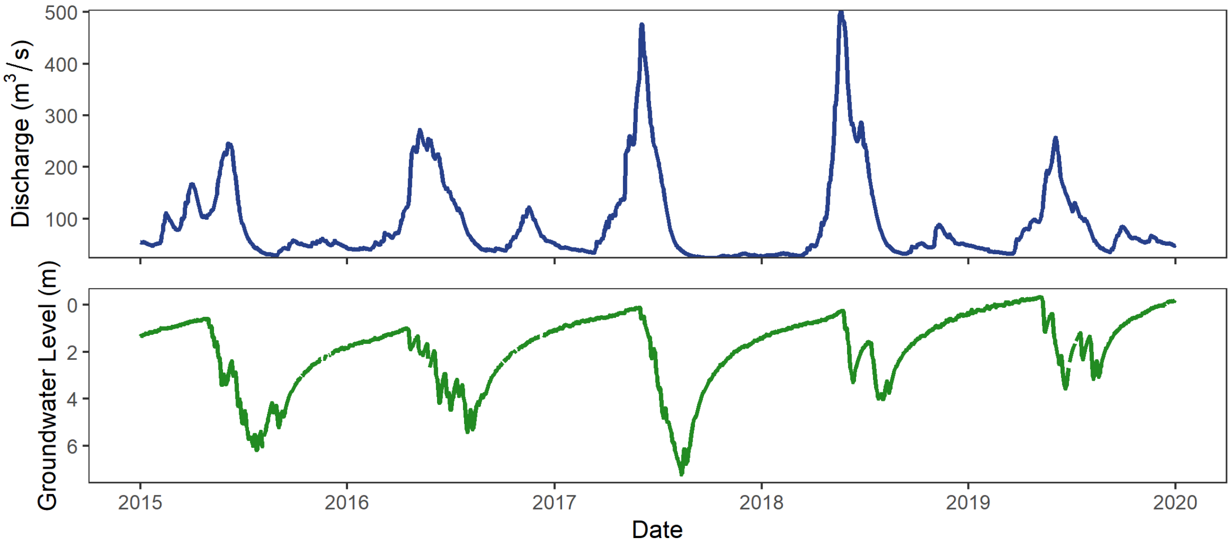

Figure 6: Daily mean discharge for the Shuswap River near Enderby (08NN002) (top) and the daily mean groundwater water level for Obs. Well 122 (bottom). Seasonal peaks and lows of groundwater levels occur before streamflow discharge peaks and lows.

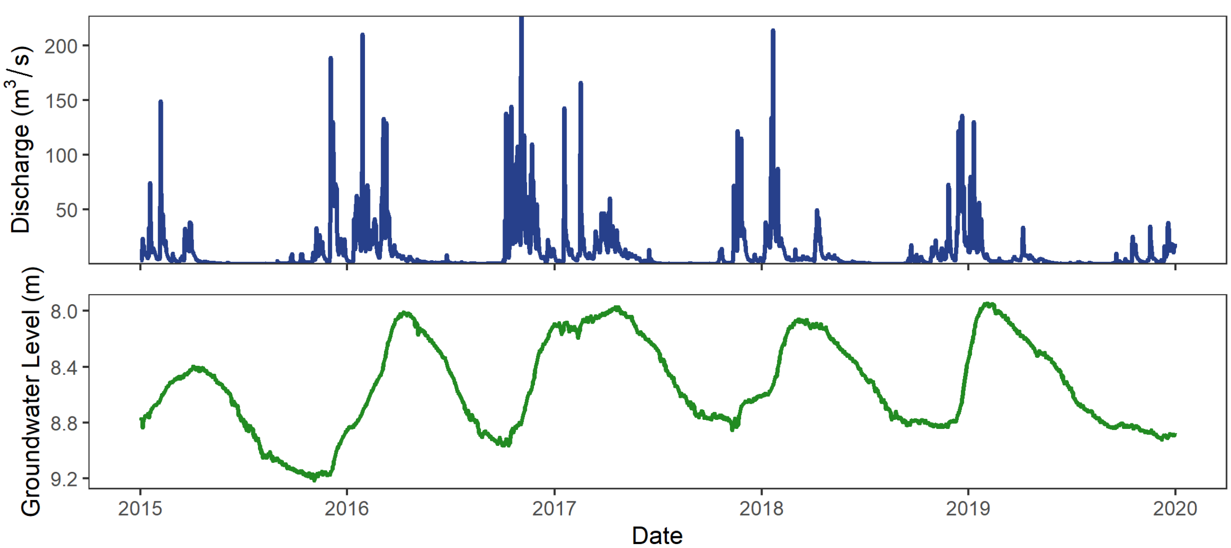

Figure 7: Daily mean discharge for the Tsolum River near Courtenay (08HB011) (top) and the daily mean groundwater water level for Obs. Well 351 (bottom). Seasonal peaks and lows of groundwater levels occur after streamflow discharge peaks and lows.

Allen et al. (2010) proposed a framework for evaluating the responses of aquifers and nearby streams in mountainous regions. They analyzed groundwater level responses from nine observation well locations across southern B.C. spanning the western coastal area eastward to just west of the Rocky Mountains. Allen et al. (2014) expanded the analysis to include 37 observation wells, specifically to examine variations in seasonality and trends in groundwater levels. The overall framework used in both of these studies is shown in Figure 8.

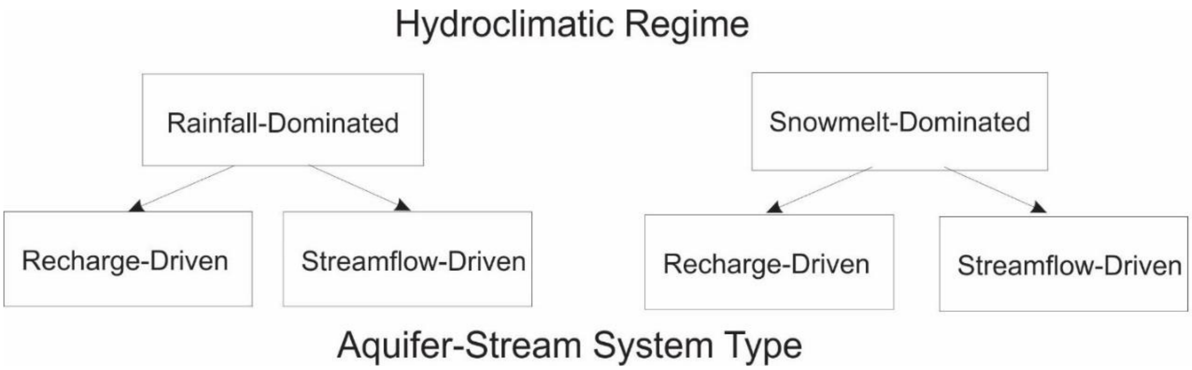

Figure 8: Framework for evaluating the responses of aquifer - stream systems. For simplicity, the hydroclimatic regime includes only rainfall- and snowmelt-dominated regimes. Hybrid regimes are not represented but are a blend of these two main types. Both recharge-driven and streamflow-driven aquifer - stream system types may be found in each hydroclimatic regime. From Allen et al. (2010).

In these previous studies, observation wells were classified according to end-member aquifer - stream system types based on the dominant response mechanism:

- **Recharge-driven: the groundwater signal leads the response (e.g. Figure 6).** In these systems, groundwater is recharged solely by precipitation and predominantly discharges to streams throughout the year. The aquifer - stream system is generally raised above the surrounding land surface and drains to lower elevation.
- **Streamflow-driven: the streamflow signal leads the response (e.g. Figure 7).** In many such systems, groundwater flow to and from streams is bi-directional and varies seasonally depending on stream stage. These aquifer - stream systems are commonly found in association with major streams/rivers. Situations can arise where the streamflow signal leads the groundwater signal even when there is no nearby stream, as discussed in more detail below.

Distinguishing between these two cases ranges from being very simple to very difficult. In the case of an aquifer which is raised above the surrounding area, the relationship is clearly that recharge is driven by precipitation, and that groundwater discharges to the local stream over the entire year. During the late summer, local streamflow is sustained primarily by groundwater discharge[4], with occasional rain events augmenting streamflow. During the winter, the stream may be quite flashy when the groundwater levels are high and local soils are wet, and the stream would respond directly to rainfall through surface runoff. At the other extreme, an aquifer associated with a large stream, whose annual hydrograph is generated by processes remote from the aquifer (i.e. allogenic), has an annual groundwater level response that primarily reflects the changes in the stream discharge (and equivalently the level of water in the stream) (Scibek et al., 2007). Streamflow-driven systems are common in mountain valleys with major rivers flowing through them, largely because the valley bottom aquifers are long and narrow and have high permeability.

[4] provided the stream is not fed by glacier melt which would sustain flow during late summer.

The fundamental difference between recharge-driven and streamflow-driven systems is whether the streamflow signal or the groundwater signal leads the response. For example, in the recharge-driven system, the groundwater signal will lead throughout the year because groundwater replenished from precipitation (i.e. diffuse recharge) flows in one direction – from the aquifer to the stream (Figure 9). Whereas, in the streamflow-driven system, the streamflow signal leads the response - a rise in streamflow is followed by a rise in groundwater level, and a decline in streamflow is followed by a decline in groundwater level. During the spring freshet in mountain regions, streamflow (and stage) is high and water can recharge the aquifer causing the groundwater level to rise. Once the freshet ends, streamflow reduces, and the groundwater flow system reverses to discharge into the stream (Figure 9).

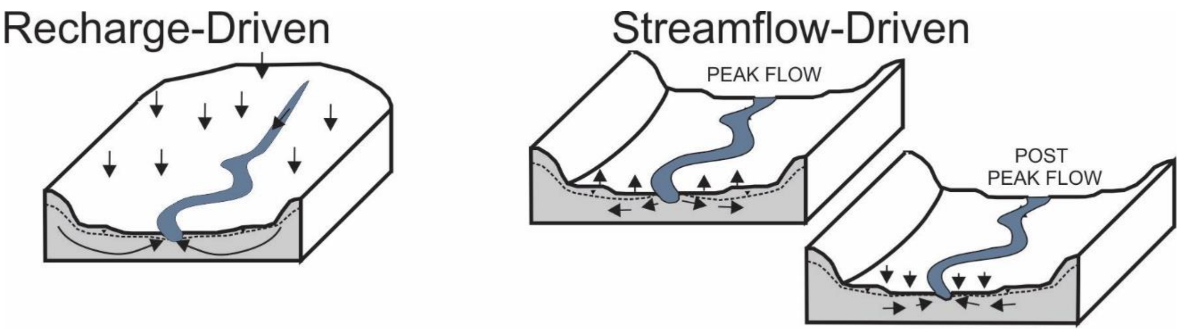

Figure 9: Conceptualization of groundwater flow directions in the two aquifer - stream system types. Recharge-driven systems: groundwater is recharged solely by precipitation and dominantly discharges to streams. Stream-driven systems: groundwater flow to and from streams is bi-directional and varies seasonally depending on the stream stage. From Allen et al. (2014).

The terms recharge-driven and streamflow-driven were specifically chosen by Allen et al. (2010) to reflect key differences in the response mechanism observed in the nine selected well hydrographs relative to a hydrograph from a nearby stream. One of the major limitations in extending this approach to other observation wells in B.C. is the lack of hydrometric stations in streams that intersect the aquifer of interest. For example, of the 37 observation wells examined by Allen et al. (2014), nine wells had no nearby stream, and so streamflow data were retrieved from the Water Survey of Canada Archived Hydrometric Data site (Environment Canada, 2004) for the nearest station. However, oftentimes, the hydrometric station was located some distance away from the well and perhaps not even in the same aquifer. As a result, 17 of the 37 wells were identified as being "potentially both" recharge-driven and streamflow-driven (see Table 1 in Allen et al., 2014). Thus, proximity of the hydrometric station to the aquifer is important. It is also important to note that the studies by Allen et al. (2010, 2014) used only monthly data (daily groundwater level data have become available since around 2005). Moreover, some of the observation wells included in those studies are no longer active, or the associated hydrometric stations are no longer active.

3. GOAL AND SCOPE OF THE STUDY

The goal of this study was to classify the dominant response mechanism, defined by Allen et al. (2010) as recharge-driven or streamflow-driven for observation wells across B.C. Practically, the goal was to identify which signal leads, the groundwater signal or the streamflow signal. The identification of the response mechanism can provide useful insight into the nature of hydrogeologic system and possibly aid in the interpretation of hydraulic connectivity between aquifers and streams.

Section 4 of this report describes the data sources and the two diagnostic tools used to determine whether the groundwater level signal leads or the streamflow signal leads: hysteresis plots and cross-correlation plots. The various data processing steps and plotting were carried out in R Statistics Software (R Development Core Team, 2006). Section 5 presents some example results, along with general observations stemming from the analysis, the limitations of the analysis, and offers some potential uses of the classification results.

The results of the classification are integrated into a MS Excel spreadsheet, along with other information pertinent to the analysis. The spreadsheet contains three sheets: 1) Summary, 2) Aquifers, and 3) Classification. Appendix A describes the metadata for this spreadsheet. Appendix B provides the various plots used to classify each well analyzed.

4. METHODS

4.1 Groundwater Level Data Source

The PGOWN currently (as of November 2020) includes 220 observation wells. In total 164 wells had nearby B.C. Federal-Provincial Hydrometric Network stations with continuous daily streamflow data and were analyzed using hysteresis plots and cross-correlation plots. Wells that did not have a hydrometric station on a stream that flows over or adjacent to a mapped aquifer were not analyzed, in addition to wells that are no longer active. Of these 164 wells, only 123 are classified as recharge-driven or streamflow-driven. Wells with a nearby hydrometric station that did not have sufficient overlap between the periods of record of the hydrometric data and groundwater level data were not classified due to lack of data.

While some of the groundwater level records are longer than 30 years, this study uses data measured since 2005 when pressure transducer dataloggers were deployed in the wells to measure groundwater levels hourly. Hourly groundwater level data were averaged to daily values using an R script provided by Paul Whitfield (personal communication, Environment and Climate Change Canada).

The study focuses on data collected over a three-year period where possible: in calendar years 2013 to 2015. A three-year period was chosen to have sufficient data to illustrate some inter-annual variability in the hysteresis plot, while at the same time not creating plots that were too cluttered to interpret. For wells without data in these years, a different period was used (18 wells in total). For example, for newer wells, more recent data up to September 30, 2020 were analyzed. The period used to analyze the data is shown in the accompanying spreadsheet, along with the full period of record for the well.

4.2 Selecting Hydrometric Stations and Smoothing Stream Discharge Data

For each observation well, daily stream discharge data from the nearest hydrometric stations were used. Where the nearest hydrometric station was not situated in a stream adjacent to the aquifer in which the observation well is located, an alternative hydrometric station at a greater distance from the well was used in the analysis. An alternative hydrometric station was chosen when the closest station was deemed to not be connected to the aquifer, such as a station located in an adjacent valley or a station at a confluence with another higher order stream between the observation well and the hydrometric station. Finding an appropriate hydrometric station in a stream adjacent to the aquifer was the most challenging part of this study.

The hydroclimatic regime for each hydrometric station was also identified: snowmelt dominated, rainfall dominated, hybrid (rain and snow), and regulated[5] following Déry et al. (2009) and Bonsal et al. (2019). While the regime classification provides context for the seasonal timing of the streamflow and groundwater level responses, it does not specifically influence whether the streamflow leads or follows the groundwater level response.

Preliminary analysis of the groundwater level and stream discharge data (as described in the following section) was very difficult in some instances due to stormflow peaks. Stormflow peaks are driven by direct precipitation on streams, overland flow and some subsurface flows (i.e., interflow above the water table). So, to improve the ability to interpret the correlation results and remove these peaks, the stream discharge data were smoothed using a recursive low-pass filter (Fuka et al., 2018). The baseflow separation function from the EcoHydRology R package was applied on the hydrometric data with three passes of a 0.925 filter in R (Nathan and McMahon, 1990; Fuka et al., 2018).

4.3 Hysteresis Plots and Cross-Correlation Plots

Hysteresis plots (or pathline scatter plots) and cross-correlation plots were used as diagnostic tools to determine the response mechanism (recharge-driven or streamflow-driven), and to assess the strength of the correlation and the lag between the groundwater level signal and the streamflow signal.

Hysteresis plots, which compare the groundwater level and the corresponding stream discharge each day, were constructed for the individual observation wells. Groundwater level is plotted on the y-axis using an arithmetic scale, and stream discharge is plotted on the x-axis using a log scale. The R script used for generating the hysteresis plots were provided by Paul Whitfield (personal communication, Environment and Climate Change Canada). The hysteresis plots were examined for the general direction (clockwise, CW, or counter-clockwise, CCW) indicating whether the groundwater level leads (CW or positive) or stream discharge leads (CCW or negative) the response, as well as shape of the hysteresis plot.

Cross-correlation plots between stream discharge and groundwater level were constructed using the ccf() function in R. Cross-correlation is a measure of similarity of two signals (waveforms) as a function of a time lag applied to one of them, and demonstrates not only the degree of fidelity between two variables, but also the correlation between two variables at specific time lags, in this case, between stream discharge and groundwater level.

[5] A regulated regime is one in which there are reservoirs or dams upstream from the hydrometric station.

5. RESULTS

5.1 Hysteresis Plots

Hysteresis plots are shown for six observation well – hydrometric station pairs: three examples in a snowmelt regime (Figure 10) and three examples in a rainfall regime (Figure 11). These examples were chosen to reflect a range of aquifer types and responses. The hysteresis plots for all wells analyzed in this study are provided in Appendix B.

Each month in the hysteresis plot is given a separate symbol, and each year is given a different colour. By tracking the symbols, the direction of hysteresis can often be determined. The direction of the hysteresis is noted on each plot: CW is denoted by a positive loop and CCW by a negative loop. In some cases, the direction was difficult to identify due to the "messiness" of the plot.

A hysteresis effect is evident in all six plots, although the shape of the hysteresis differs. The hysteresis is due to the lag between stream discharge and groundwater level, which generates a loop structure that repeats itself in general shape but not in position between years.

In Figure 10 (snowmelt regime), Obs. Well 236 (Figure 10a) is completed in a confined sand and gravel aquifer #464 (Greater Kelowna Aquifer). It has a positive (CW) loop indicating that the groundwater level leads the response (recharge-driven). The aquifer mapping report #464 suggests that at higher elevations, recharge to the confined aquifer may be from infiltration of runoff to upper slopes and discharge of bedrock flow into alluvial fan and colluvium at the bedrock-overburden interface. Therefore, the aquifer may be rapidly recharged during the snowmelt season and respond similarly to an unconfined aquifer. Obs. Well 306 (Figure 10b) is located in an unconfined sand and gravel aquifer #482 (unnamed aquifer), along the Kettle River valley at Beaverdell. Unsurprisingly, due to the narrowness of the aquifer along the river valley and thus high hydraulic connectivity of the aquifer with either or both of Beaverdell Creek or the Kettle River, the response is negative (CCW), and the system is streamflow-driven. The aquifer mapping report #482 does not speak to hydraulic connection. Similarly, Obs. Well 409 is completed in an unconfined sand and gravel aquifer #103 (Hullcar Aquifer). Here, the streamflow leads the groundwater level response (negative) (Figure 10c). The aquifer mapping report #103 indicates that groundwater flow is expected to be towards Deep Creek where it crosses the Hullcar valley. Overall, among these examples, there is a consistent annual pattern with variations between years, although Wells 236 and 409 had unusual responses in 2015. Many areas of the province experienced drought in 2015, and these deviations could be related to the unusual climate conditions that year.

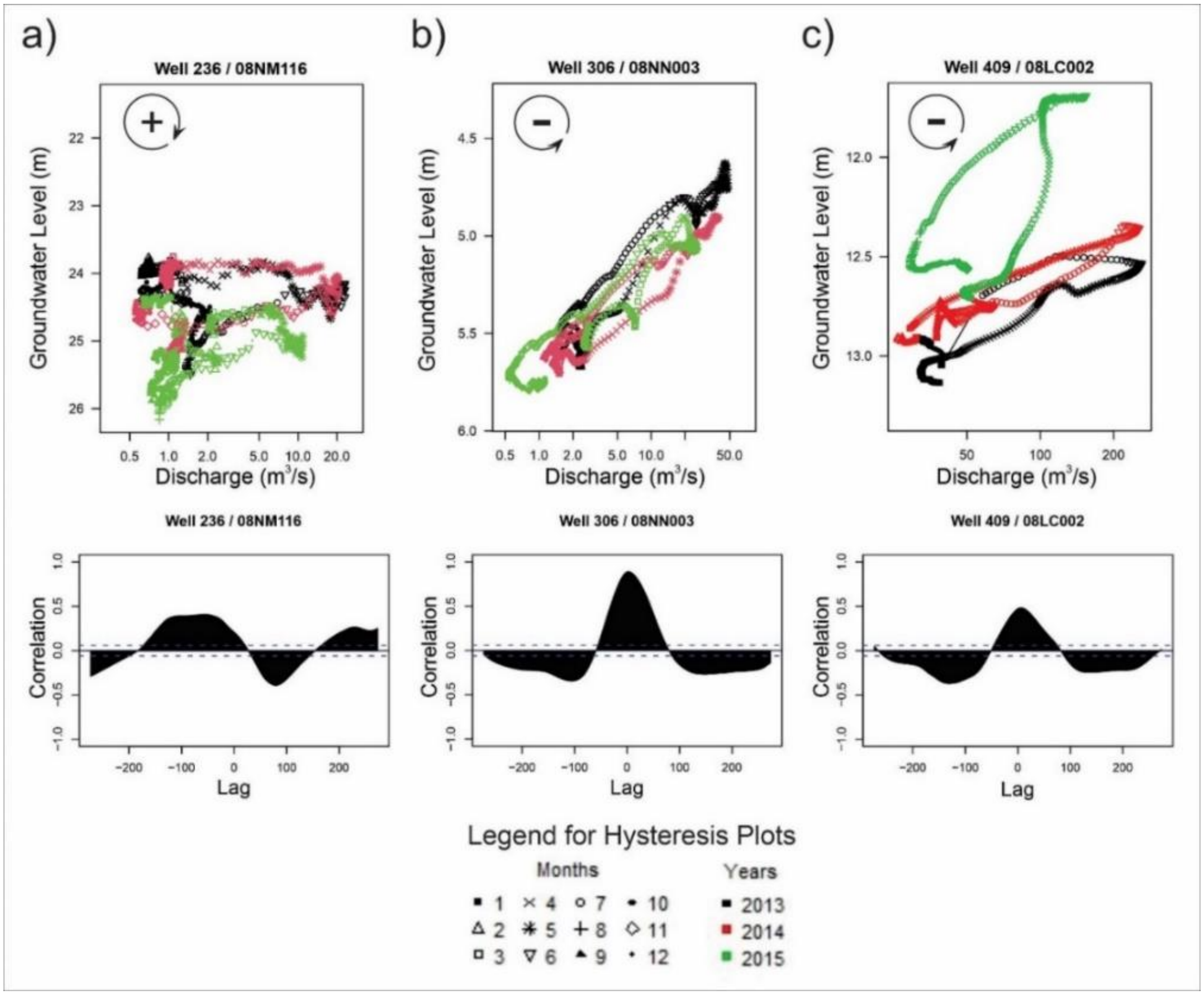

Figure 10: Hysteresis plots and cross-correlation plots for three observation well – hydrometric station pairs in a snowmelt regime. Obs. well 236 is completed in a confined sand and gravel aquifer #464 (positive); 306 is located in an unconfined sand and gravel aquifer #482, at Beaverdell (negative), and 409 is completed in an unconfined sand and gravel aquifer #103, near Spallumcheen (negative).

In Figure 11 (rainfall regime), Obs. Well 255 (Figure 11a) is completed in a crystalline bedrock aquifer #1216 (Vedder Mountain NW Aquifer). This bedrock aquifer extends along the northeast side of Vedder Mountain. Here, the groundwater level leads the response (positive) suggesting a recharge-driven system. The aquifer mapping report #1216 indicates that recharge is inferred to be primarily from precipitation through areas of bedrock exposure, particularly at higher elevation on Vedder Mountain. Obs. Well 406 is completed in an unconfined sand and gravel alluvial or colluvial fan aquifer #8 (Sardis Vedder Aquifer). The aquifer mapping report #8 suggests the aquifer is recharged by the Chilliwack River; however, here the groundwater level leads the response (positive) (Figure 11b). Finally, Obs. Well 002 is located in an unconfined sand and gravel aquifer #15 (Abbotsford-Sumas Aquifer). The aquifer mapping report #15 indicates that recharge to the aquifer is likely from direct infiltration of precipitation, localized perched groundwater systems, and from local creeks or lakes. The hysteresis plot suggests streamflow leads the groundwater level (negative) (Figure 11c). These contradictory interpretations are discussed in Section 5.3.3.

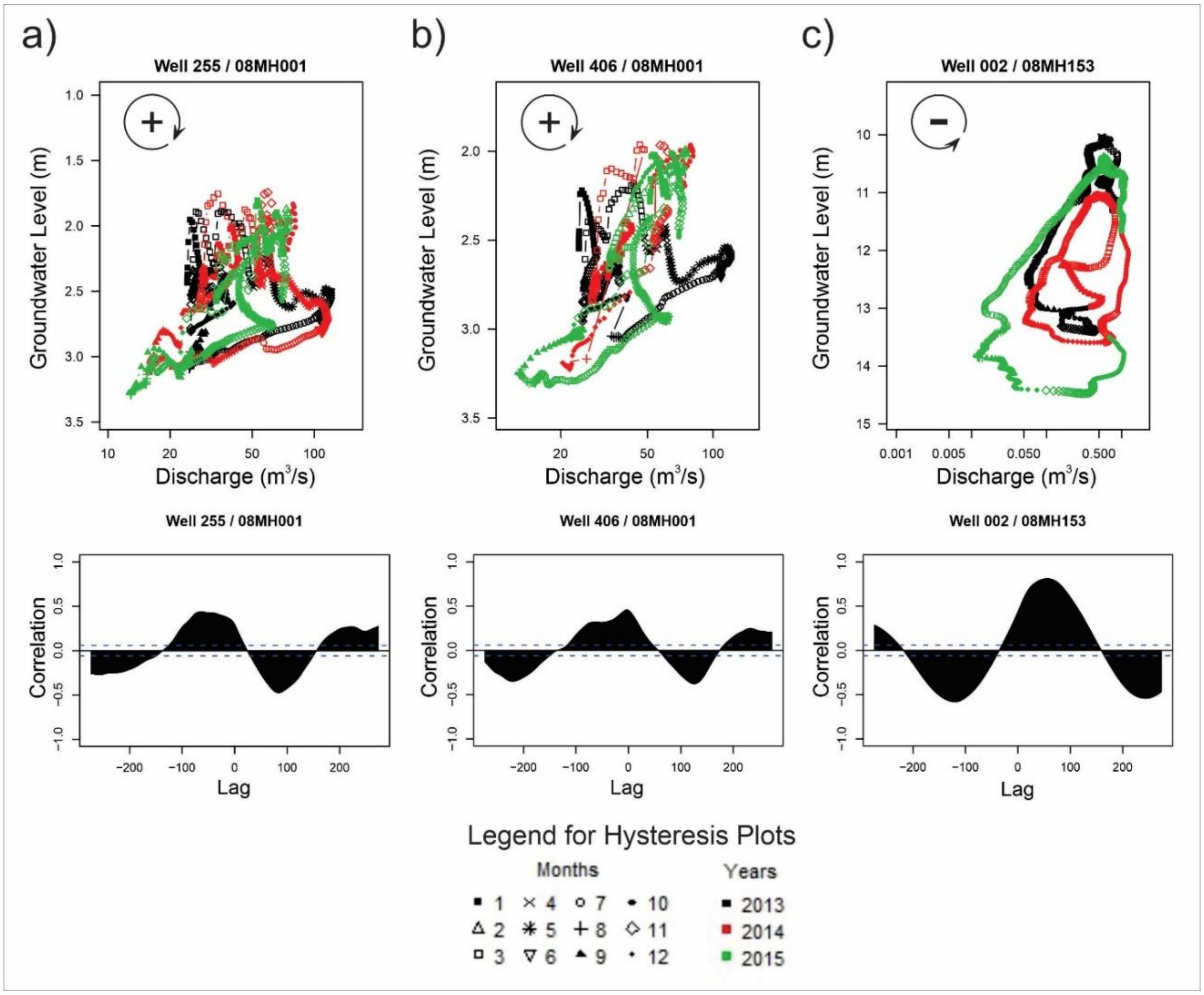

Figure 11: Hysteresis plots and cross-correlation plots for three observation well – hydrometric station pairs in a rainfall regime. Obs. well 255 is completed in a fractured crystalline bedrock aquifer #1216 (positive); 406 is completed in an unconfined sand and gravel alluvial or colluvial fan aquifer #8 (positive); and 002 is located in an unconfined sand and gravel aquifer #15 (negative).

5.2 Cross-correlation Plots

The accompanying cross-correlation plots in Figures 10 and 11 show that peaks (and troughs) repeat roughly at yearly intervals (lags of multiples of 365 days). A high cross-correlation factor (referred to simply as the **correlation** on the x axis of the plot) indicates fidelity (high R^2) between stream discharge and groundwater level (similar shape), while a time shift reflected in the lag shows the timing delay (**in days**) of the response of the groundwater level relative to the stream discharge. A positive lag indicates streamflow leads, while a negative lag indicates the groundwater level leads. ***Note that positive and negative lags are opposite to hysteresis direction. This is simply because stream discharge is defined as the y variable in the cross-correlation analysis and groundwater level the x variable. If y leads x, then x is lagging behind and so x has a negative lag.***

If there is a high correlation value at zero lag, this means that the two signals are of similar shape and are synchronous. For all plots, the lag at the peak correlation value was recorded (see spreadsheet). For this study, a weak correlation is identified if the correlation coefficient is less than 0.3339 (these weak correlations are identified in the spreadsheet). The cross-correlation plots are provided alongside the hysteresis plots in Appendix B for all wells analyzed in this study.

In Figure 10, the observation well – hydrometric station pair with the highest correlation is for Obs. Well 306 (Figure 10b). The lag is also slightly positive, which means that the streamflow leads, i.e. the same as the hysteresis plot, but does not lead by much. In contrast, Obs. Well 236 (Figure 10a) has a negative lag (close to -100). This suggests that the groundwater level leads streamflow by roughly 100 days. Obs. Well 409 (Figure 10c) has a slightly positive lag, but a lower correlation compared to Obs. Well 306.

In Figure 11, both Obs. Wells 255 (Figure 11a) and 306 (Figure 11b) have negative lags (groundwater leads). The low correlation values and negative lags exhibited by both wells point to the low fidelity and lack of synchronicity between the groundwater level and stream discharge hydrographs. In contrast, Obs. Well 002 shows high fidelity ($R^2 > 0.8$) at a positive lag, as evidenced by the shift in the center peak to the right of the center line (Figure 11c).

The cross-correlation plots also show a consistent correlation at lag multiples of 365 days, suggesting that annually, the responses do not vary significantly.

5.3 Discussion

5.3.1 General Observations

Hysteresis loop patterns are a function of the connectivity between the aquifer and the stream. If the groundwater level and stream discharge rise and fall together, the result would be a straight line. None of the observation well – hydrometric station pairs had perfect 1:1 correlation. However, narrow hysteresis curves (e.g., Figure 10b) were observed. These are often associated with wells and streams situated in deep narrow valleys in the Interior. Here, the narrowness of the hysteresis loop reflects the almost synchronous rise and fall of the groundwater level and the stream discharge. In contrast, broad circular loops (e.g., Figure 11 or the plots for Obs. Wells 386, 416, 337 in Appendix B) represent a greater lag between the groundwater level and the stream discharge.

For many wells, the hysteresis plots were difficult to interpret. In general, the hysteresis plots for recharge-driven systems tend to be “messier” than those of streamflow-driven systems which are smoother. In some cases, the direction changed (CCW to CW or vice versa) from one year to the next, and in many cases the hysteresis direction was clear for one year and unclear for other years. The Classification tab in the spreadsheet identifies the excursions in the Hysteresis Direction column.

Also, commonly, during the recession period, the groundwater level and stream discharge decline synchronously, both appearing as straight lines, while during the period of rise the plots are messier, notably in the recharge-driven systems (e.g. Figure 11a). These excursions are shown by large variations in discharge without changes in water level. As stream discharge increases, the groundwater levels remain the same for some time (e.g., there is a horizontal line of data points above the x-axis). As stream discharge decreases, groundwater levels do not drop, instead they remain constant for some time. Thus, during the recharge season, the hysteresis plots can be difficult to interpret.

Of the 220 Provincial Observation wells, 149 had sufficient data to generate plots. Of these 149, only 123 could be classified as either recharge-driven (34%) or streamflow-driven (66%). The remaining 26 wells were classified as indeterminant because either (or both) the hysteresis plot or the cross-correlation plot yielded indeterminant results. For most of these indeterminant cases (22 wells), it was the hysteresis plot that could not be interpreted. For nine (9) wells, the hysteresis plot and cross-correlation plot yielded conflicting classification results. For these, local hydrogeological conditions were examined to classify the well.

Figure 12 shows the classification results grouped by aquifer subtype. It is important to note, however, that some aquifer subtypes have very few wells, so these results should not be scrutinized too closely. The two aquifer subtypes most represented are 4a and 4b. Wells in subtype 4a were dominantly classified as streamflow-driven, while for 4b there were moderately more streamflow-driven compared to recharge driven. A streamflow-driven classification was expected for aquifer subtypes 1a, 1b, 1c and 2, because these are associated with unconfined fluvial or glacio-fluvial sand and gravel aquifers situated along rivers or forming river deltas and so would likely respond strongly to changes in streamflow. However, only slightly fewer observation wells were classified as recharge-driven in these aquifer subtypes. In contrast, observation wells in bedrock aquifers, including subtypes 5a, 6a, 6b and unmapped bedrock aquifers, were expected to be dominantly recharge-driven. But most wells in 5a and 6b aquifers are streamflow-driven. No observation wells are located in aquifer subtype 5b across the province, and none of the observation wells in subtypes 6a could be classified (Figure 12).

Observation wells in rainfall-dominated hydroclimatic regimes are predominately (81.6%) classified as streamflow-driven (Figure 13). In contrast, the relative proportions of recharge-driven and streamflow-driven systems in snowmelt and hybrid hydroclimatic regimes are similar (Figure 13).

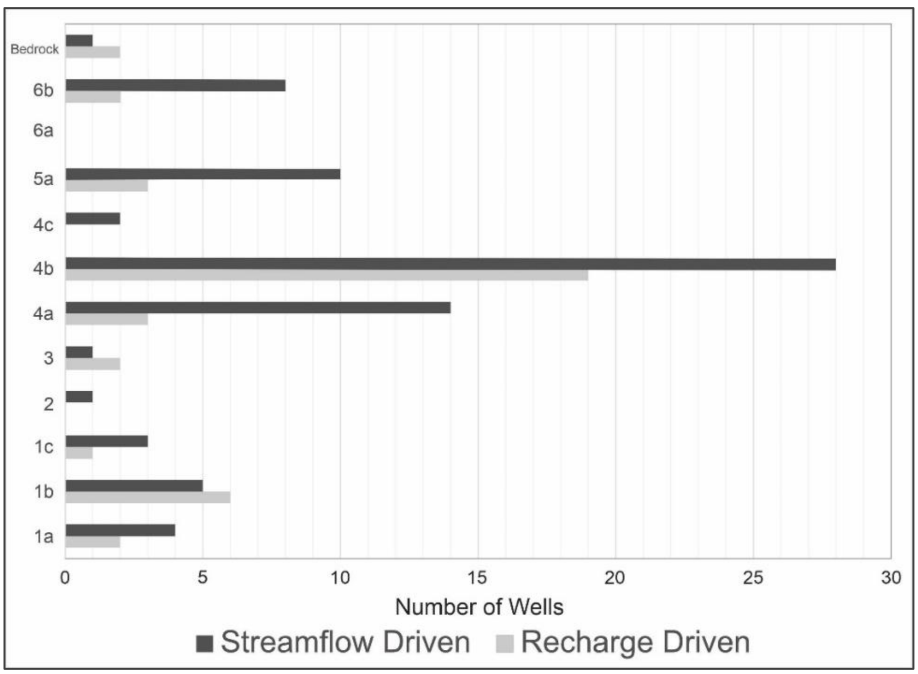

Figure 12: Summary of the aquifer - stream system classification by aquifer subtype. Refer to Table 1 for a description of aquifer subtype. Bedrock is unmapped bedrock.

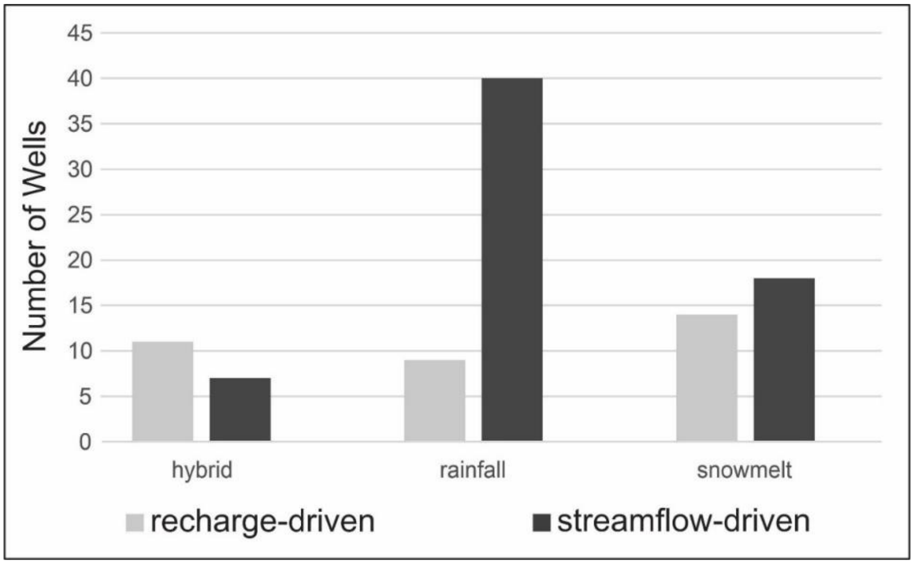

Figure 13: The number of recharge-driven and streamflow-driven systems for each hydroclimatic regime (hybrid, rainfall, or snowmelt dominated).

5.3.2 Snowmelt Regime

Overall, most wells in the Interior have a negative hysteresis and positive lag, reflecting that streamflow leads the groundwater level in most settings. This is not surprising because most provincial observation wells are located in valley bottom aquifers comprised of highly permeable aquifer materials and there is often a major stream (or lake system) flowing through them. During the freshet, snowmelt at higher elevation generates streamflow that drives the groundwater level response in the valley aquifers. As a generality, then, many valley bottom aquifers in interior mountain regions will likely be streamflow-driven systems.

In contrast, aquifers in upland areas are more likely to be recharge-driven systems. Aquifers are commonly comprised of bedrock, but some areas have small unconsolidated aquifers (e.g. terraced glacial deposits). In these upland areas, the proximity of the well to the nearest stream is an important consideration. If a well is close to a stream, the response may be justifiably streamflow-driven. In some upland cases, a streamflow-driven system was suggested by the analysis, even though the well is nowhere near a stream. In these upland areas, the aquifers are likely dominantly recharged by snowmelt and if the aquifer is comprised of bedrock, it may take some time for the meltwater to percolate to the water table. Thus, the streamflow response may be more rapid and appear to lead the aquifer. In some cases, however, the nearest hydrometric station used in the analysis may be at a distance from the well or indeed not even in a stream connected to the aquifer in question. Thus, the analysis is simply describing the aquifer response relative to a generalized hydrologic response, not a specific (or localized) hydrologic response. Overall, there is a lack of hydrometric stations in high elevation areas, so the classification results should be viewed with caution in these areas.

The responses in the confined aquifers in the Interior (e.g. 236 shown in Figure 10a) are interesting because many were classified as recharge-driven – i.e. they have positive hysteresis loops and negative lags. Intuitively, because these aquifers are confined, it might be expected that the aquifer would have a delayed response to snowmelt and so would lag streamflow. However, Obs. Well 236 (Figure 10a) led the streamflow response by 100 days. The aquifer (#464) has been interpreted as being internally well-connected below upgradient geographic areas and recharge is thought likely to be from infiltration of runoff to upper slopes of the aquifer. Therefore, it is possible that some confined aquifers are being recharged by snowmelt along their edges where the aquifer meets the upland bedrock at the valley bottom edge, and so are responding more like unconfined aquifers. Here, fractures might deliver snowmelt to the valley bottom rapidly. Importantly, confined aquifers are rarely truly confined, and there is often some transmission of water through confining units or the confining unit may be discontinuous and allow for some recharge through “windows”. Moreover, streams may incise confining units, allowing for hydraulic connection. In the case of aquifer #464 (Obs. Well 236), the aquifer report notes that there may be some hydraulic connection with Mission Creek where it flows over, and next to, exposures of the aquifer. Thus, the response mechanism of confined aquifers may strongly depend on local confining conditions.

Finally, most observation wells in the Interior are located in valley bottom aquifers because this is where the majority of people live. This point is important because the response of valley bottom aquifers reflects a combination of local climate influences and remote climate influences. For example, diffuse recharge to the aquifer may occur from spring snowmelt within the valley and from spring and early summer precipitation. Focused recharge from a stream, however, may also be significant in some valley bottom aquifers. These streams originate at higher elevation in headwater regions of the watershed. Thus, the timing of the groundwater response may be more strongly tied to climatic conditions outside of the valley bottom.

5.3.3 Rainfall Regime

In coastal areas, snowpack is minimal and streams are not supported by snowmelt in the summer months (except at higher elevations). Early winter rains generate high stream discharge and rains continue throughout the winter sustaining streamflow into spring. This intense early winter rain also rapidly recharges the aquifers by infiltration. Interestingly, most wells in the Fraser Valley are classified as streamflow-driven, with peak groundwater levels lagging precipitation on average by ~60 days. For example, groundwater levels in Obs. Well 002 (Figure 11c) lag stream discharge by approximately 50 days. The apparent sluggish response of groundwater level to precipitation (i.e. groundwater level lags stream discharge) is attributed to the high conductivity (K) and high specific yield (Sy) of the unconfined aquifer. As discussed in Section 2.1.2, aquifers with high K values drain rapidly, so as the aquifer is recharged the water level does not rise significantly. Compounding this effect, the high Sy results in more water needing to be added to the aquifer to observe a groundwater level change. The high Sy also leads to sustained groundwater levels over a long period of time. Therefore, due to the high Sy, the magnitude of the groundwater level response is small when compared to a change in discharge and so the groundwater level appears to lag stream discharge. A deep water table (e.g. below 10 m) and associated moisture deficit in the unsaturated zone may also delay the water table response to recharge. These aquifers are ‘raised’ aquifers and are mostly recharged by precipitation and should perhaps be classified as recharge-driven. However, in the spreadsheet, they are classified strictly based on the results of the analysis. It is important to note that Obs. Well 002 is located at some distance from any stream, and perhaps if the well had been closer to a stream, even in this type of aquifer, there may have been some actual influence from high stream discharge in the winter due to the high permeability. Therefore, this well, and many other wells in the Fraser Valley, are likely mis-classified as streamflow-driven.

Many of the streams in the Fraser Valley have low discharge during the months of July, August and September. When there is streamflow during late summer, it is generally groundwater discharge. During these low flow periods, changes in groundwater levels are near synchronous with stream discharge as evident on the hysteresis plots by the steady decline in both groundwater level and streamflow. See for example, Obs. Well 406 in Figure 11b. The symbols for June, July and August (in black for 2013) track linearly from the far right of the plot to the lower to the lower left, representing the recession of both groundwater level and streamflow. In contrast, groundwater levels are inconsistent with large stream events during the recharge period and give rise to messy hysteresis plots as discussed previously. See for example, the messiness of the plot for Obs. Well 406 (Figure 11b) for the other months of the year.

The groundwater level response in bedrock aquifers (e.g. Obs. Well 255 in Figure 11a) is very similar to that of other unconfined aquifers (e.g. Obs. Well 406 in Figure 11b). In bedrock wells, the low storage coefficient means that when it starts to rain in the fall, there is a limited capacity for infiltration, but what water does enter the groundwater system translates rapidly into an increase in groundwater level. Thus, groundwater levels in the aquifer will generally rise more rapidly in comparison to aquifers with a larger storage capacity and will reach their maximum value within a relatively short period of time. The recession in groundwater levels also occurs quickly due to the limited storage capacity of the bedrock system.

5.4 Limitations of the Analysis

The most important limitation of this analysis is the lack of hydrometric stations on streams that intersect the aquifers with the observation wells. In most cases, the nearest hydrometric station was used, but in cases where the nearest hydrometric station was not situated in a stream adjacent to the aquifer in which the observation well is located, an alternative hydrometric station at a greater distance from the well was used in the analysis (see notes column on the Classification tab in the spreadsheet). Oftentimes, an ideal hydrometric station was nearby, but it was no longer active, or the period of record did not overlap with the groundwater level data. As a result of this data limitation, some of the classification results may not be correct.

The aquifer – stream classification results interpreted from the hysteresis plot was sometimes (9 wells) inconsistent with that interpreted from the cross-correlation plot. For such cases, the location, surrounding topography, and aquifer characteristics noted in the aquifer mapping report, such as recharge and groundwater abstraction, were examined to ultimately classify the well (final classification in Appendix A). Thus, no single method should be relied upon to determine the classification, and some hydrogeological interpretation may be needed in certain cases.

For 26 wells, the final classification was indeterminant because either (or both) the hysteresis or the cross-correlation plot yielded indeterminant results. For most of these, the hydrometric station was simply too far away or had insufficient data. In these cases, the final classification was considered indeterminant; however, re-examination of the results in concert with local hydrogeological knowledge may enable classification.

Some wells may be mis-classified. For example, for some upland wells in the Interior, a streamflow-driven system was suggested by the analysis, even though the well is nowhere near a stream. The slow water table response to snowmelt recharge in these dominantly bedrock aquifers may explain why streamflow leads the response. However, in some cases, the nearest hydrometric station may be too far away for an accurate analysis. Overall, there is a lack of hydrometric stations in high elevation areas, so the classification results should be viewed with caution in these areas. As well, most wells in the Fraser Valley were classified as streamflow-driven, but the high specific yield of the aquifers, possibly in combination with a deep water table, may delay the water table response relative to streamflow (see Section 5.3.3 for an explanation). So, despite being classified as streamflow-driven, they may in fact be recharge-driven.

The observation wells were not pre-screened to eliminate those that might be influenced by pumping or storage reservoirs. Such influences may be the reason for difficulties in classifying the response mechanism for some wells. Therefore, the classification results for observation wells suspected of being impacted by pumping or storage reservoirs should be viewed with caution.

Many aquifers have only one observation well, while some aquifers have more than one observation well. It is important to recognize that the groundwater level response may not be the same in all parts of the aquifer. A major factor is the proximity of the observation well to any streams or other sources of water (e.g. recharge along the mountain front) or locations of groundwater abstraction. Thus, it is not the aquifer that is being classified, but rather the well itself.

A final outcome of this study is the classification of the aquifer – stream system type (i.e., recharge-driven or streamflow-driven) for each observation well that could be analyzed. For the reasons above, the final classification may be indeterminant or possibly incorrect. So, the use of this classification should be done with caution. Nevertheless, the individual hysteresis and cross-correlation plots provided in Appendix B of this report are considered representative of the time period analyzed. This does not mean that the results are invalid outside of the time period used for analysis, but certainly the statistics (correlation values and lags) would be different for different time periods. Unless there is some significant change to the hydrologic regime, it is expected that the response mechanism would remain largely unchanged.

5.5 Potential Uses of the Classification Results

The main outcome, and perhaps the most useful and less subjective outcome, is simply the identification of the response mechanism, that is, whether the groundwater level or the stream discharge leads the response. Identification of the response mechanism can provide useful insight into the nature of hydrogeologic system and possibly aid in the interpretation of hydraulic connectivity between aquifers and streams. The Government of B.C. (2020d) states that groundwater level data can be used for a variety of purposes, including:

1. Understanding local and regional hydrogeological processes, including:
    a) groundwater and surface water interactions including environmental flow needs and hydraulic connectivity;
    b) recharge and discharge mechanisms, rates and timing in lowland and upland areas, short and long-term impacts of climate change and using groundwater levels as an indicator when assessing drought and flood conditions; and
    c) fundamental aquifer and basin characteristics including water table and potentiometric levels, hydraulic properties and baseline groundwater chemistry.
2. Supporting sustainable use of the groundwater resource and minimizing conflicts between multiple groundwater users or between groundwater and surface water users by providing data to assess:
    a) water authorization decisions including the impact of groundwater withdrawals in specific areas to determine if further groundwater withdrawal is sustainable;
    b) short and long-term local and regional effects of human activity on groundwater and surface water levels; and
    c) the development of water budgets.

How might knowing the response mechanism for a well better inform some of these objectives? Some examples are:

1. Understanding what is driving the groundwater level response measured in the observation well. This is particularly important if groundwater level data for one observation well are being compared to groundwater level data from another observation well. Two wells completed in

different aquifers of the same subtype may have very different response mechanisms depending on the proximity of the wells to local streams.

2. Inferring the degree of hydraulic connection between an aquifer and a stream. If a well is classified as streamflow-driven, then there is a high likelihood that the aquifer is hydraulically connected to the stream (assuming the hydrometric station used for the analysis is situated on a stream connected to the aquifer).
   a) The degree of synchronicity between the groundwater level response and the streamflow response is a strong indicator of hydraulic connectivity. If the hysteresis plot is narrow, changes in the groundwater level and stream discharge are almost synchronous and so there is high hydraulic connectivity between the aquifer and the stream.
   b) Wells classified as streamflow-driven due to their high aquifer specific yield, but that are more likely recharge-driven (e.g. many wells in the Fraser Valley), likely have high hydraulic connectivity with local streams due to the high hydraulic conductivity of the aquifers.
3. Informing whether the groundwater level record for that well is suitable for estimating recharge. The Water Table Fluctuation (WTF) method is premised on the well being located in a recharge area so that the well hydrograph is reflecting only diffuse recharge due to precipitation. If the well is streamflow-driven, then the well is not suitable for recharge analysis. Accordingly, some wells in the Fraser Valley may not be suitable for use in the WTF method unless their response is carefully scrutinized to ensure that the groundwater level is responding to diffuse recharge and not streamflow.
4. Providing insight into how long it might take for a change in groundwater level in a recharge-driven system to propagate to the stream, and vice-versa for the streamflow-driven system. The stronger the correlation coefficient and the shorter the lag, the more immediate the response will be. Weaker correlation values indicate lack of fidelity between the two signals. This may be useful when trying to link wells and hydrometric stations for predicting interactions with strong correlations for onset of drought or flooding.
5. Inferring the response mechanism for aquifers across the province that are unmapped, or that have no observation well or no nearby hydrometric station. When considered alongside the aquifer subtype, this additional information may be useful for understanding potential hydraulic connectivity.

6. CONCLUSIONS

A consistent graphical (hysteresis plot) and statistical (cross-correlation) approach was used in this study to classify provincial observation wells according to the dominant response mechanism: recharge-driven, where the groundwater level response leads the streamflow; and streamflow-driven, where the streamflow leads the groundwater level response. While an attempt was made to analyze and classify all 220 provincial observation well, only 123 were ultimately classified as recharge-driven or streamflow-driven primarily due to a lack of nearby hydrometric station data with an overlapping period of record. The hysteresis and cross-correlation results were sometimes inconsistent and difficult to interpret.

The majority of wells across the province (66%) were classified as streamflow-driven, and in the Interior (snowmelt regime), most wells were classified as streamflow-driven. This result is unsurprising given the physiography of B.C. with its steep mountainous terrain and narrow valleys with streams that are dominantly fed by snowmelt. However, most observation wells in the Fraser Valley that were classified as streamflow-driven, may in fact be recharge-driven (see Section 5.3.3 for an explanation).

No single method, either hysteresis plots or cross-correlation analysis alone, can be used to determine the dominant response mechanism, and some hydrogeological interpretation is needed in certain cases. Moreover, the two response mechanisms represent end members of a continuum of responses that reflect the relative contribution of diffuse recharge to the influence of streamflow on groundwater levels.

The limited number of hydrometric stations in close proximity to observation wells limited the number of observation wells that could be classified. In order to facilitate aquifer - stream system characterization as well as future hydraulic connectivity research, new observation wells should be located near pre-existing hydrometric stations, and new hydrometric stations should be located near pre-existing observation wells. As well, hydrometric stations could be added where understanding of the response mechanism is important.

The classification scheme and diagnostic tools presented in this study have the potential to provide a framework for evaluating the responses of wells in other settings. Anticipating the type of response of an aquifer based on its physical characteristics and hydroclimatic regime would allow for more strategic data collection for detailed studies, such as water sampling for geochemical or isotopic analysis, and physical characterization of the linkages between hydrology and hydrogeology. In addition, understanding the driving mechanisms and consequent aquifer responses would aid in selecting appropriate codes for modelling and setting boundary conditions within the models themselves. Such specialized studies would provide insight into processes at the local scale that influence the aquifer responses at small spatial and temporal scales. Finally, this framework could also be used to guide studies or perhaps provide a broader view on the potential consequences of future climate change on groundwater systems, particularly when detailed analyses are not possible.

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APPENDIX A. META DATA FOR SPREADSHEET

This appendix describes the metadata for the Results Spreadsheet that accompanies this report.

A.1 Summary Sheet

Summary Sheet

The observation wells are sorted and coloured by region (columns A and B):

- Red - North Natural Resource Area (NNRA)
- Yellow - West Coast Region (WCR)
- Green - South Natural Resource Area (SNRA)
- Blue - South Coast Region (SCR)

General Well Information (columns C to P):

*Well Tag Number, Finished Well Depth (ft and m), Geographic Coordinates, Ground Elevation**, were obtained from https://apps.nrs.gov.bc.ca/gwells/.

Period of Record Start: the dates of the oldest available record.

Period of Record End: the dates of the most recent available data. If blank, real-time data are available.

Data Availability: states if real-time data are available.

Long Term Groundwater Level Trend: obtained from the British Columbia Data Catalogue (https://catalogue.data.gov.bc.ca/dataset/indicator-summary-data-long-term-trends-in-groundwater-levels-in-b-c-). The colours represent the trend of the groundwater level, the darker the shade of blue the larger the rate of decline. The grey is for wells that were not included in this data set or did not have enough observations to determine a trend.

- Dark blue - Large rate of decline
- Medium blue - Moderate Rate of decline
- Light blue - Stable or Increasing

Aquifer Info (columns Q & R):

Aquifer Number: obtained from the Well Summary of each observation well (https://apps.nrs.gov.bc.ca/gwells/)

Aquifer Subtype: obtained from the Aquifer Mapping Report or Aquifer Factsheet via a link on the Aquifer Summary page (https://apps.nrs.gov.bc.ca/gwells/aquifers/)

Hydrography and Topography (columns S to Y):

Distance to Streams: The nearest stream and next nearest stream where located and measured from the observation well perpendicular to the stream. Values were compared with Allen et al. (2010, 2014). Distances to the nearest lake/reservoirs were measured to the closest point of the lake shore.

Topography: inferred from satellite imagery and contour lines. Cardinal directions indicated are the down slope directions.

Distance** to Nearest and Next Nearest Active Hydrometric Station/Period of Record (Columns Z to AM): located from iMapBC and the distance from the station to the observation well were measured.

Hydroclimatic Regime: inferred by comparing the hydrographs from the hydrometric stations to the pluvial, nival, and glacial hydrographs from: Déry et al. (2009) and Bonsal et al. (2019, p.288).

Distance** to Nearest Climate Station/Period of Record (columns AN to AT): located using the Pacific Climate Impacts Consortium B.C. Station Data – PCDS (https://data.pacificclimate.org/portal/pcds/map/), iMap BC, and the Historical Climate Data from Environment and Climate Change Canada (http://climate.weather.gc.ca/). Active climate stations were preferred over inactive station. In cases where there are no active stations in close proximity, inactive stations are identified.

Notes (column AU): additional information

*Ground elevation is missing from the Well Summary website for numerous observation wells and is not included in this dataset.

**All distances are measured in metres

Aquifers Sheet

The aquifers are sorted by number. The observation wells are colour-coded according to region (see Summary sheet).

The aquifer data (columns A to G) were accessed through https://apps.nrs.gov.bc.ca/gwells/aquifers. Information on specific aquifers (Aquifer Number, Aquifer Type, Likelihood of Hydraulic Connection, Degree of Confinement, Area, and Calculated Well Density) was collected from the Aquifer Mapping Report or Aquifer Factsheet via a link on the Aquifer Summary page. Additional clarification is provided below.

Calculated Well Density (column G): Calculated and classified based on the number of wells known to be completed in the aquifer per square kilometer:

- Light ≤ 4 wells per km²
- Medium 4 – 20 well per km²
- High > 20 wells per km²

Other well use besides domestic (column H): as reported in the Aquifer Mapping report.

Aquifer Response Type (column I): the aquifer response type was inferred using the aquifer type, likelihood of hydraulic connectivity, and hydrometric data from nearby streams, as well as hysteresis plots of stream discharge and groundwater levels.

Recharge (column J): as reported in the Aquifer Mapping report.

Classification Sheet

The observation wells are sorted and coloured by region (column A).

Hydrometric station number (column B): is the hydrometric station that was used to classify the aquifer - stream system.

Years Used (column C): the years of data that were used for the hysteresis and cross-correlation plots. Calendar years 2013, 2014, and 2015 were used, unless otherwise identified in red.

Hysteresis Direction (column D): the direction of the monthly symbols in the hysteresis plots. The directions are either clockwise (CW), counter-clockwise (CCW), looped, or indeterminate. A “looped” direction is one is which the path the symbols make crosses over and forms multiple loops. A “indeterminate” is one in which there is no clear pattern or direction in the monthly symbols.

AQUIFER-STREAM (hysteresis) (column E): classification of aquifer-stream system type based on the hysteresis plot. A CW direction indicates a recharge-driven system, and CCW direction indicates a streamflow-driven system. Looped or indeterminate indicate neither a recharge-driven system nor a streamflow-driven system.

Correlation coefficient and lag (columns F and G): the lag (in days) is reported at the maximum correlation coefficient between the groundwater level data and the hydrometric data. A weak correlation (<0.3999) is identified in red.

AQUIFER-STREAM (lag) (column H): classification of aquifer-stream system type based on the lag. A negative lag indicates a recharge-driven system whereas a positive lag indicates a streamflow-driven system.

Aquifer Subtype (column I) obtained from the Aquifer Mapping Report or Aquifer Factsheet via a link on the Aquifer Summary page (https://apps.nrs.gov.bc.ca/gwells/aquifers/)

Final AQUIFER-STREAM Classification (column J): final classification of aquifer-stream system type based on the results of the hysteresis plots and lag. In some cases the results were contradictory. For such cases, the location, surrounding topography, and aquifer characteristics noted in the aquifer mapping report, such as recharge and groundwater abstraction, were examined to ultimately classify the well using best judgement.

Notes (column K): additional information related primarily to availability of nearby hydrometric stations and their period of record.

APPENDIX B. COMPILATON OF HYSTERESIS PLOTS AND CROSS-CORRELATION PLOTS FOR ALL OBSERVATION WELLS ANALYZED

North Natural Resource Area

West Coast Region

South Natural Resource Area

South Coast Region

Classification of Groundwater Response Mechanisms in Provincial Observation Wells Across British Columbia

Appendix B. Compilation of Hysteresis Plots and Cross-Correlation Plots for all Observation Wells Analyzed

April Gullacher, Diana M. Allen, and Jon Goetz

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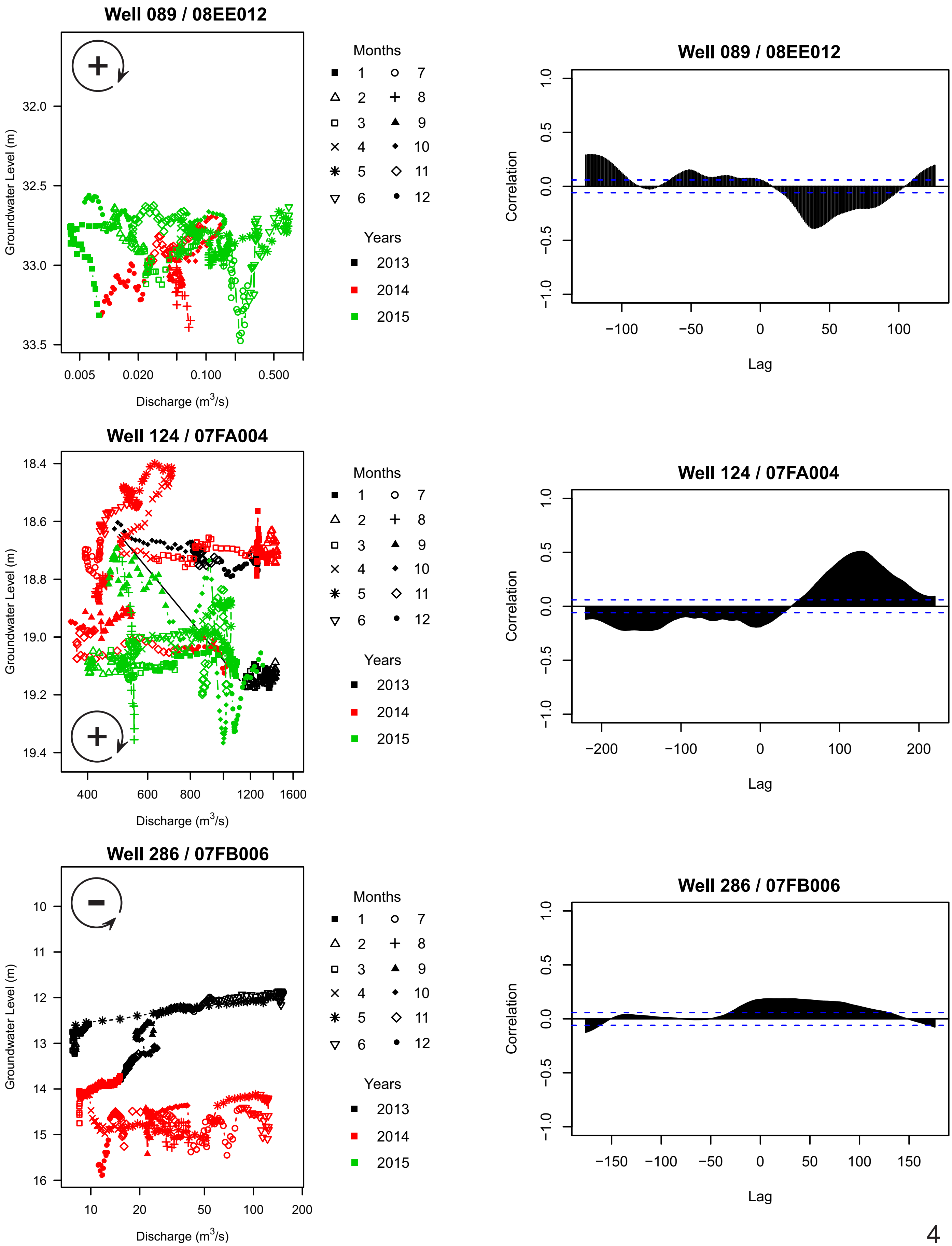
CONTENTS

North Natural Resource Area

North Natural Resource Area



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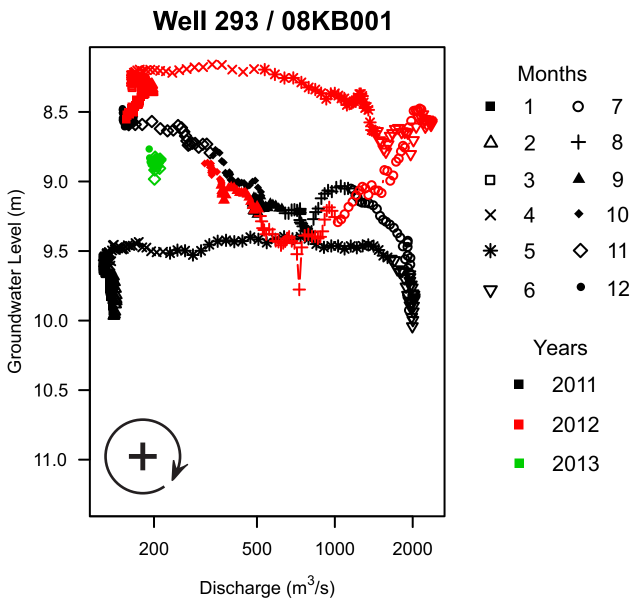

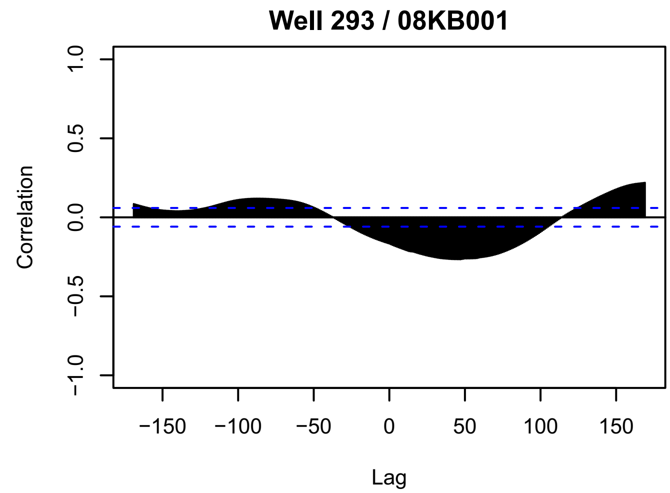

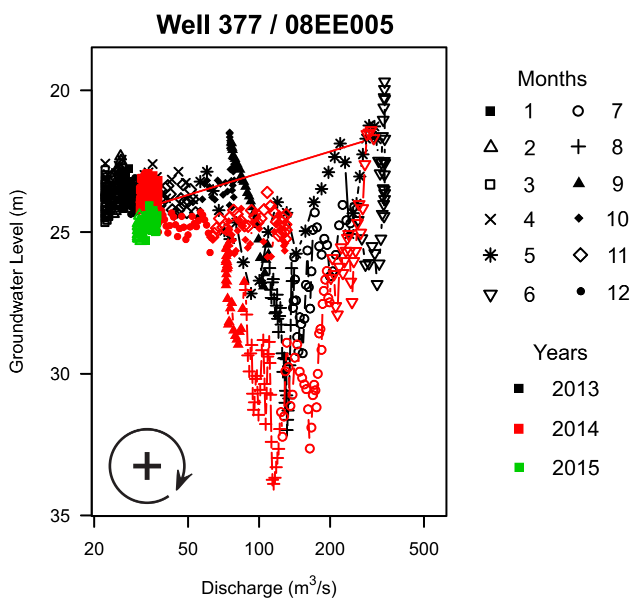

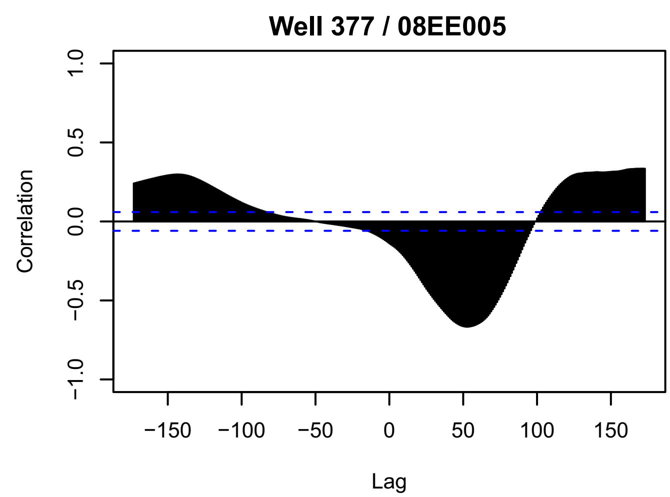

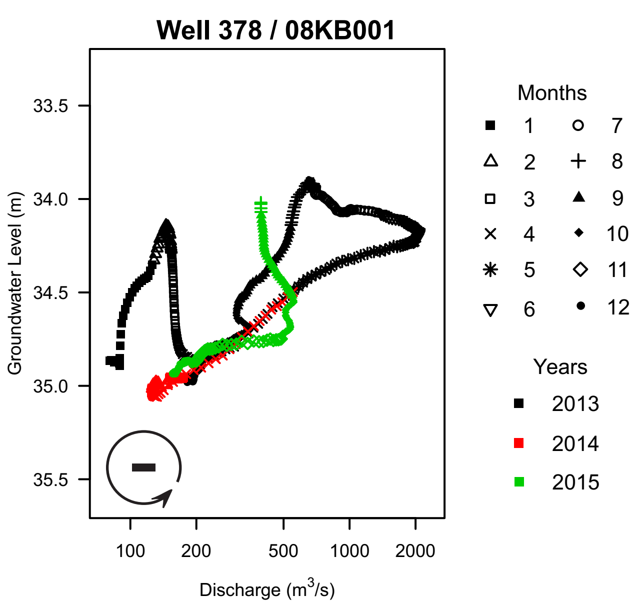

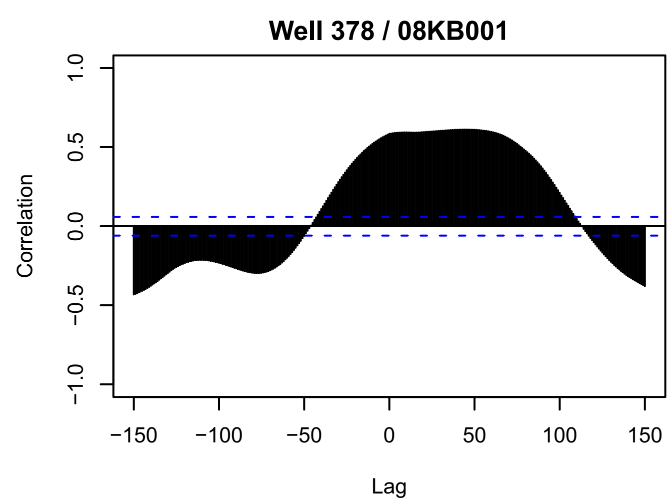

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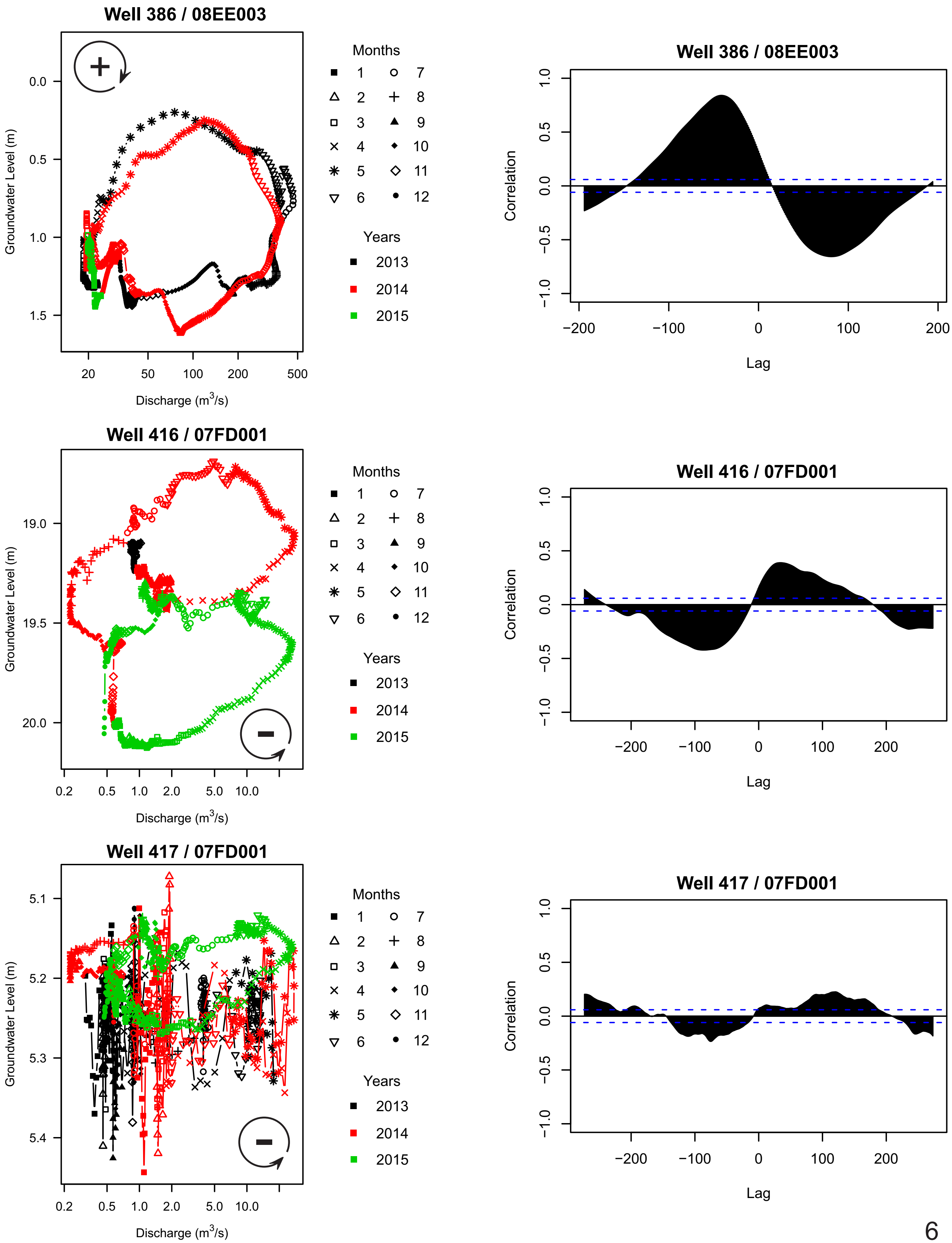

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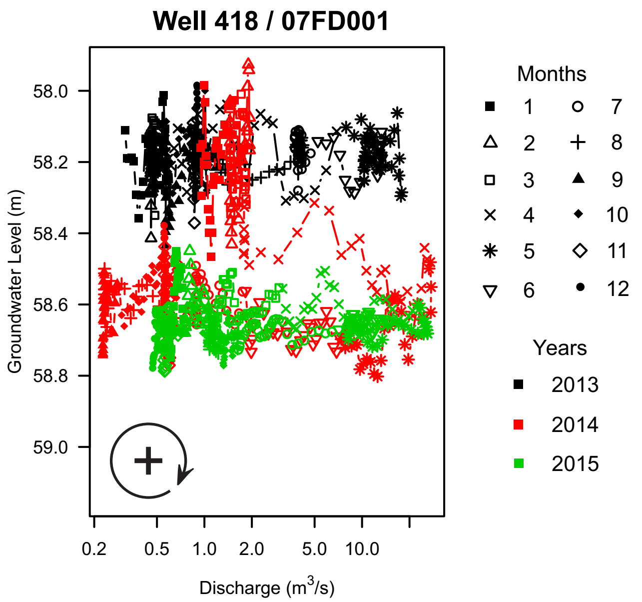

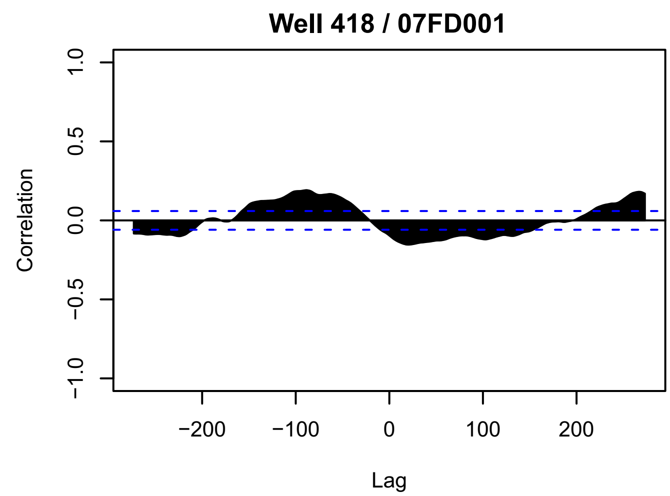

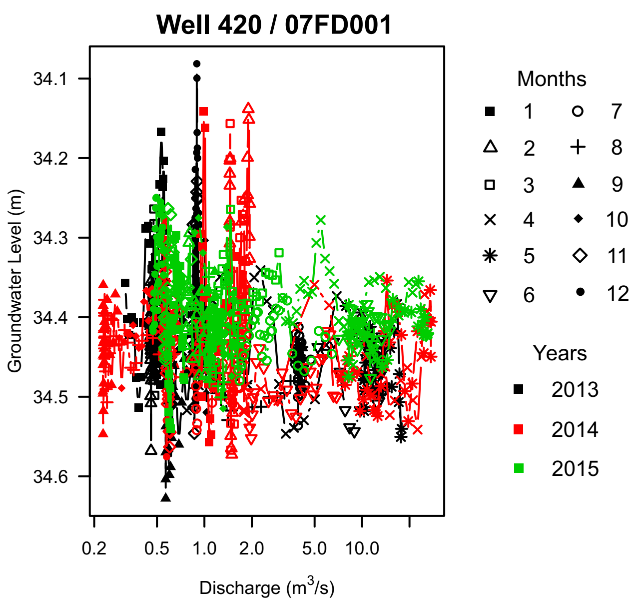

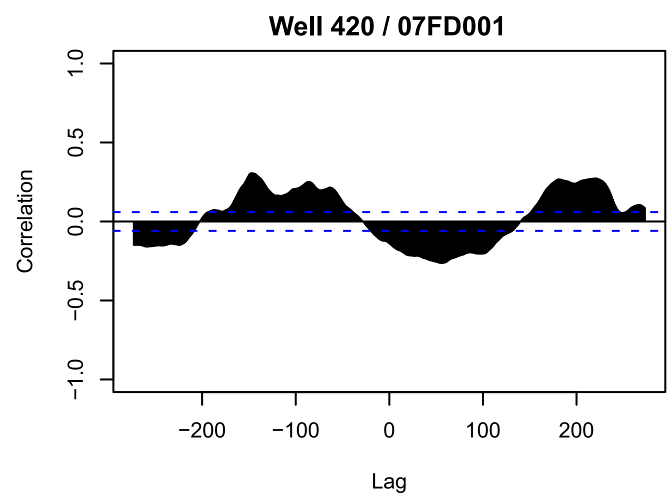

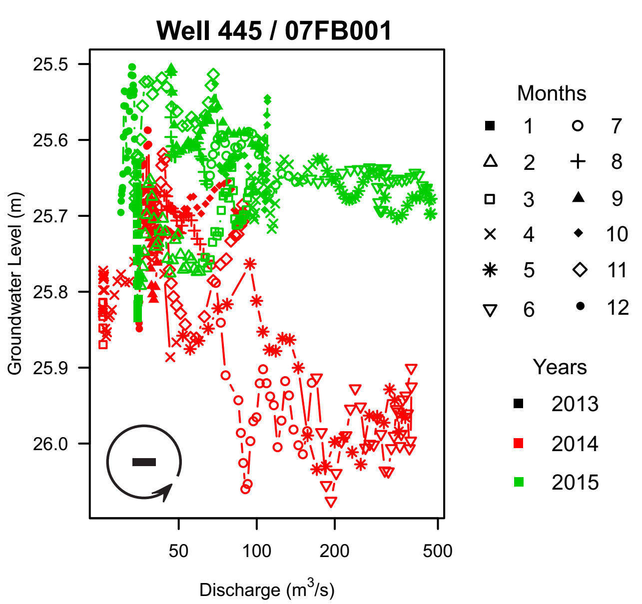

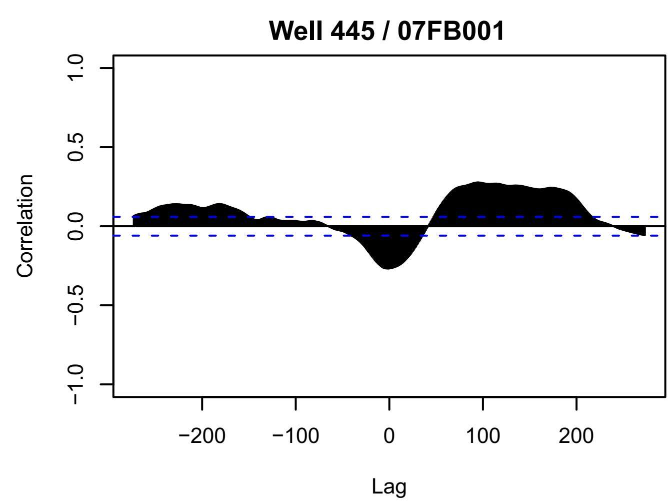

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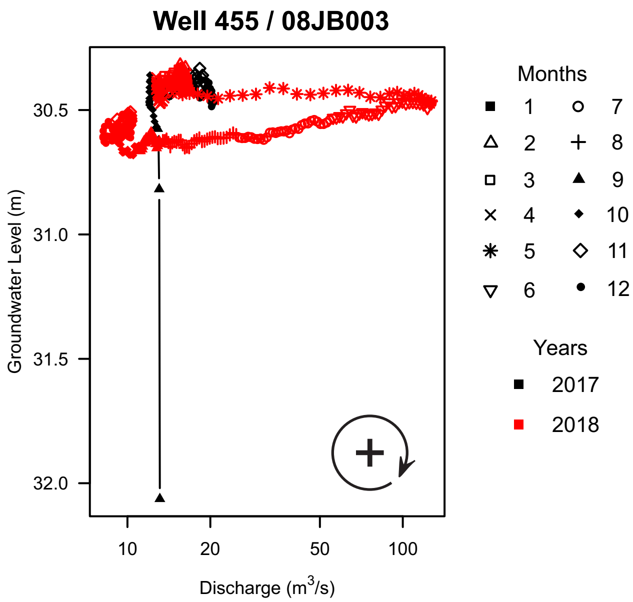

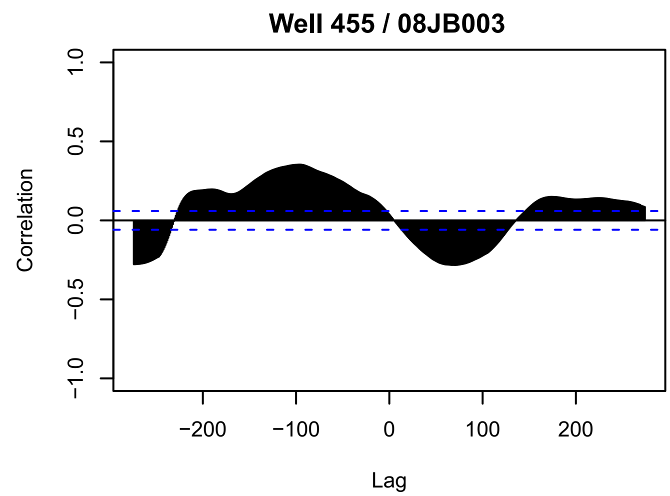

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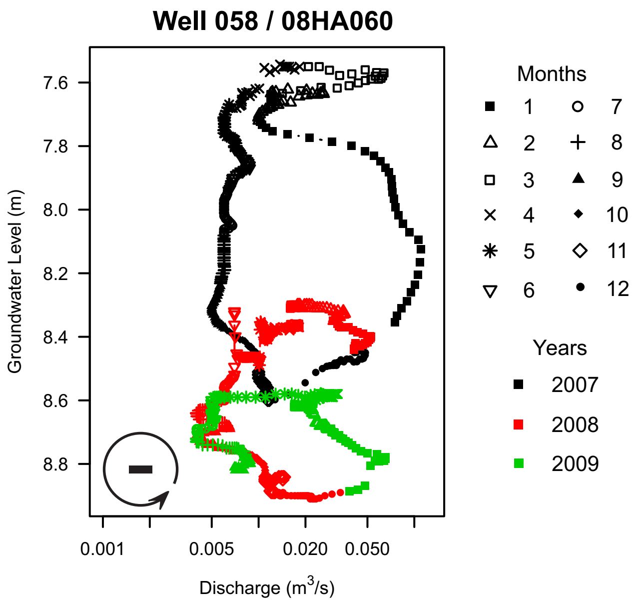
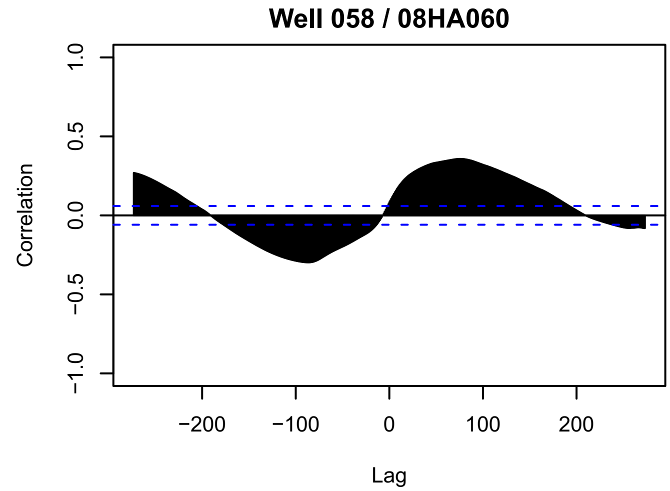
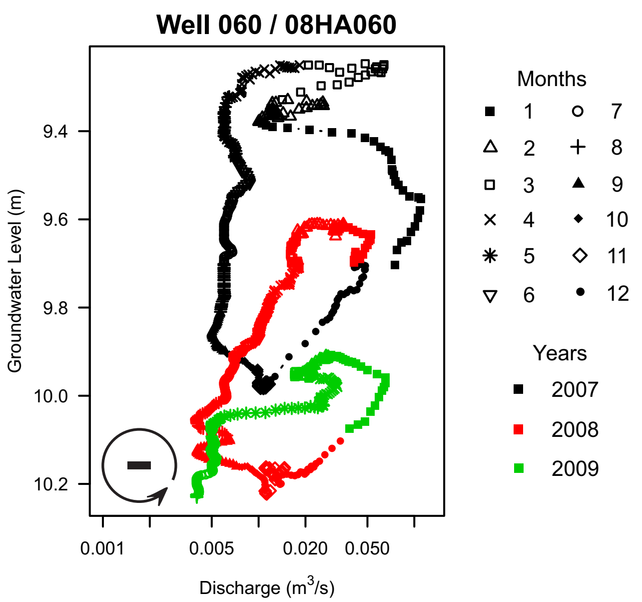
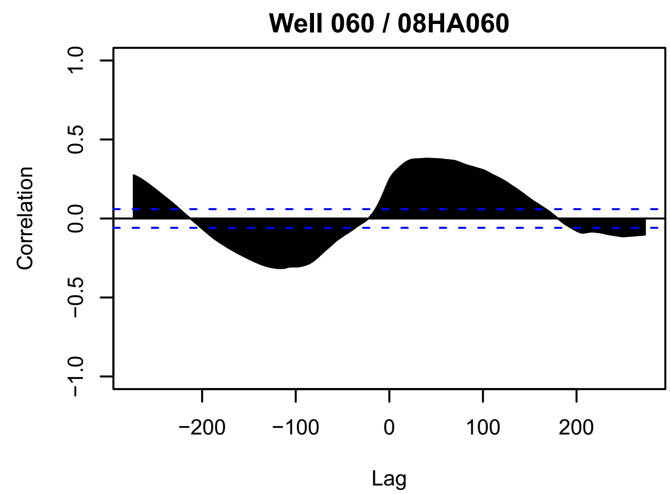
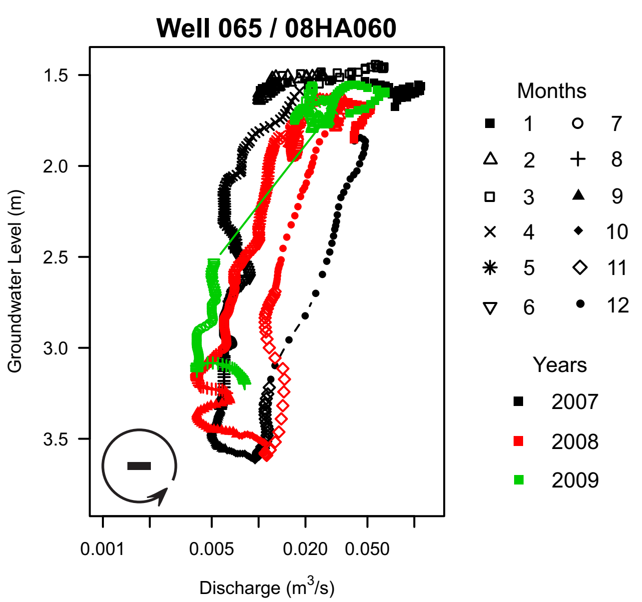
West Coast Region

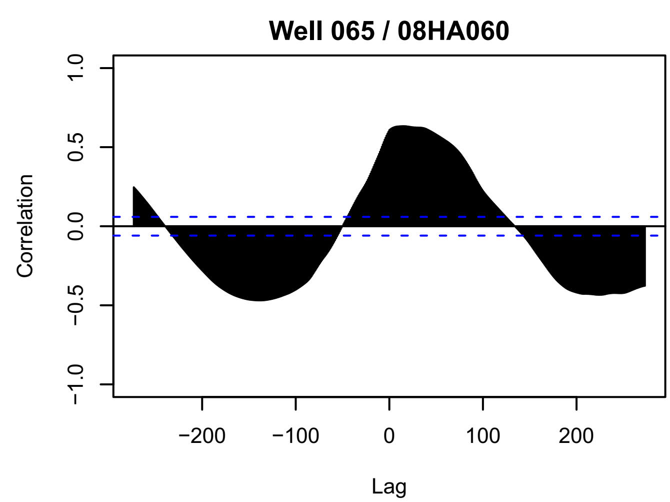












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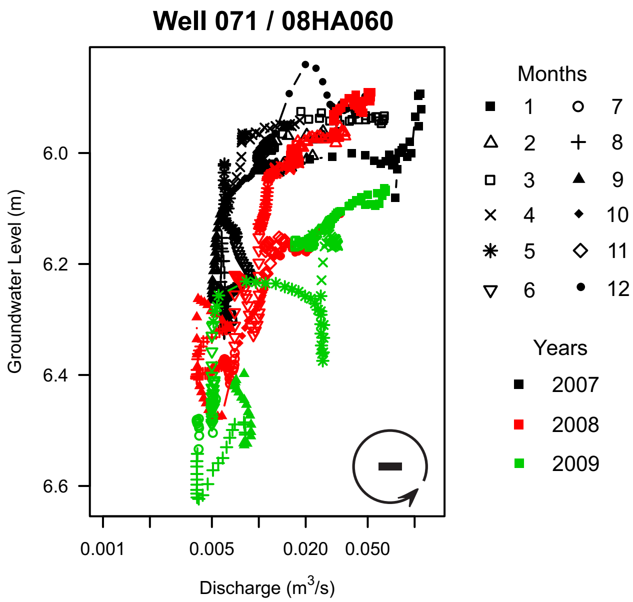

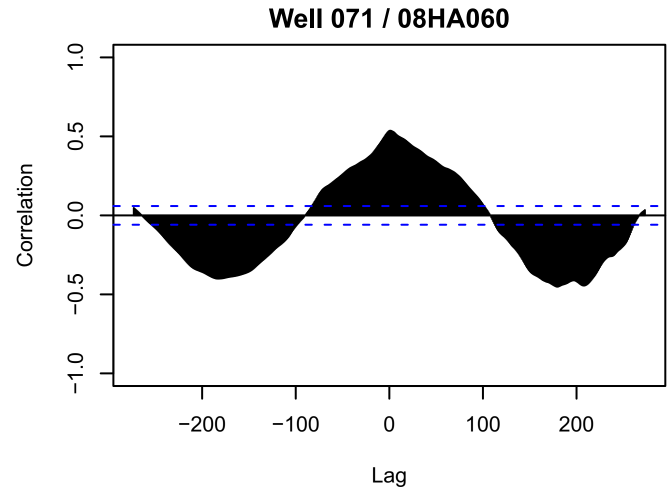

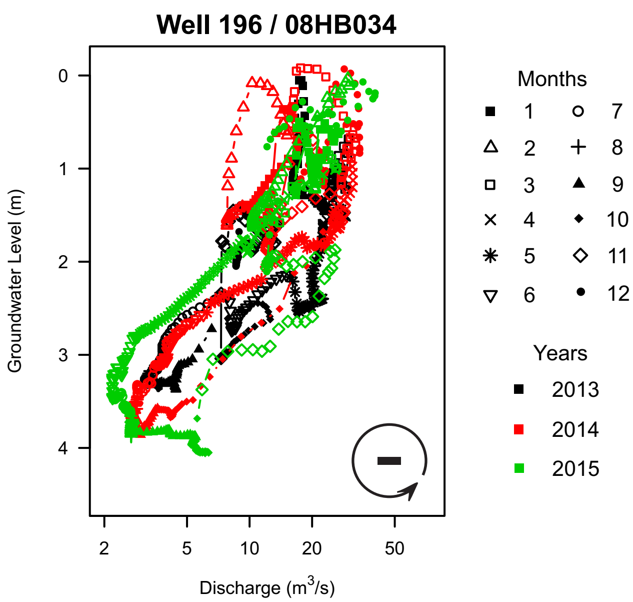

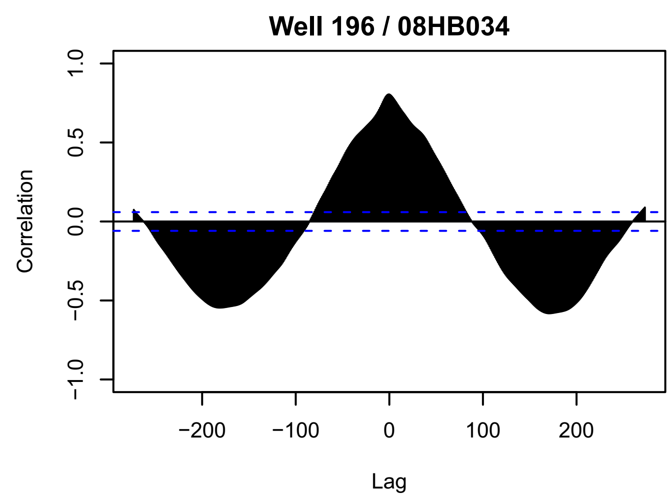

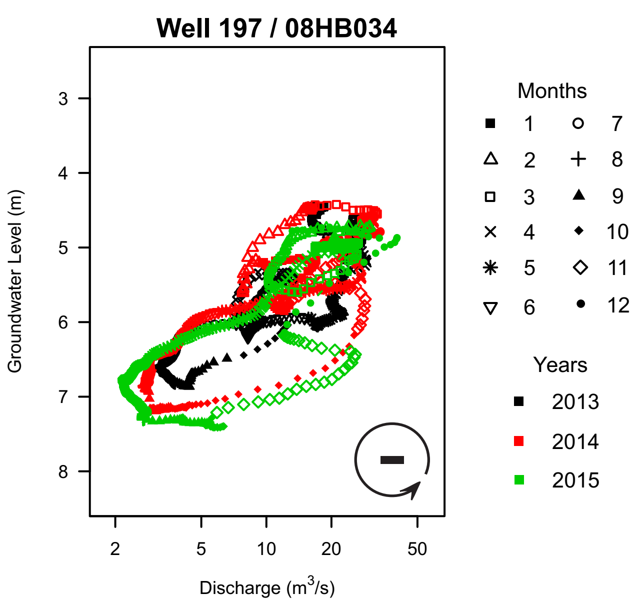

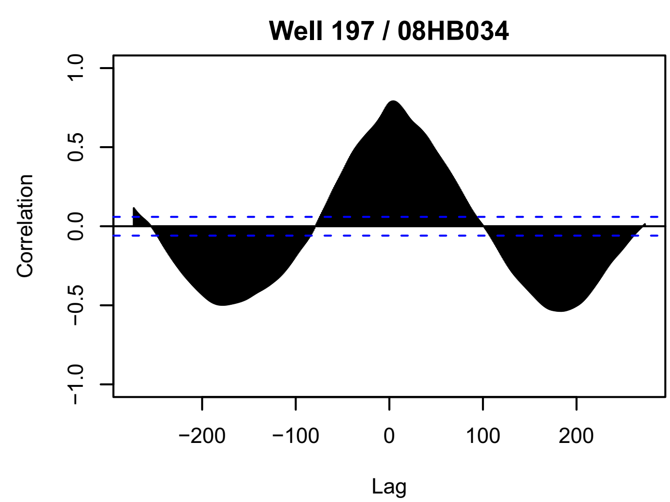

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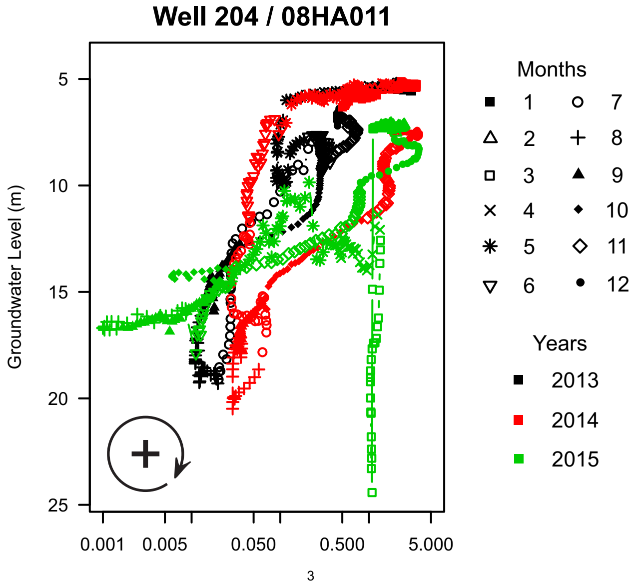

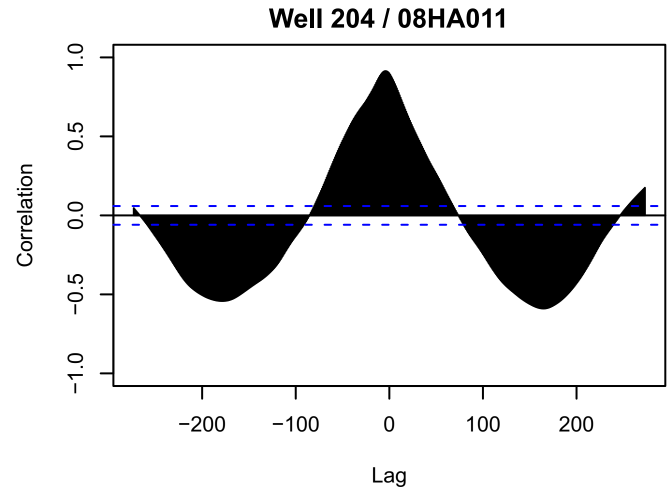

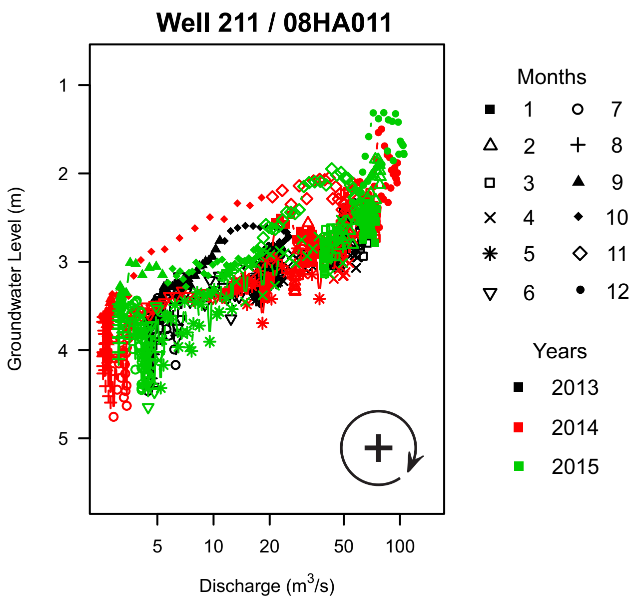

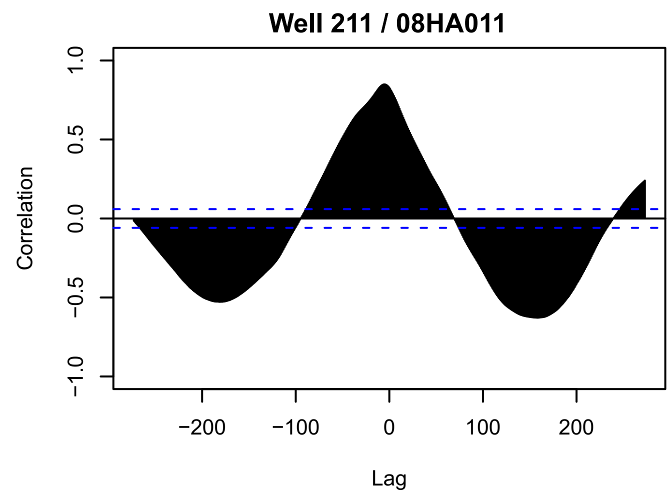

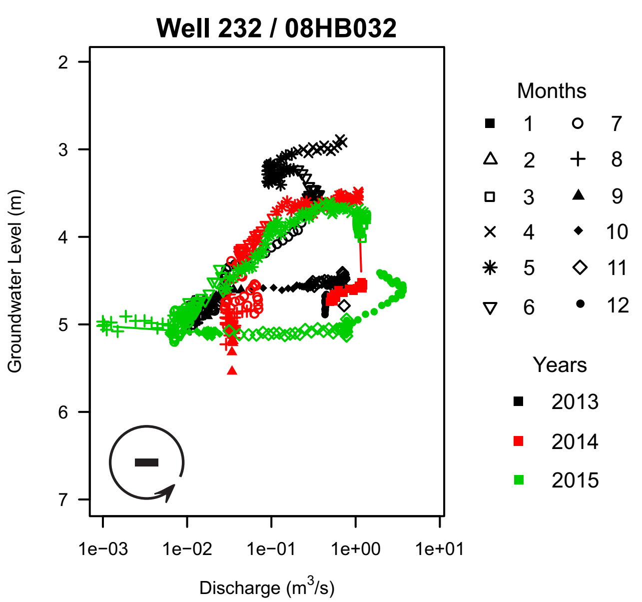

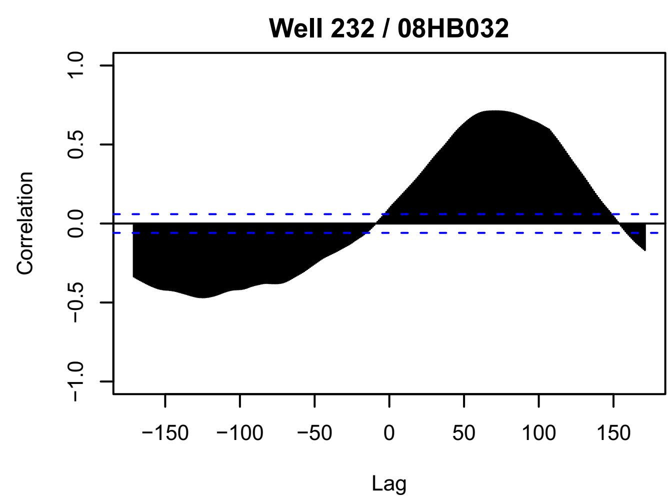

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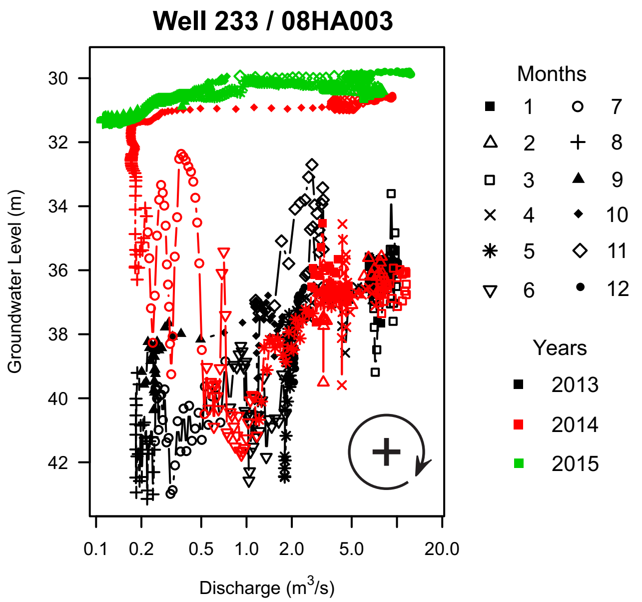

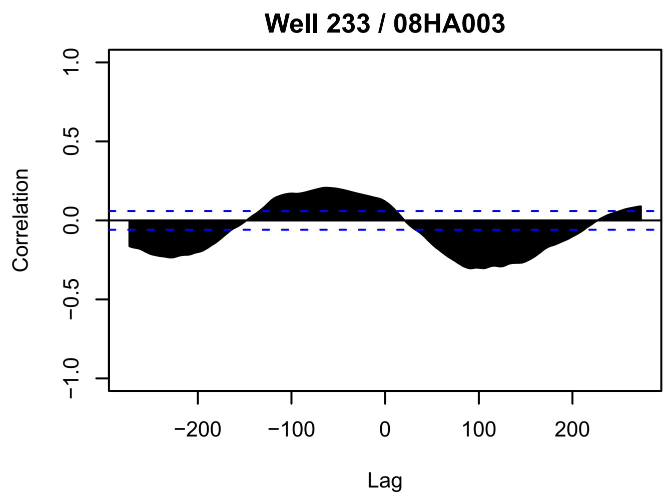

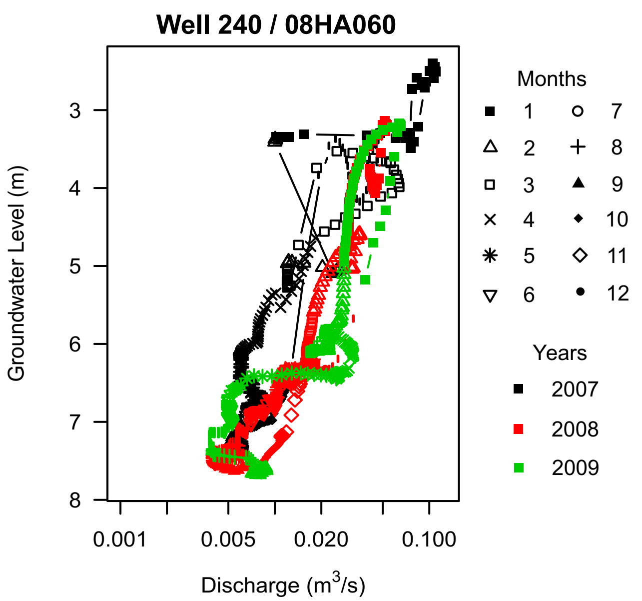

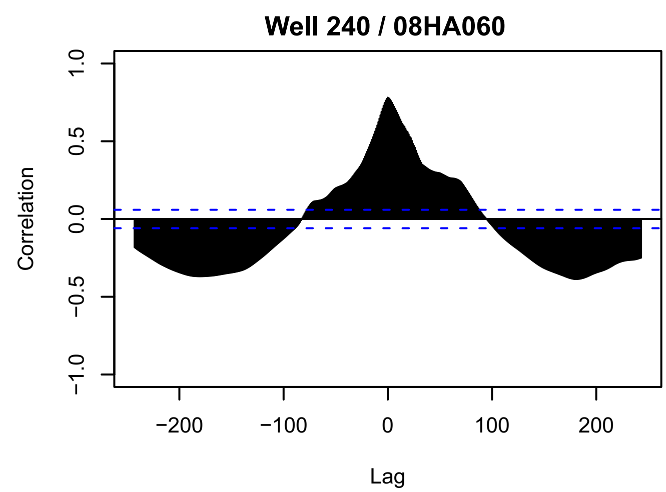

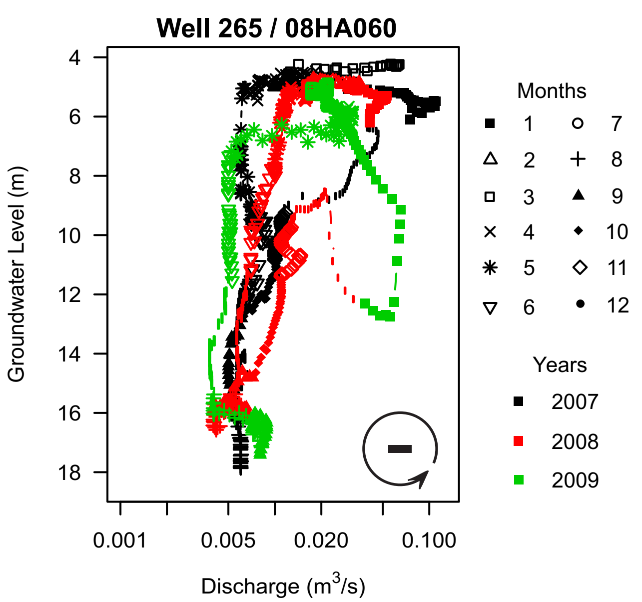

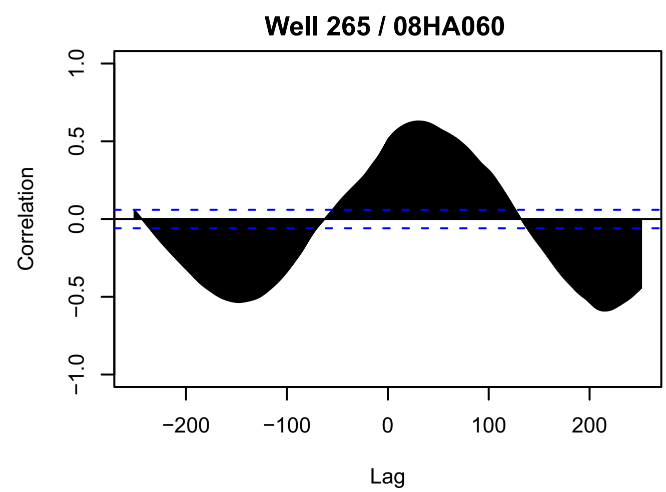

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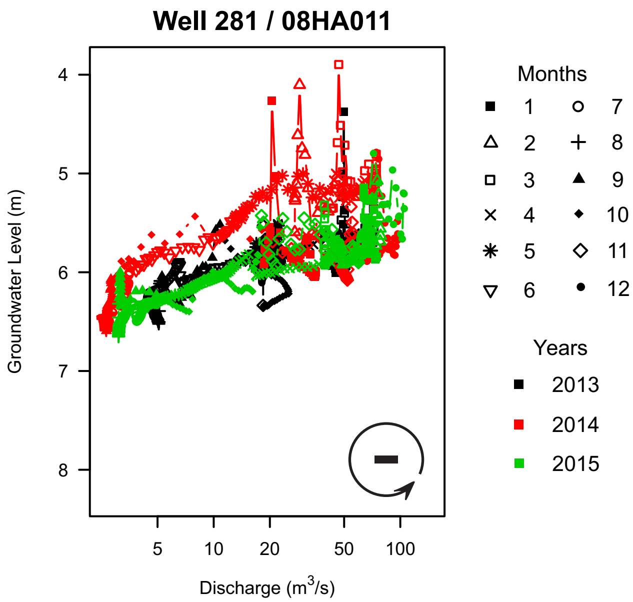

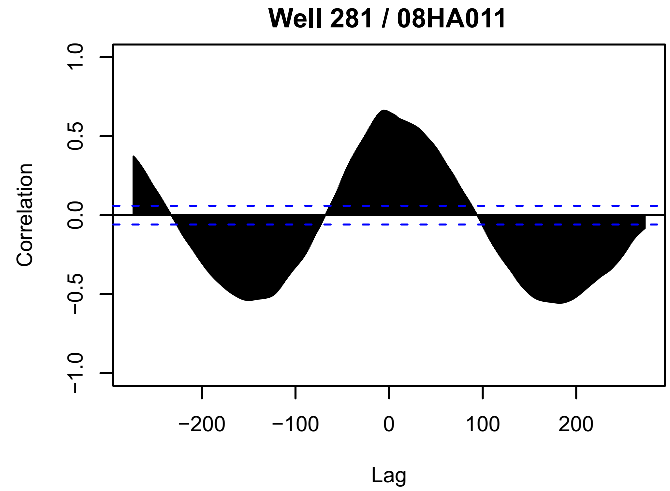

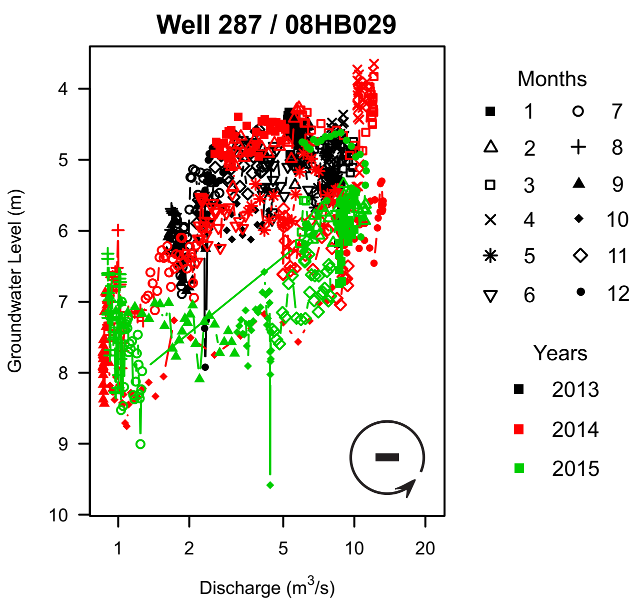

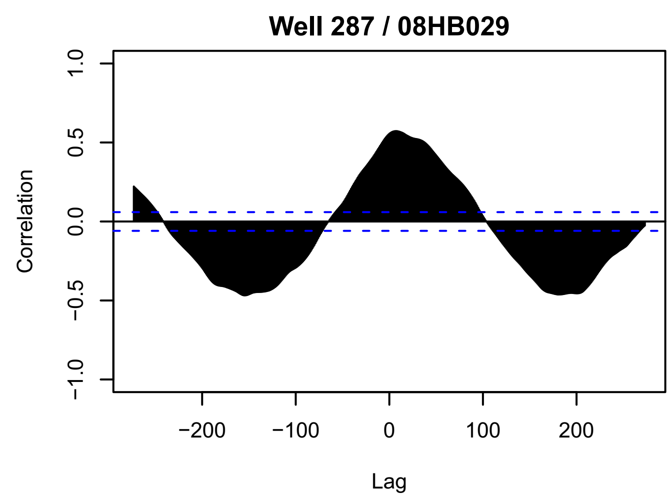

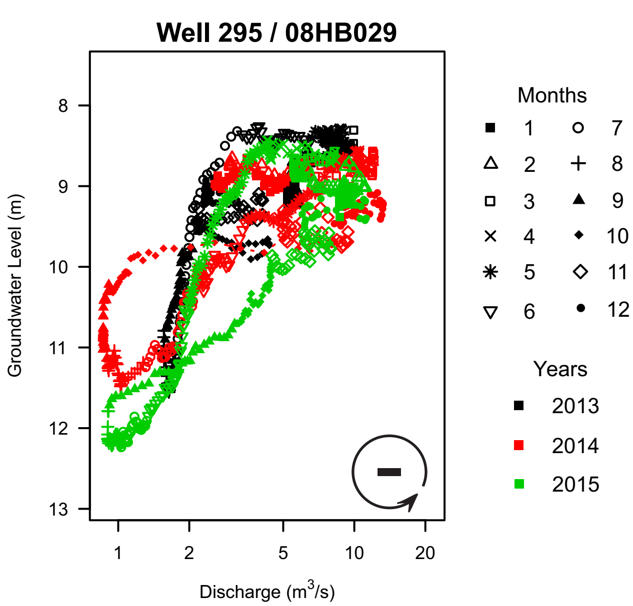

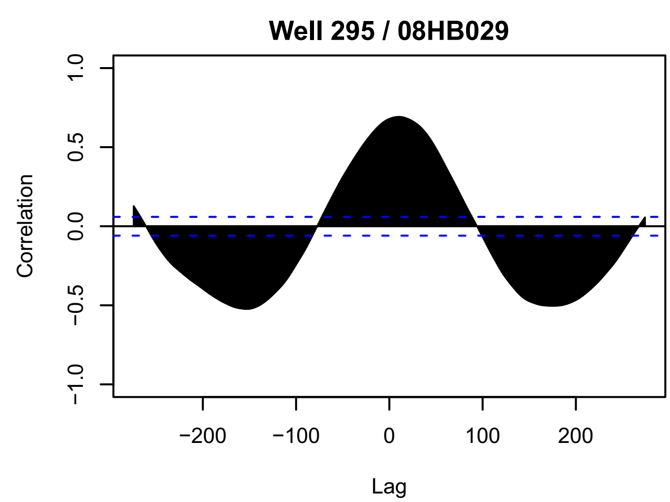

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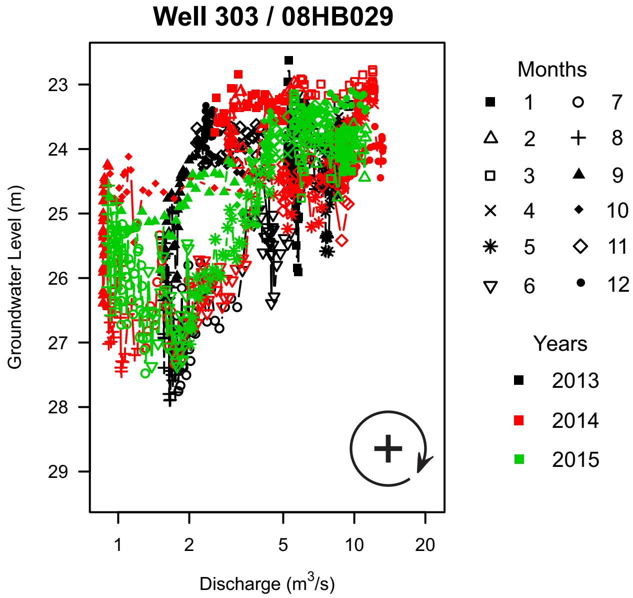

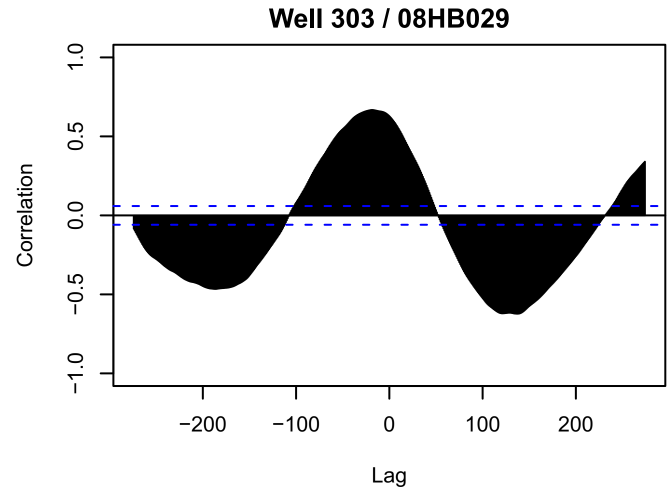

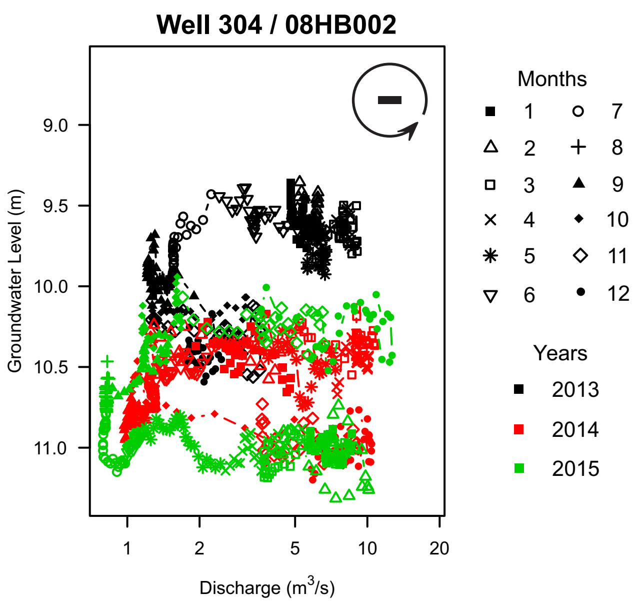

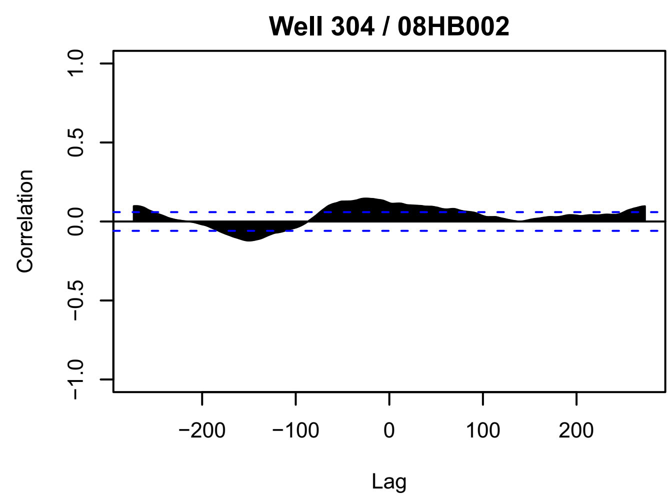

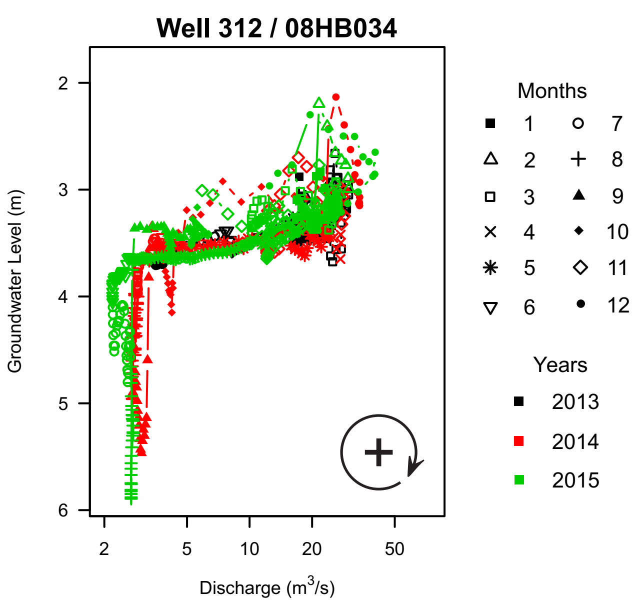

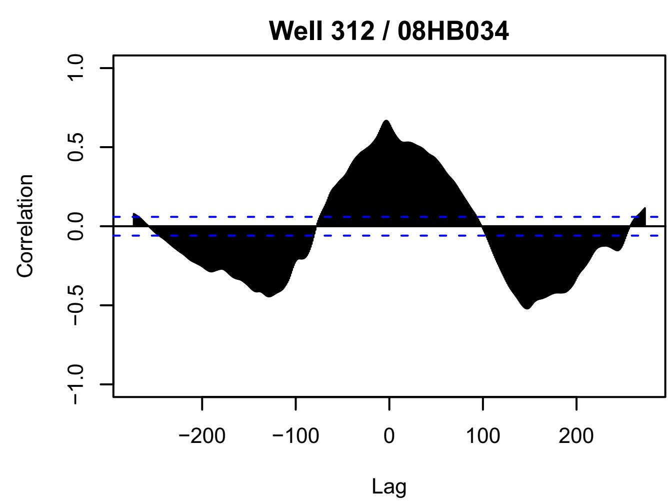

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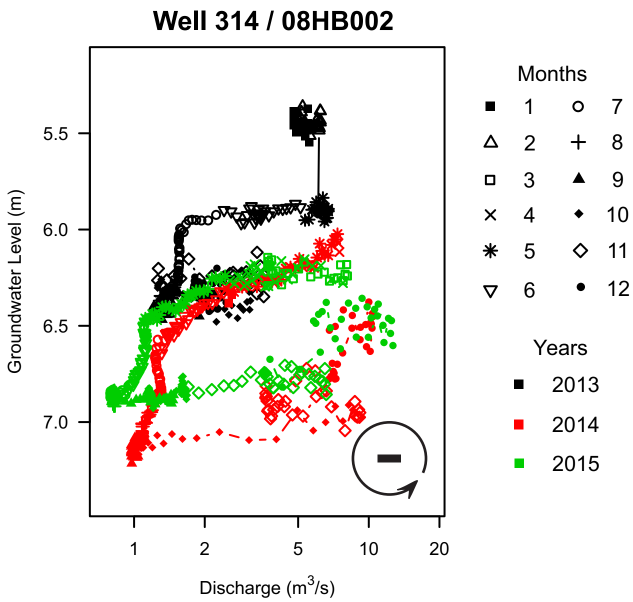

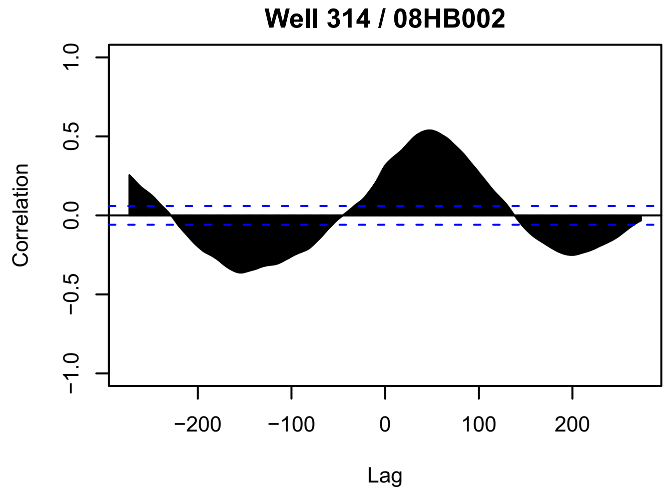

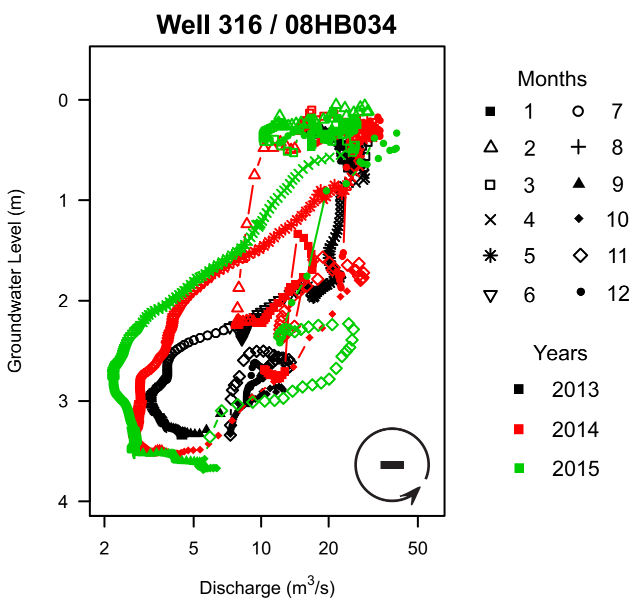

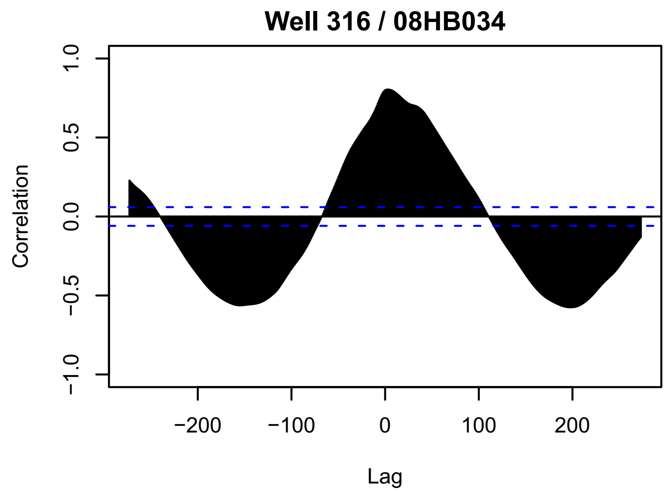

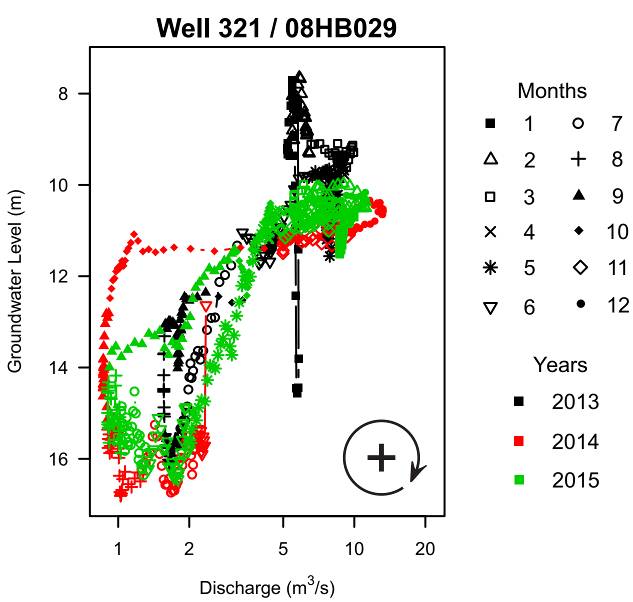

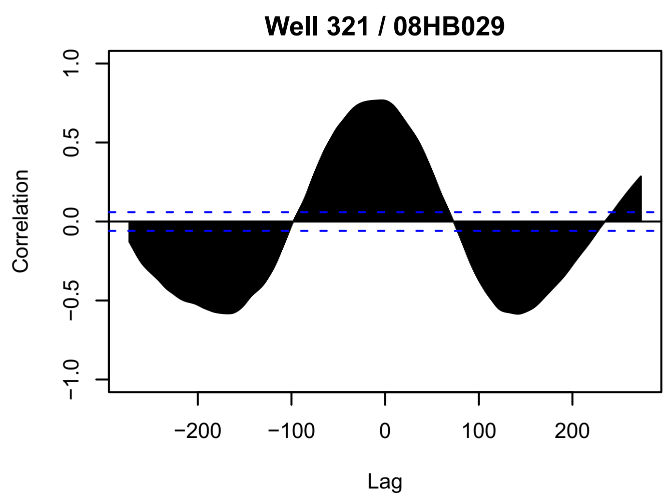

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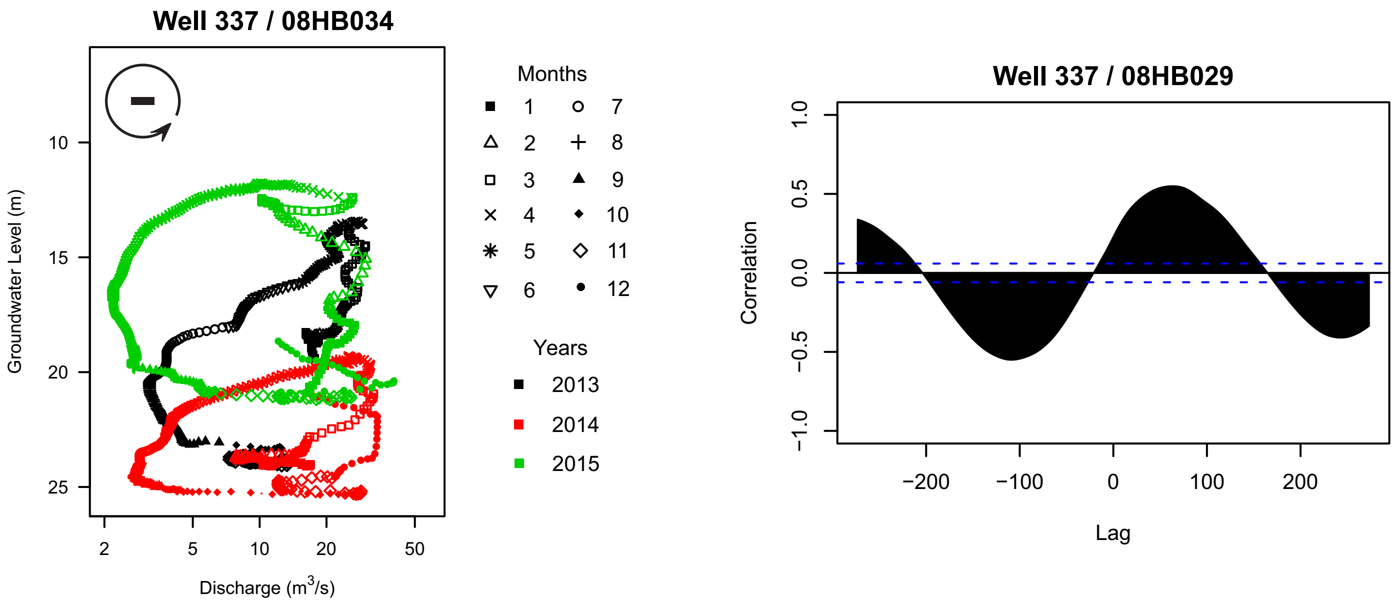

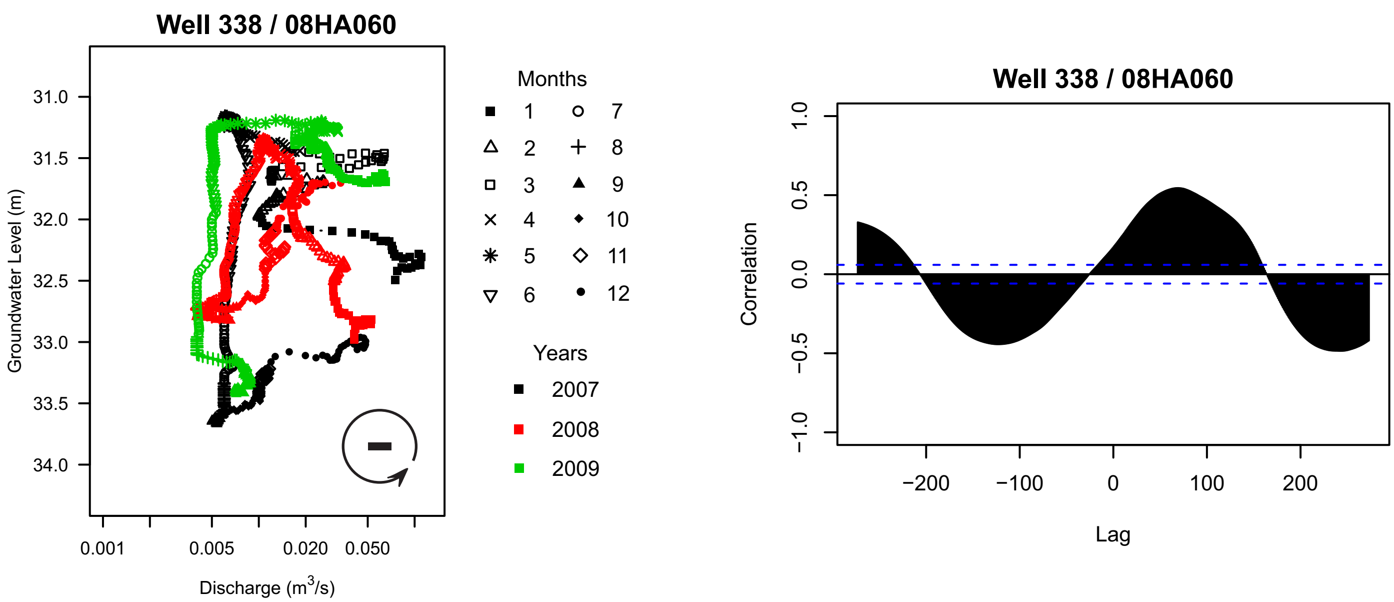

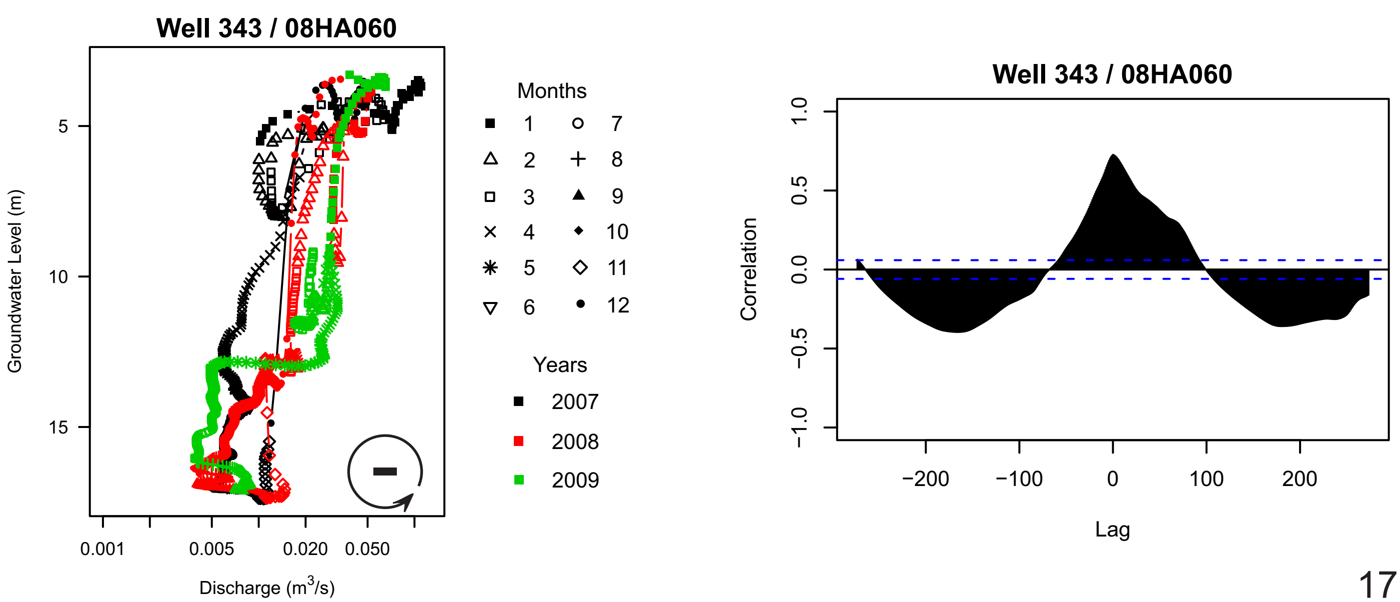

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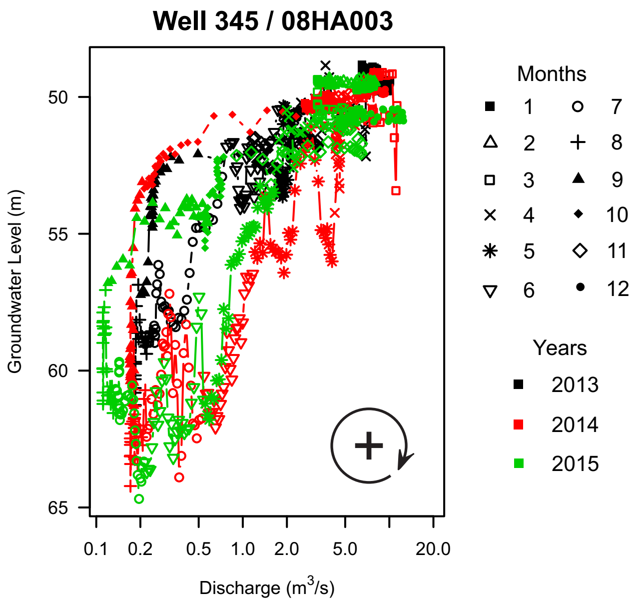

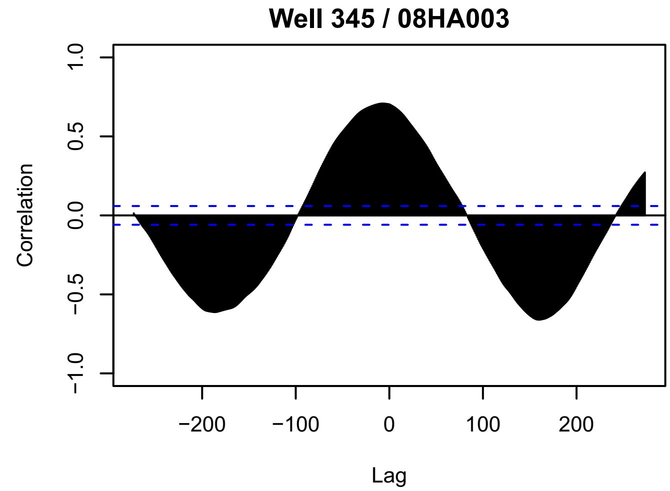

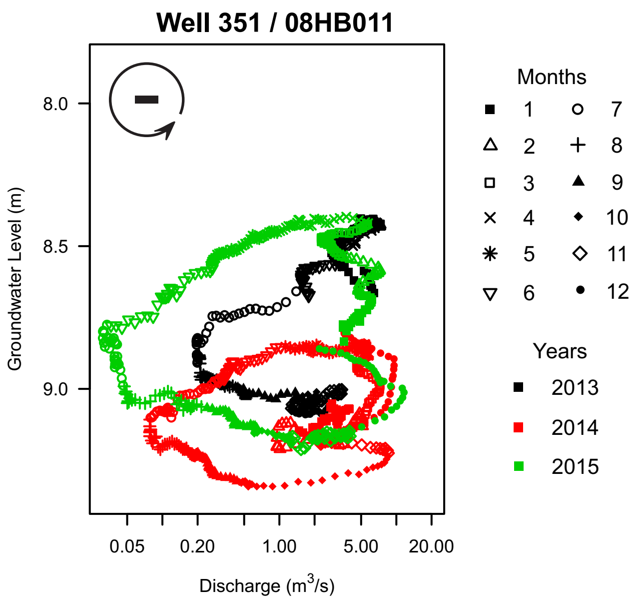

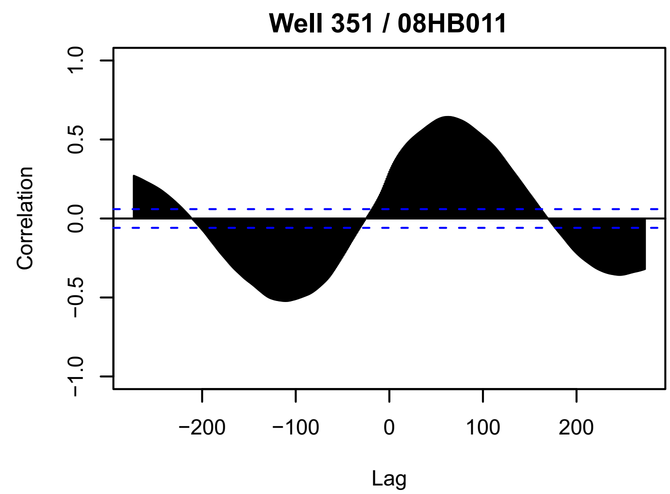

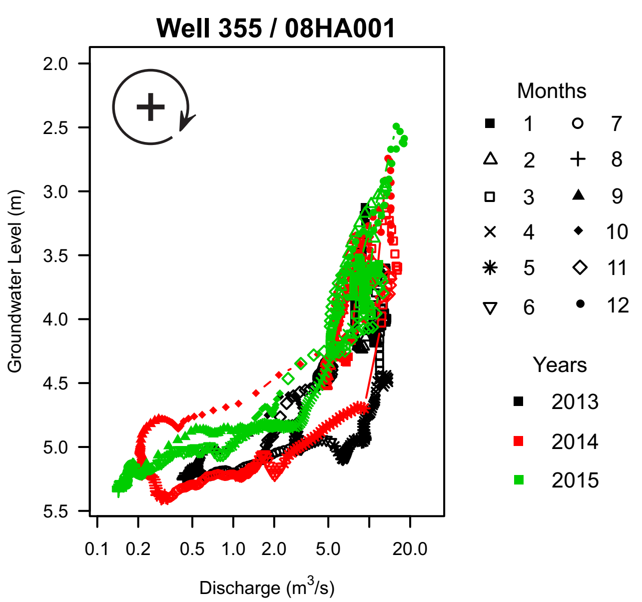

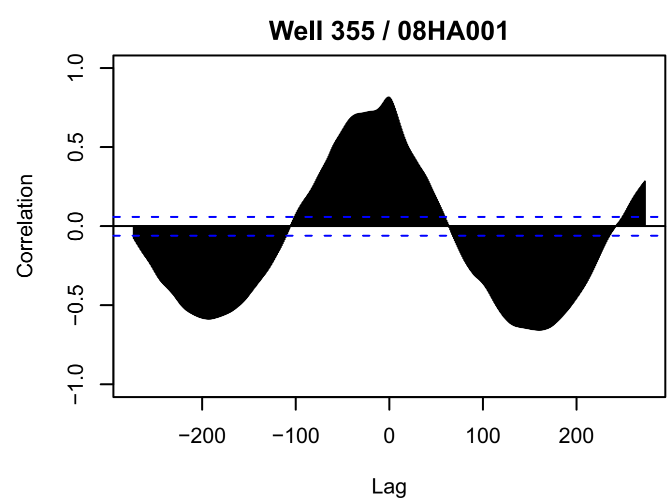

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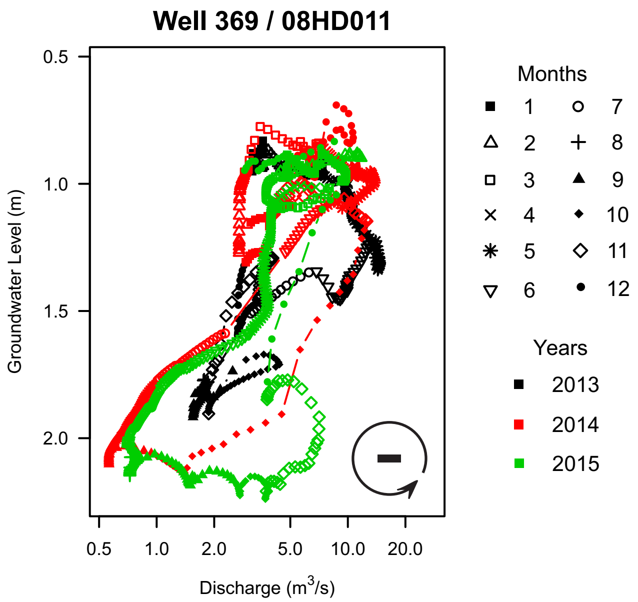

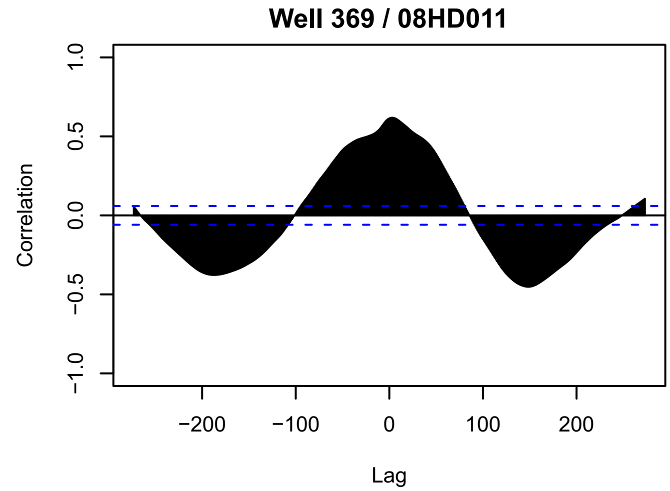

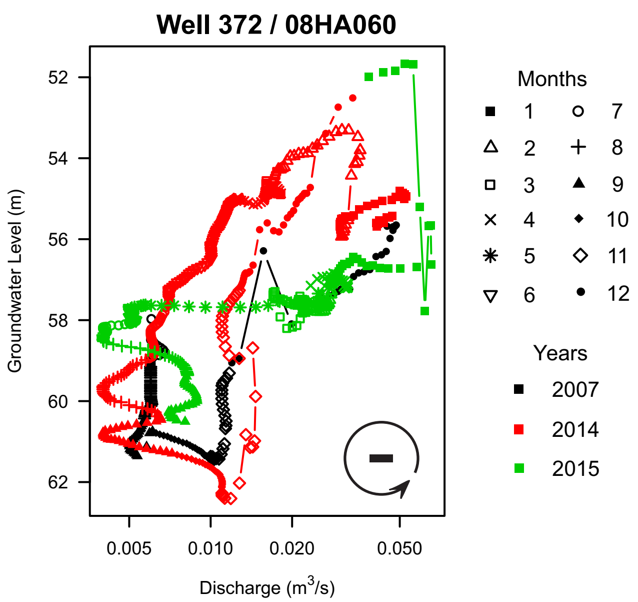

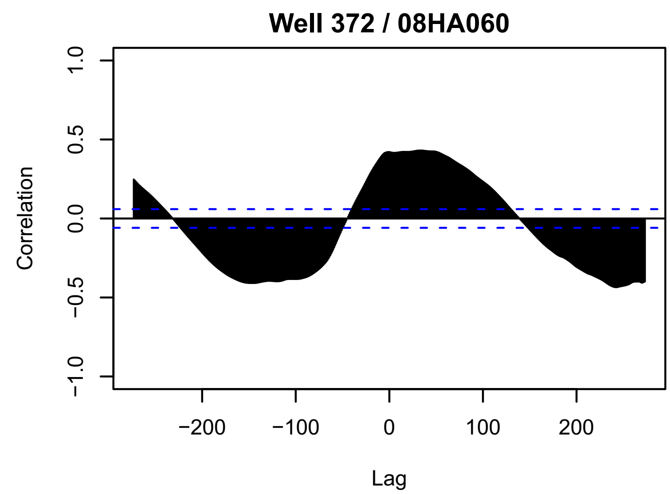

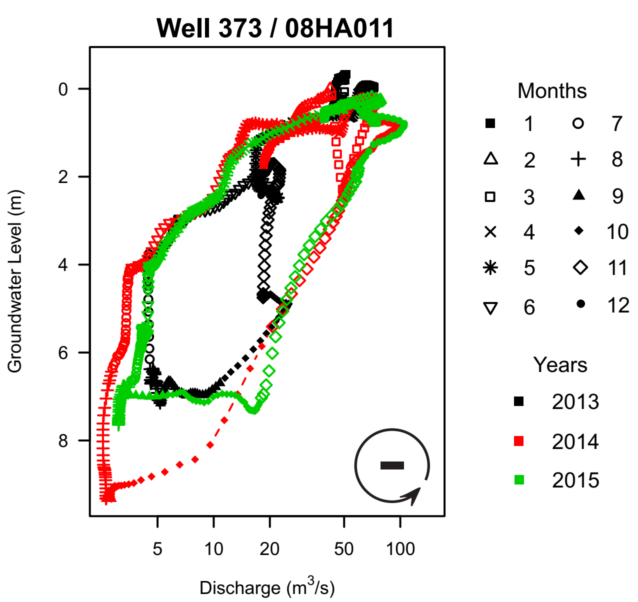

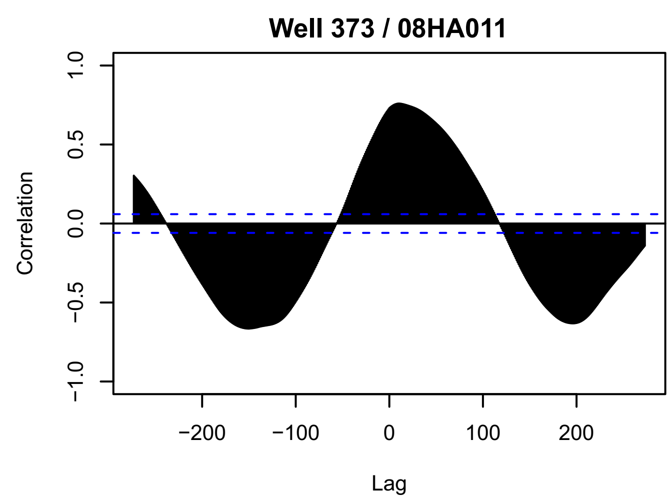

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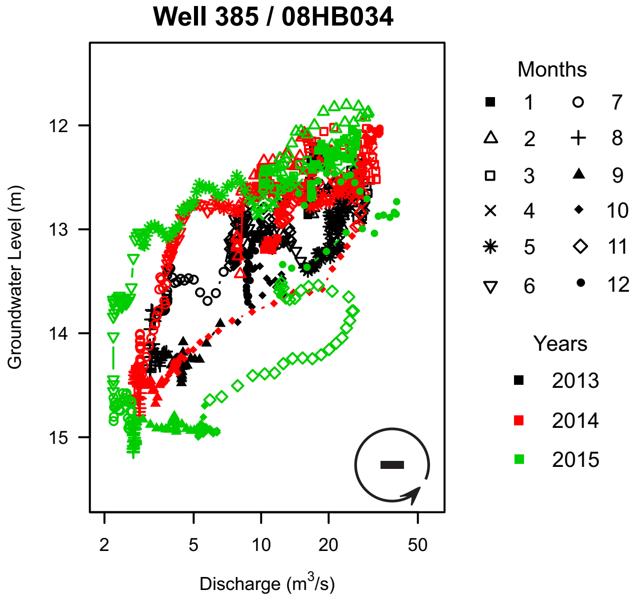

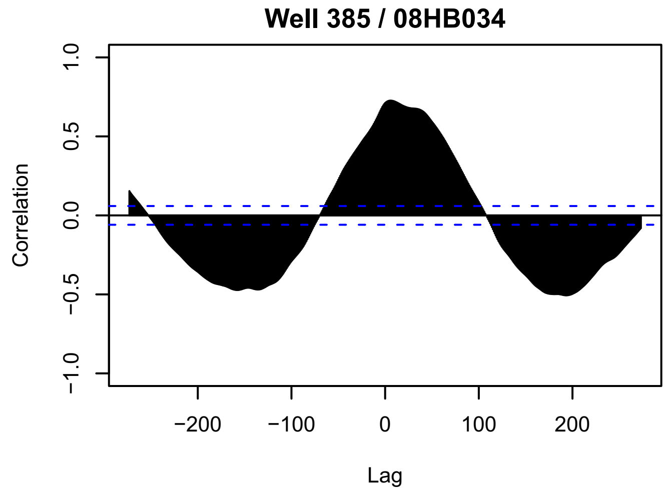

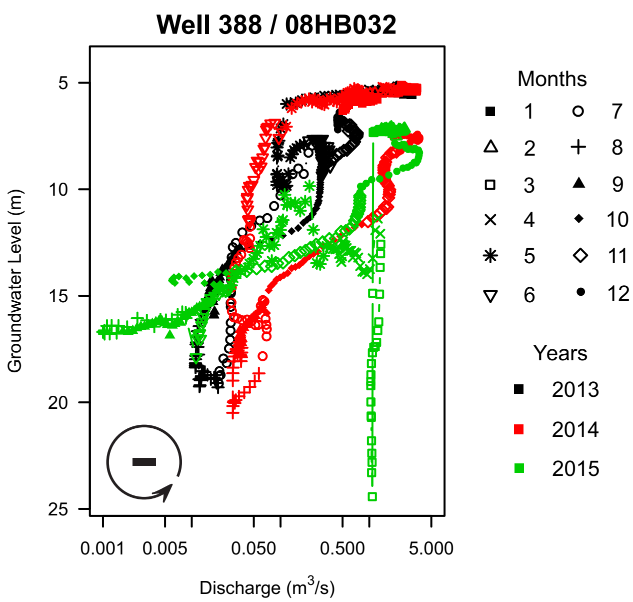

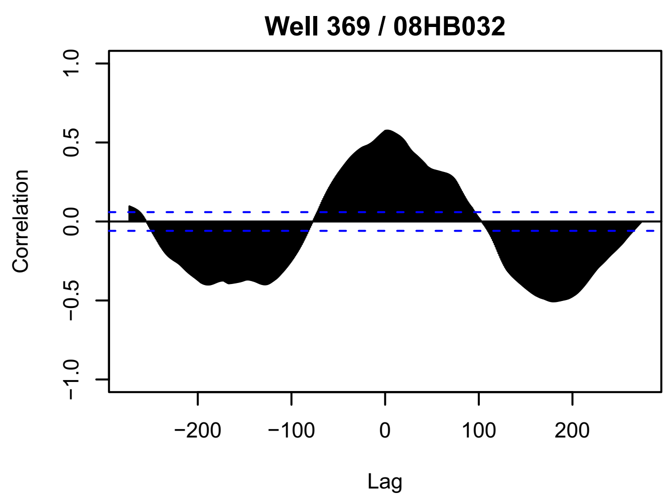

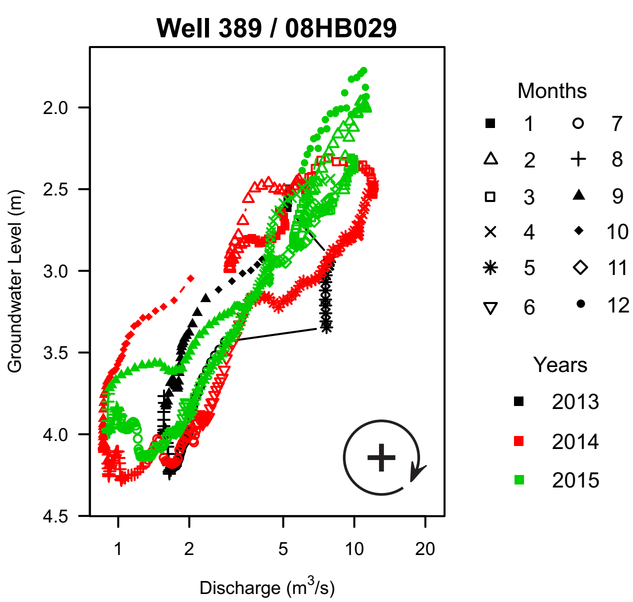

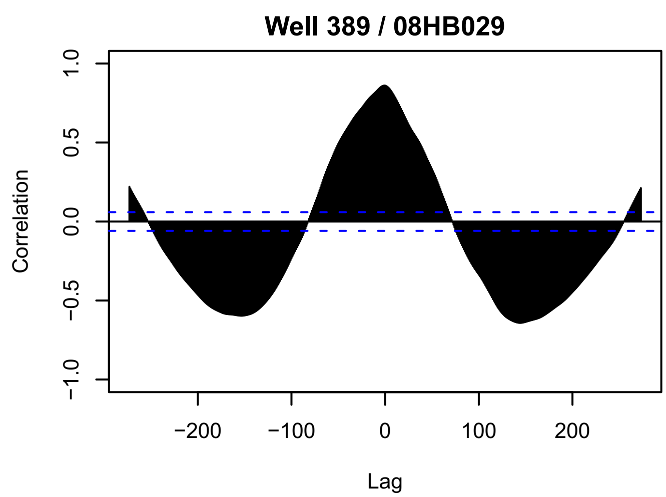

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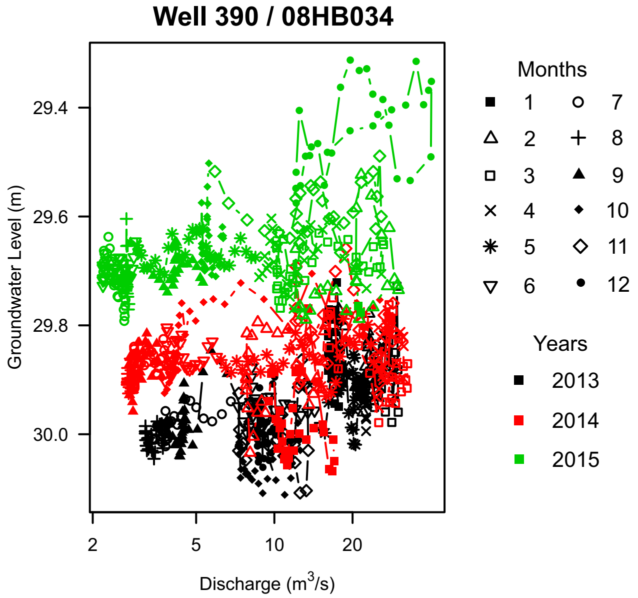

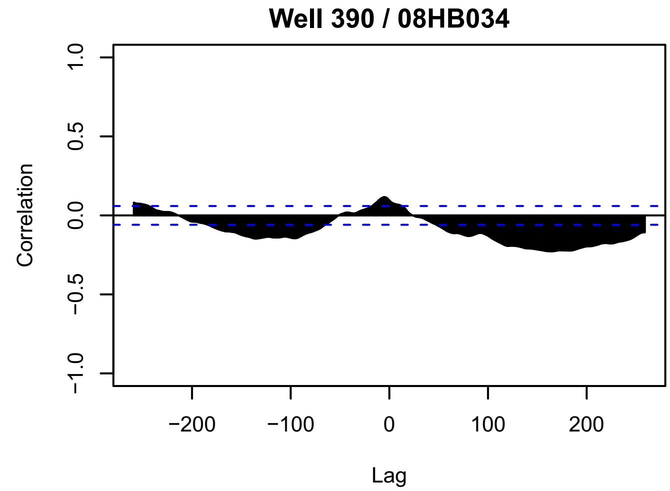

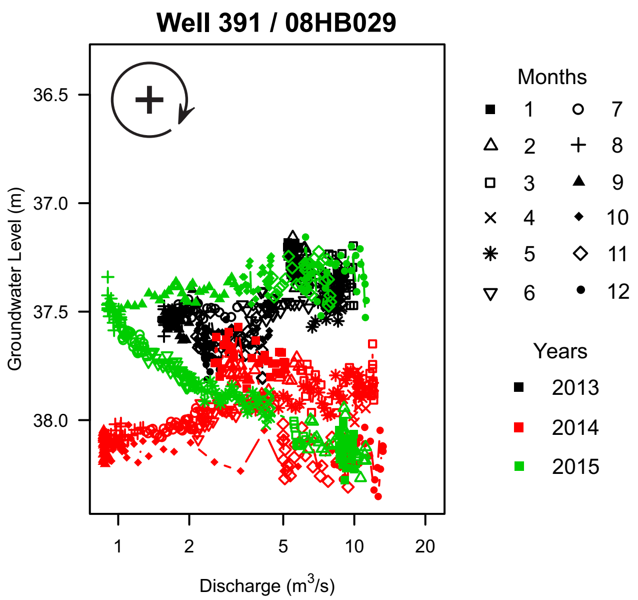

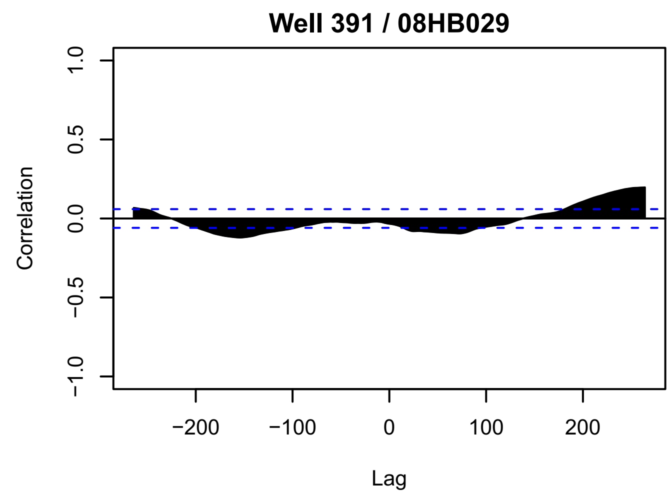

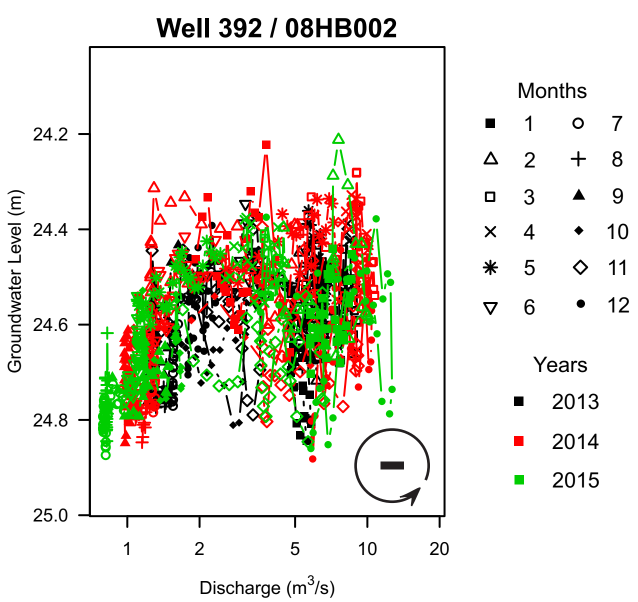

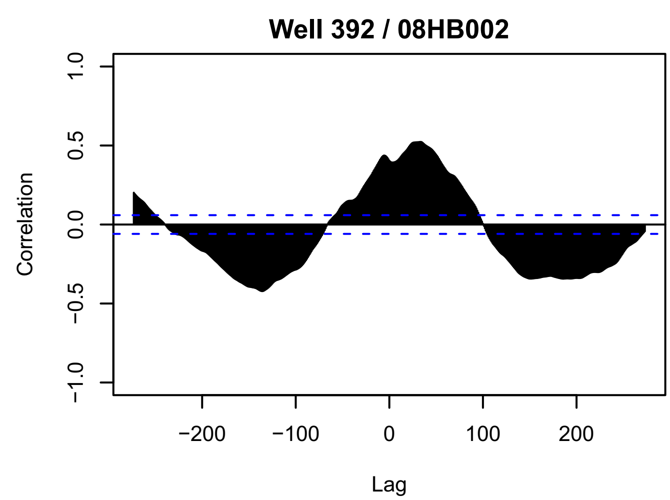

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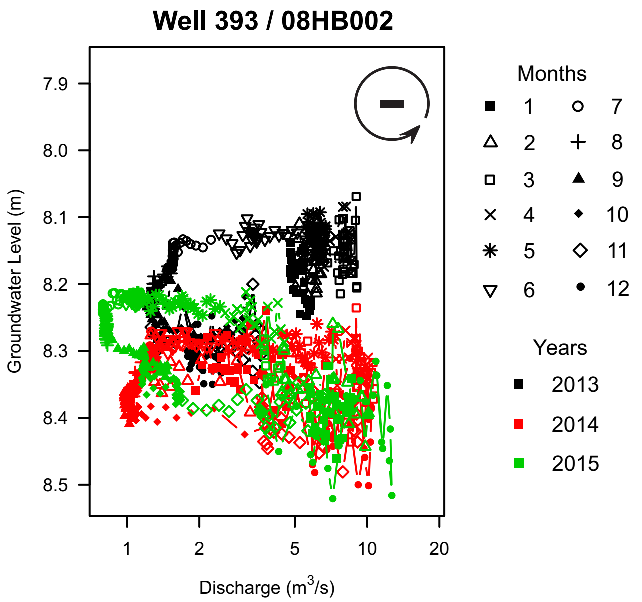

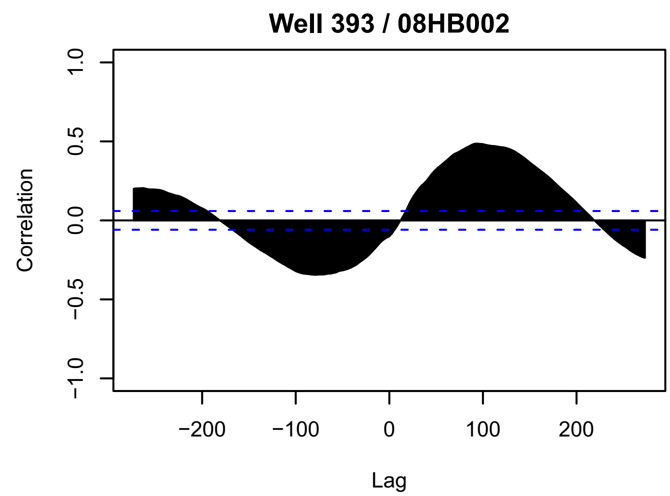

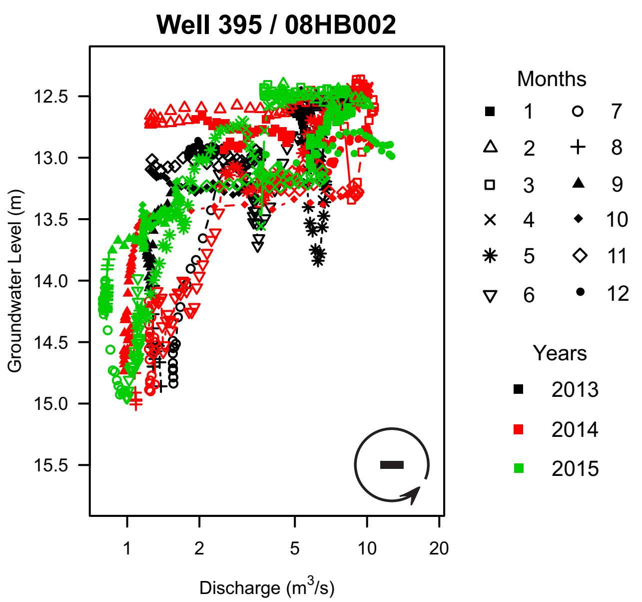

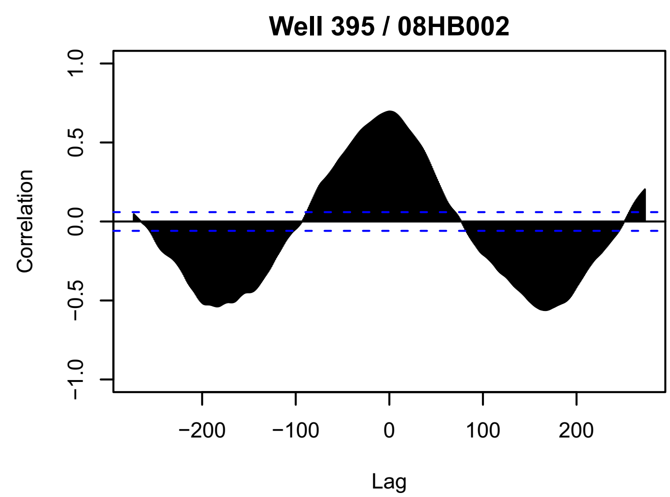

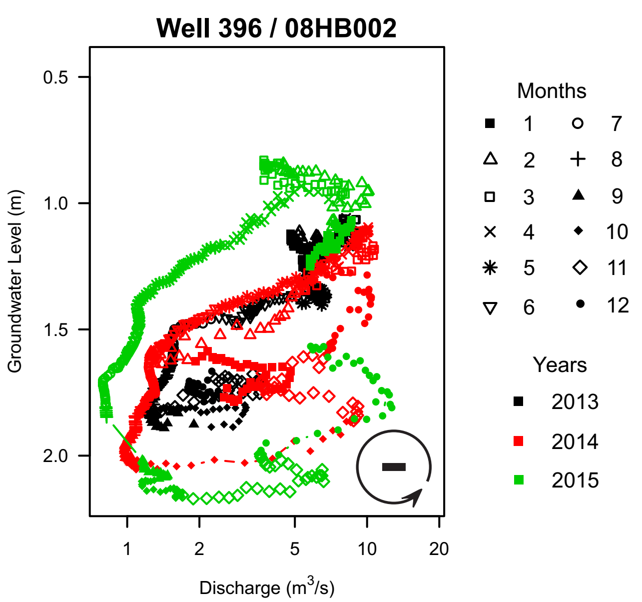

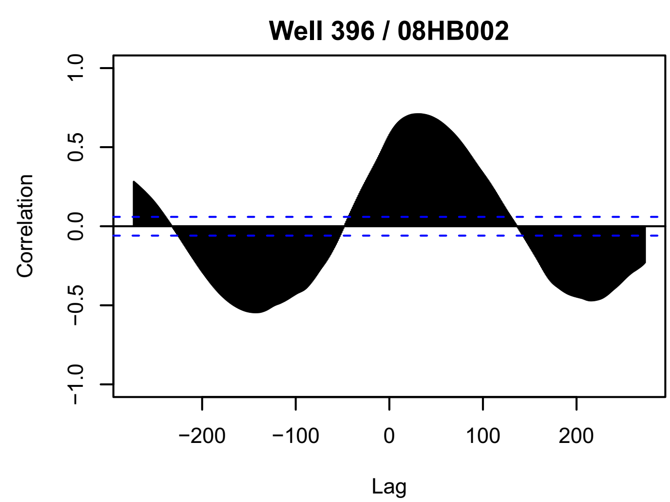

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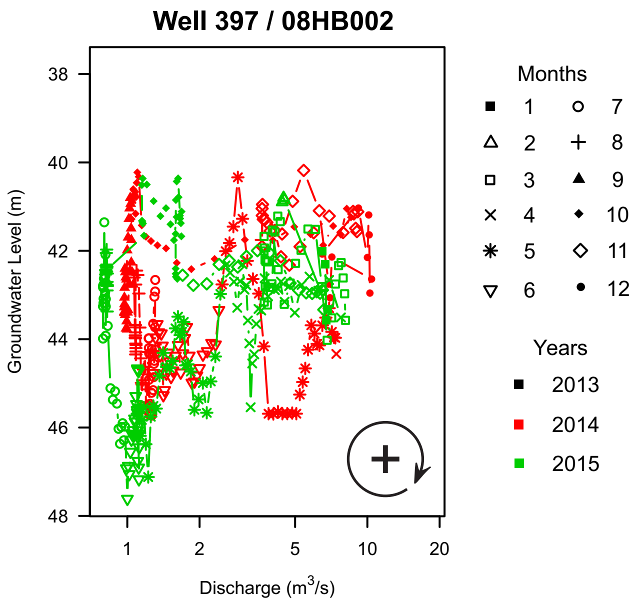

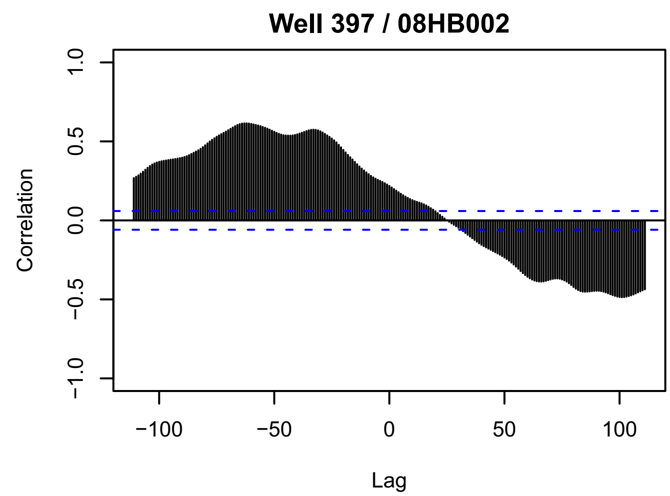

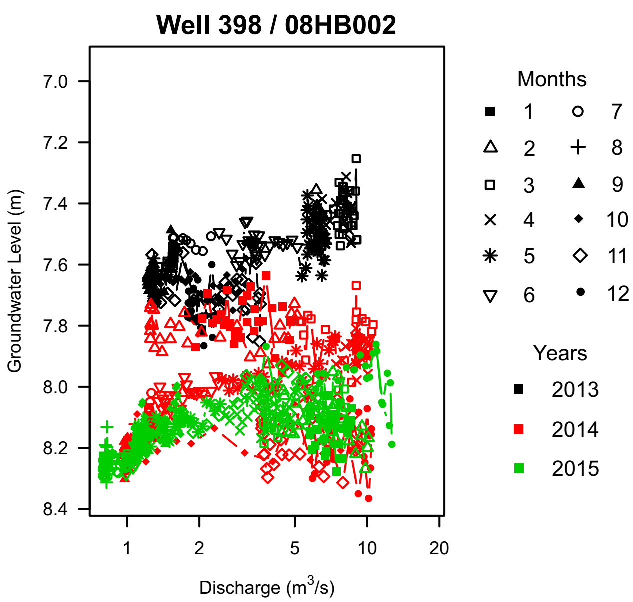

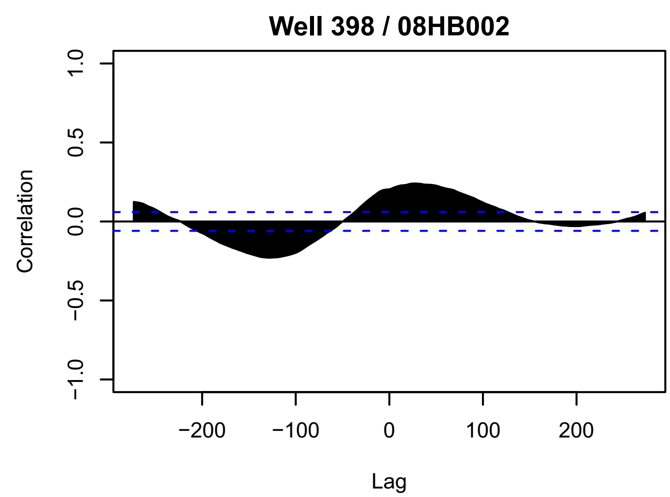

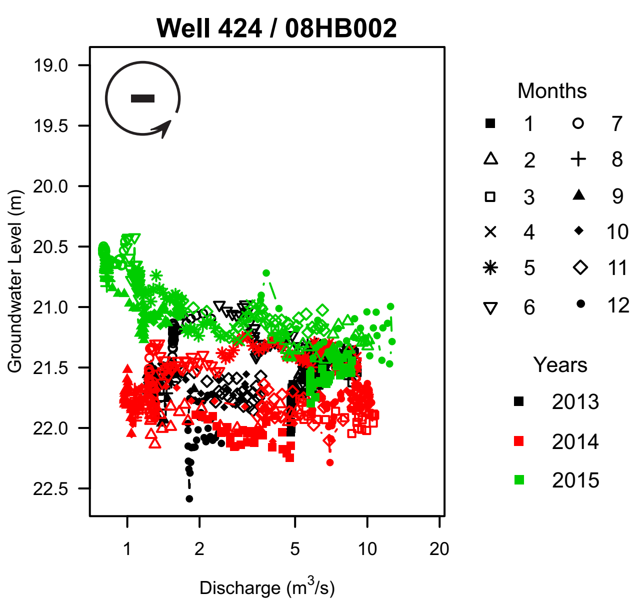

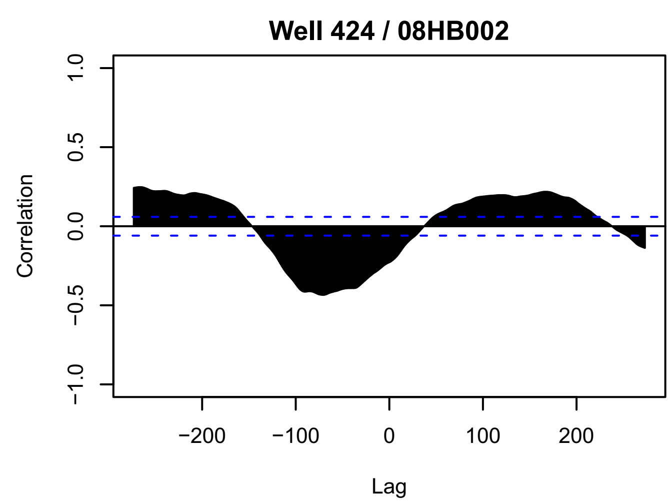

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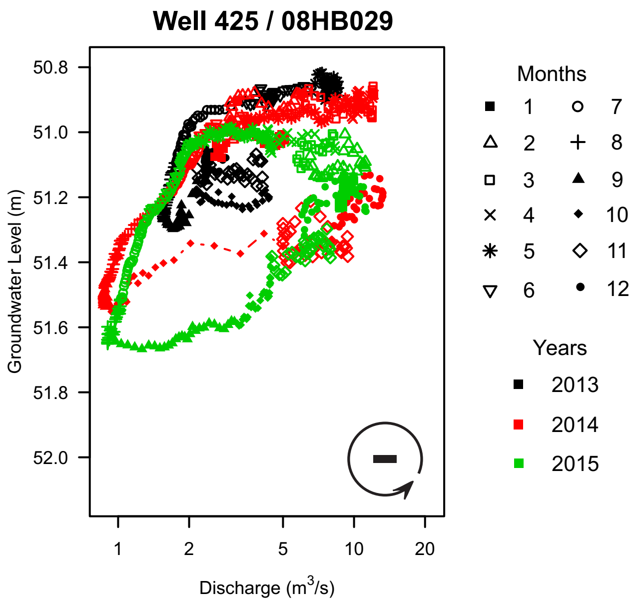

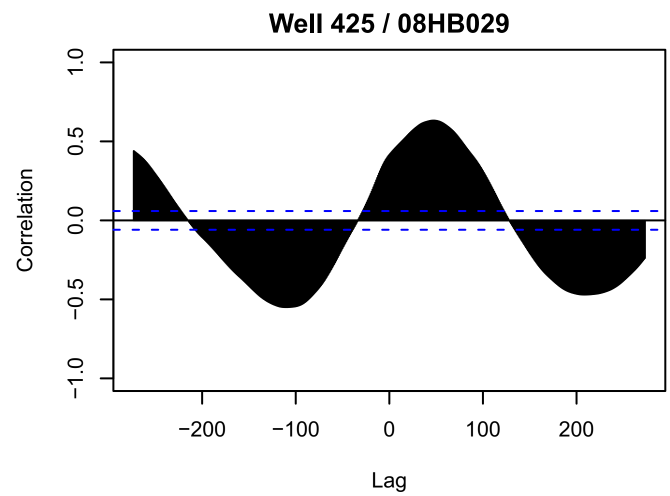

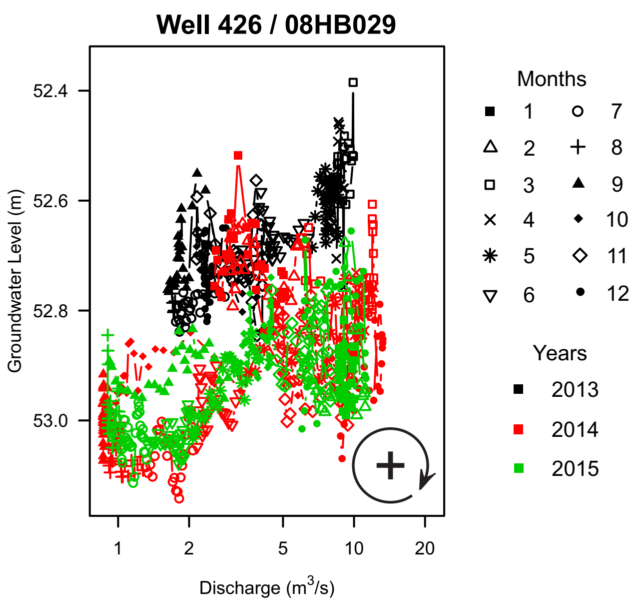

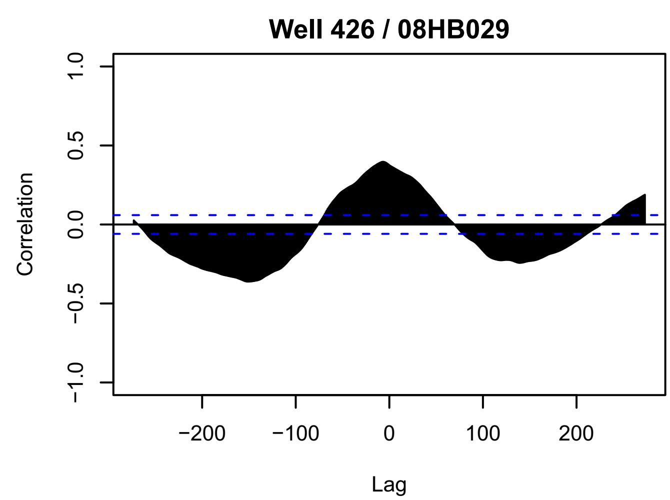

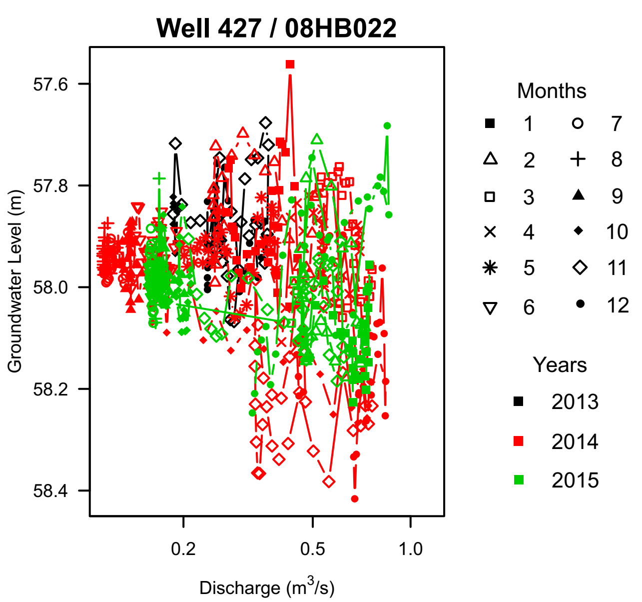

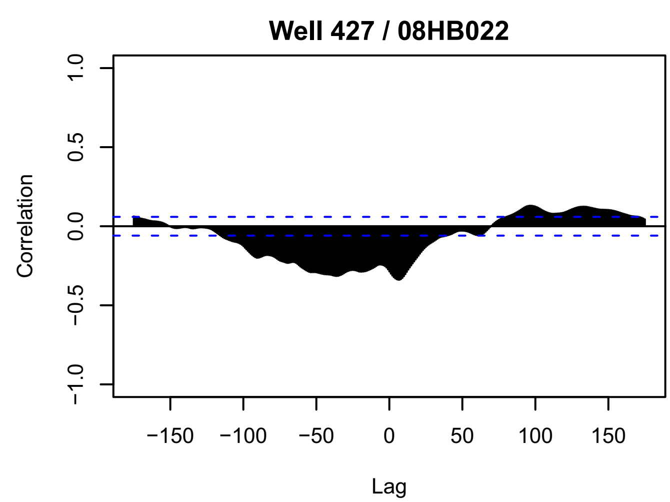

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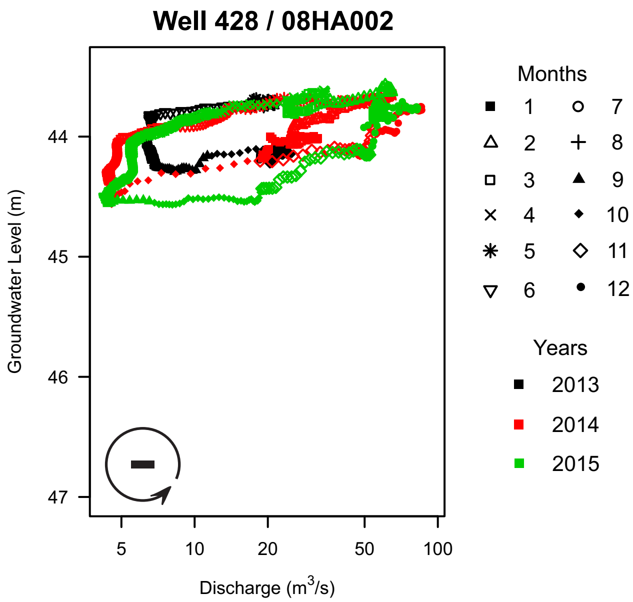

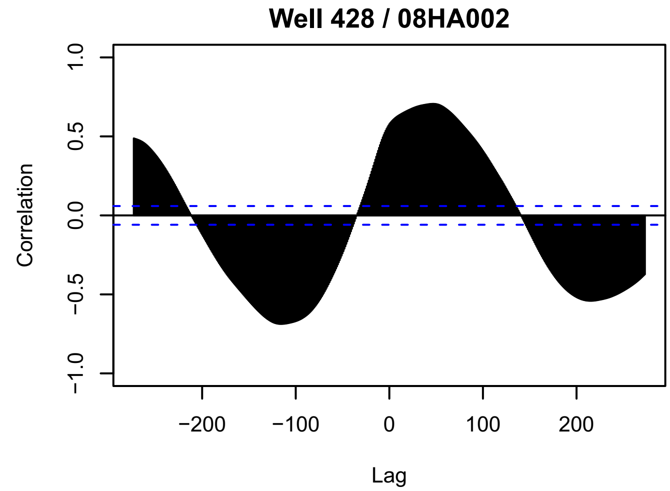

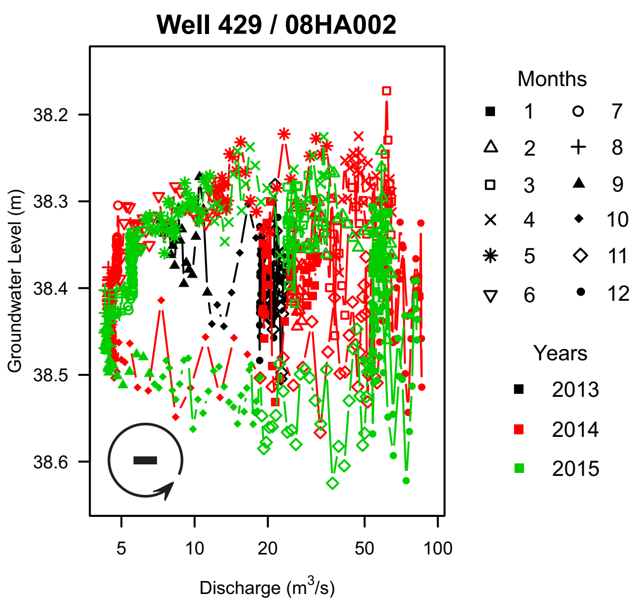

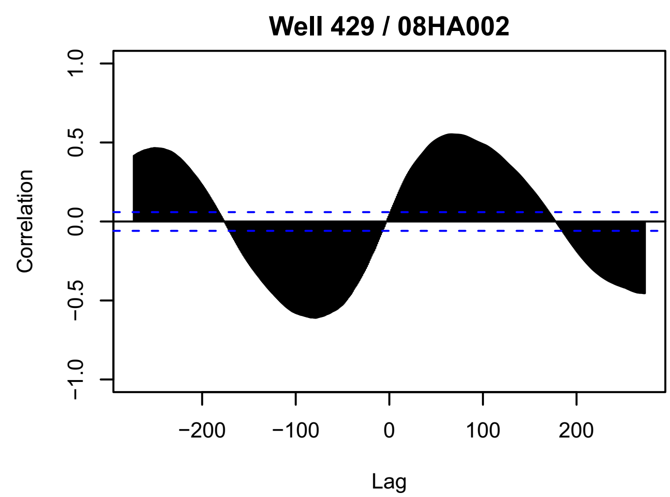

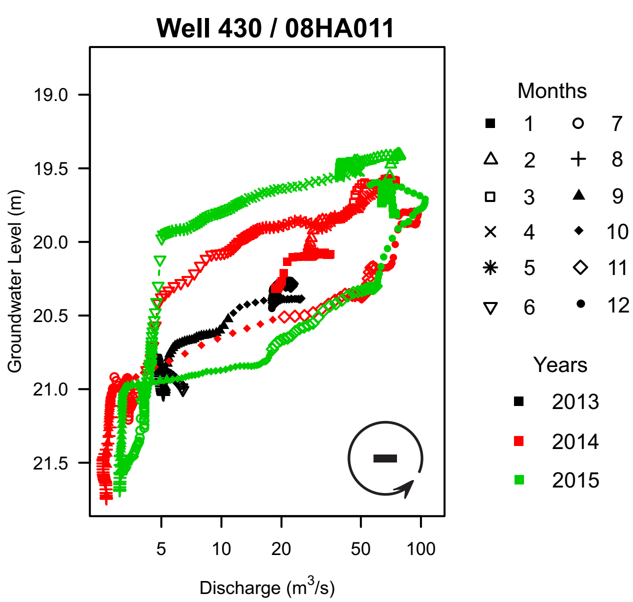

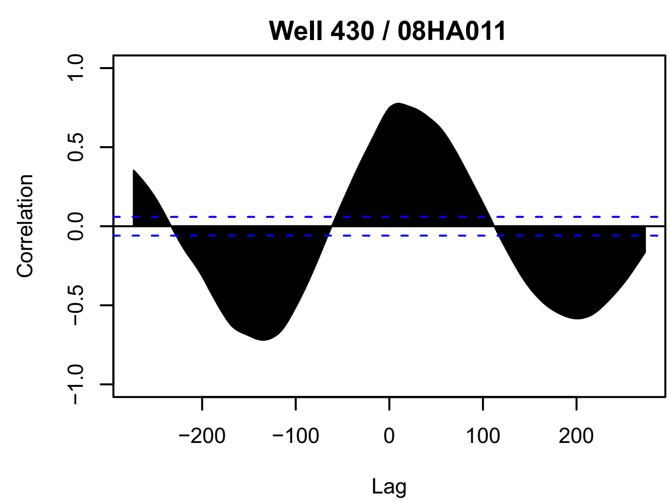

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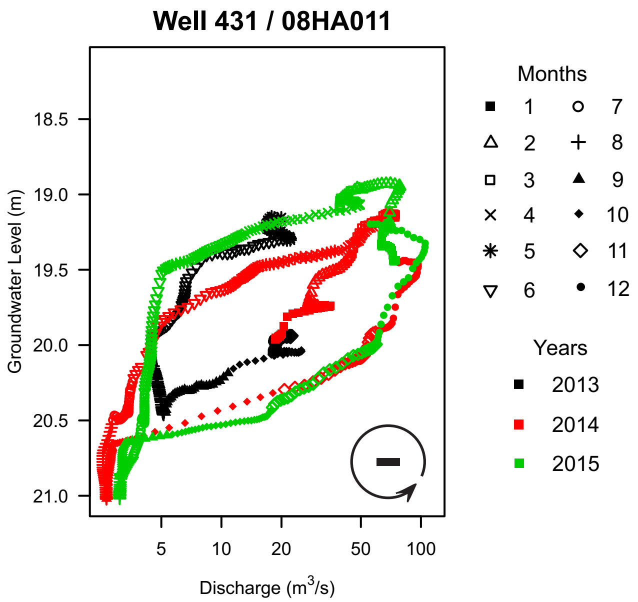

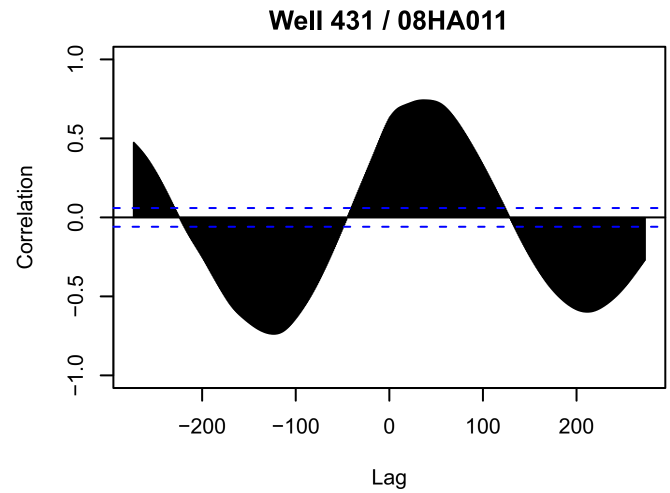

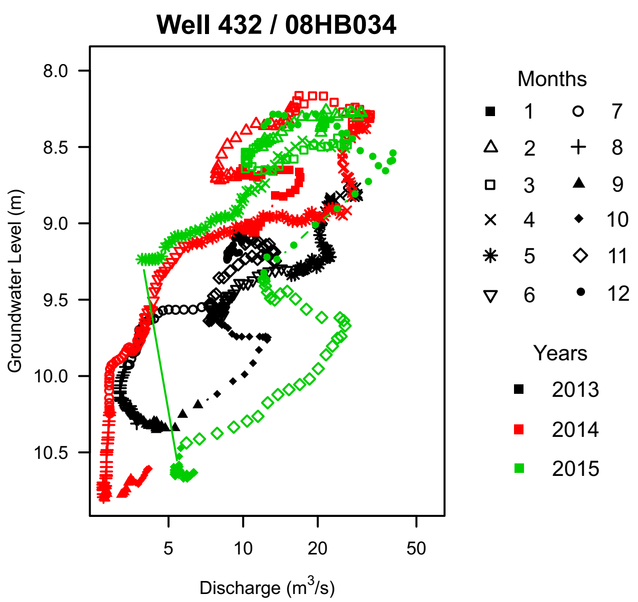

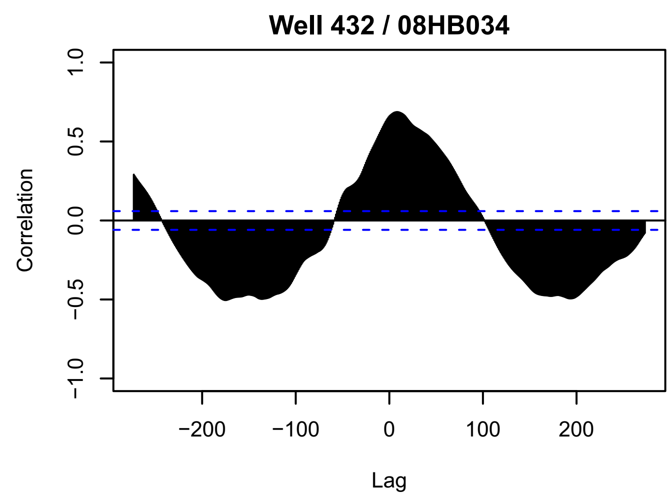

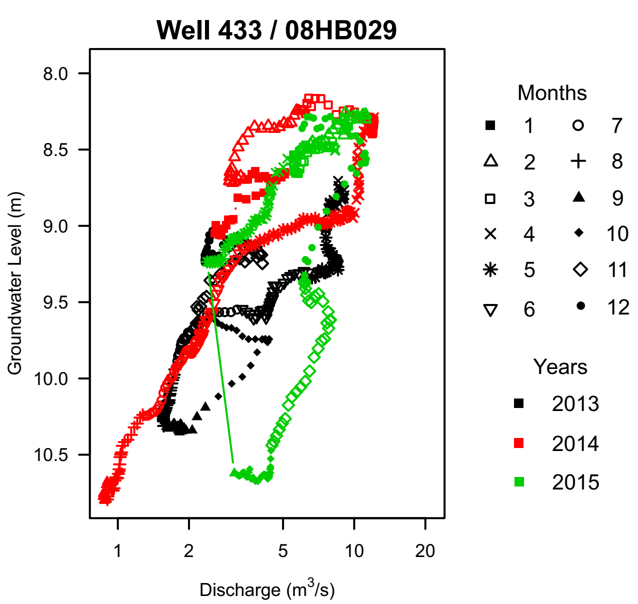

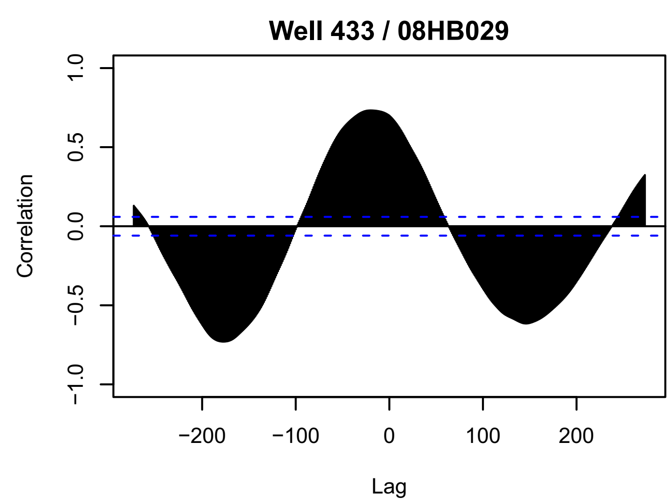

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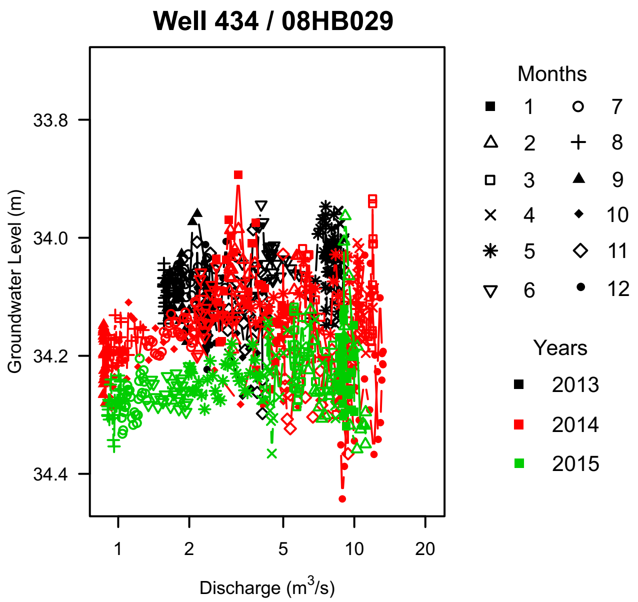
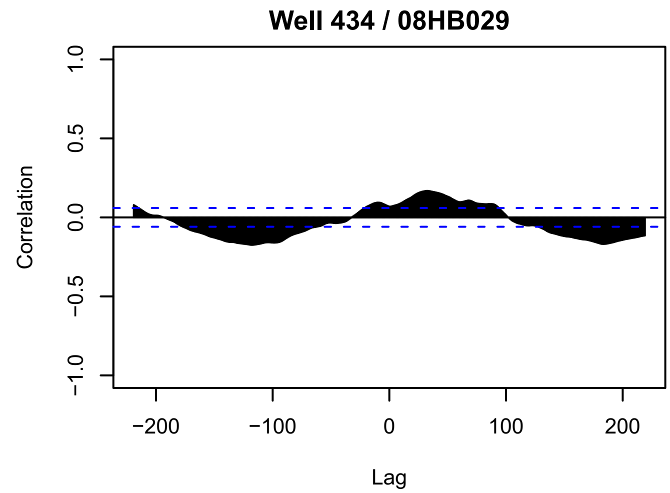
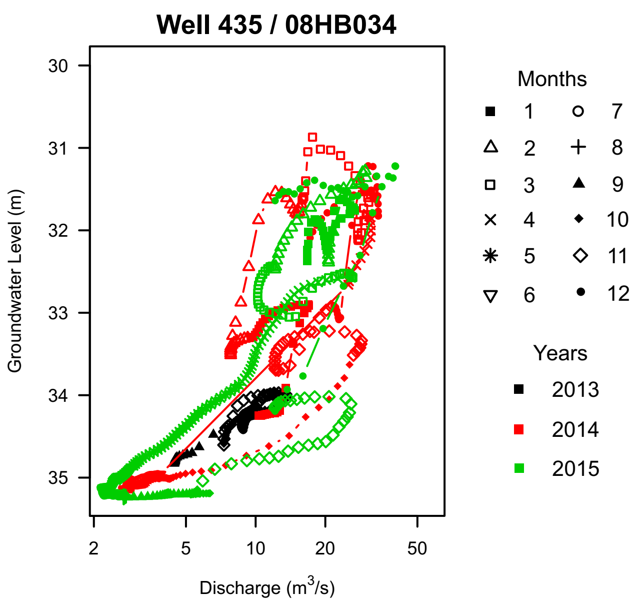
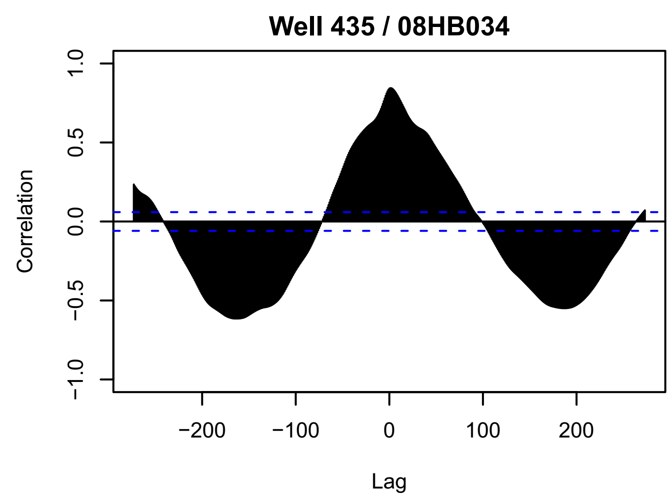
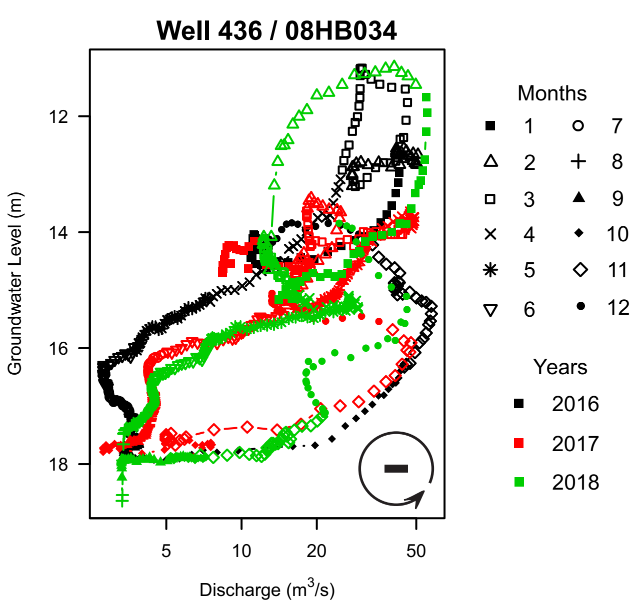
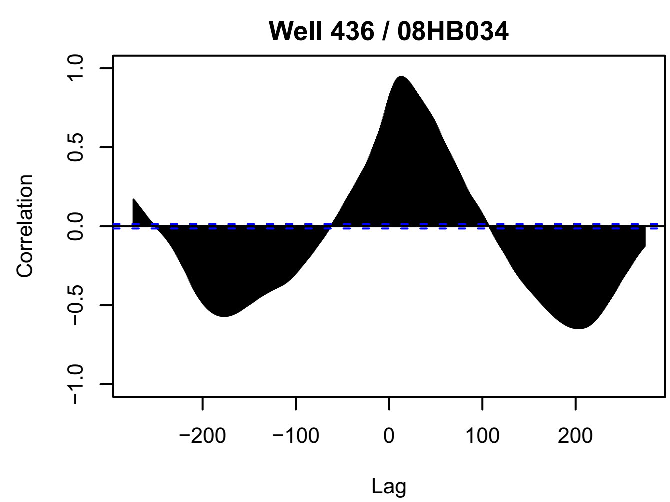




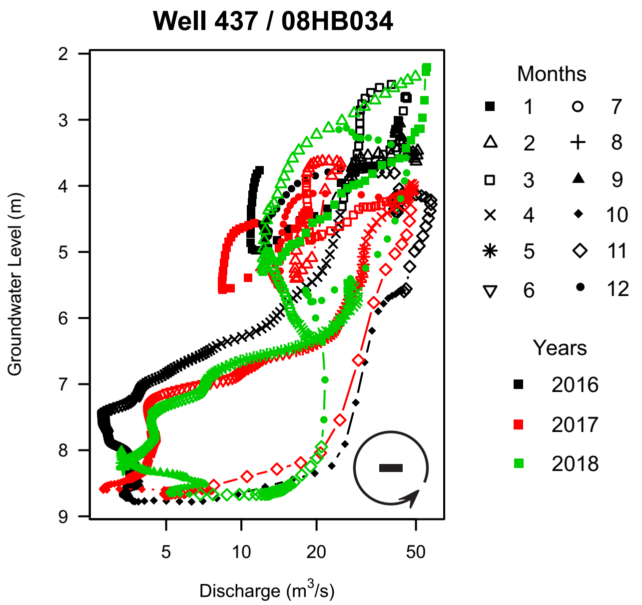


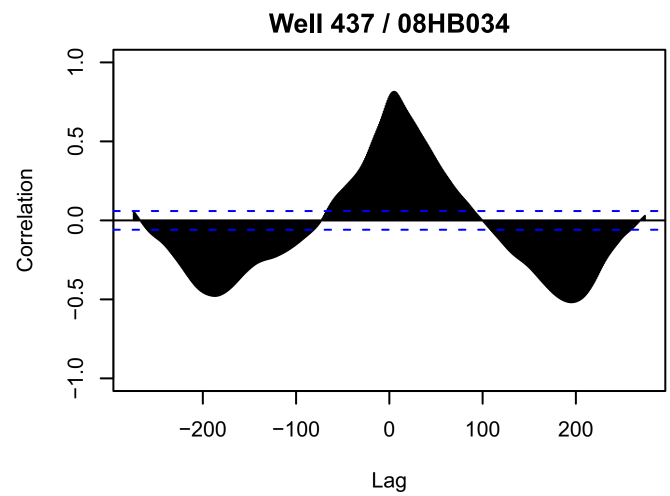


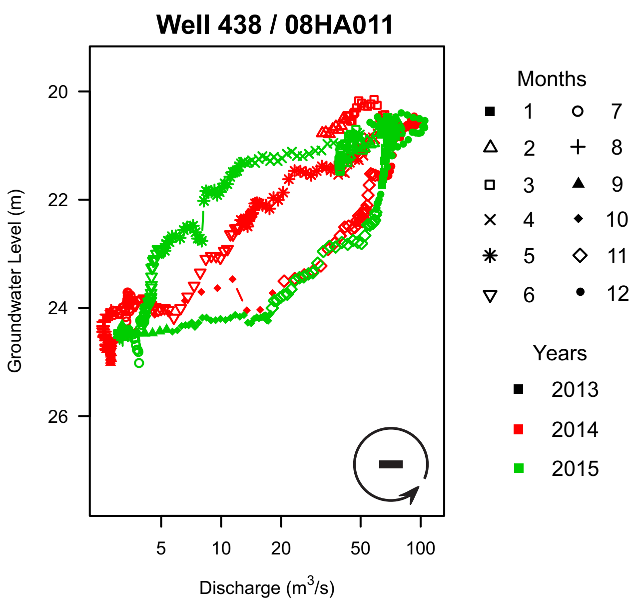


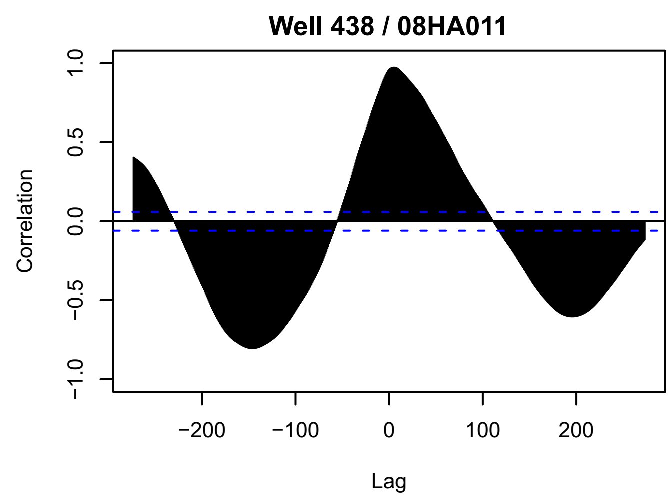


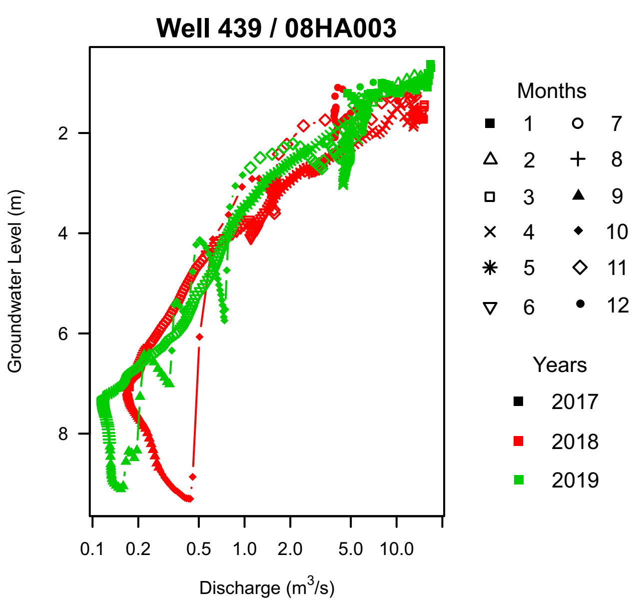
West Coast Region

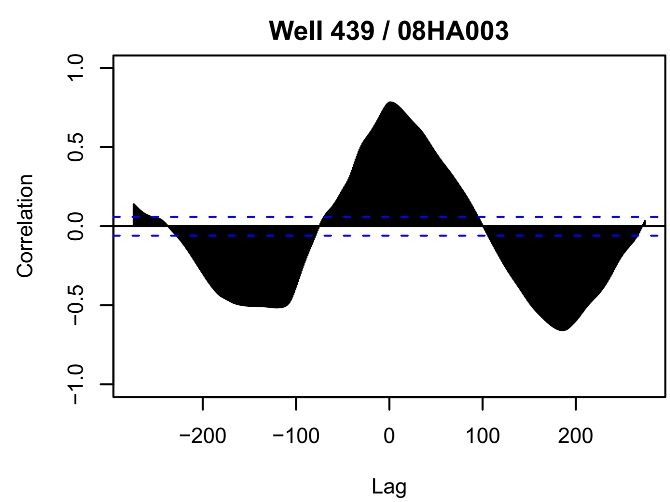






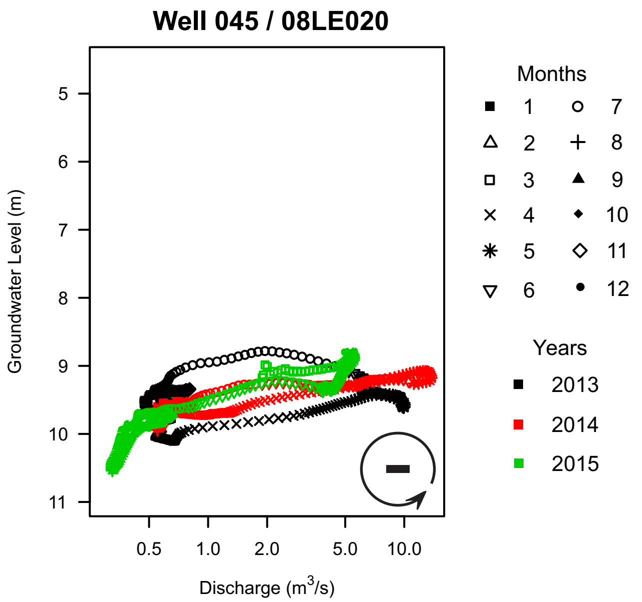


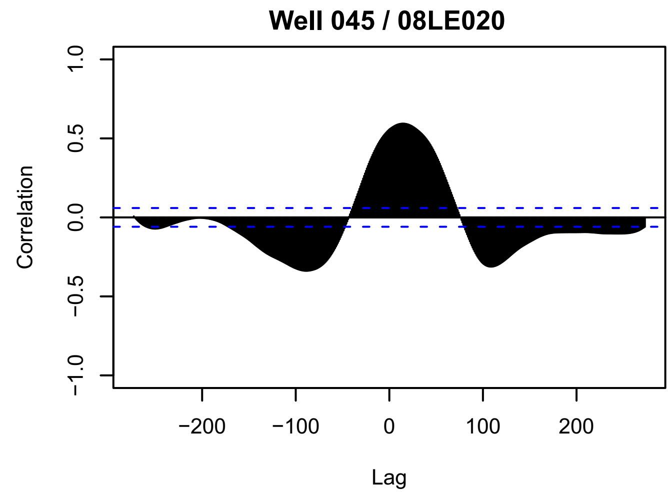


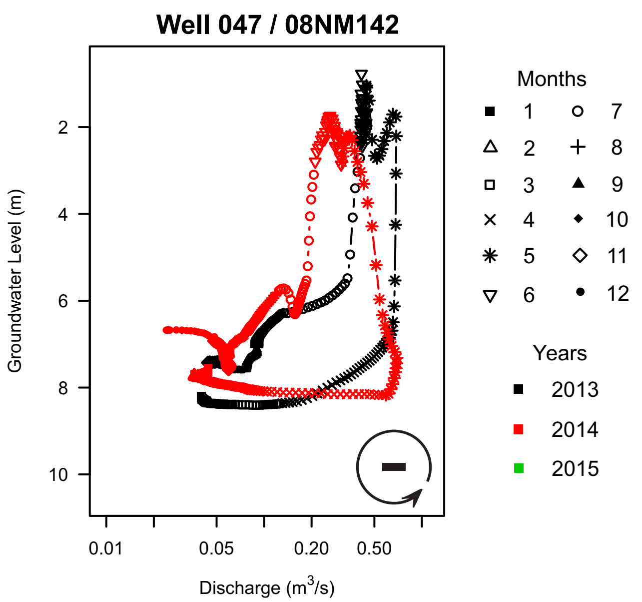


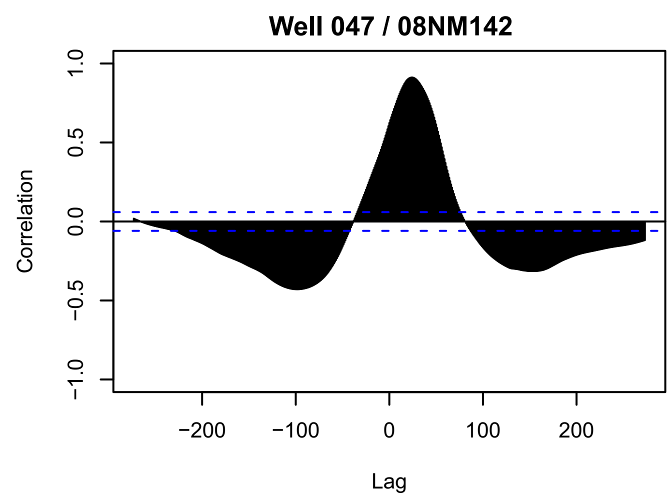
South Natural Resource Area

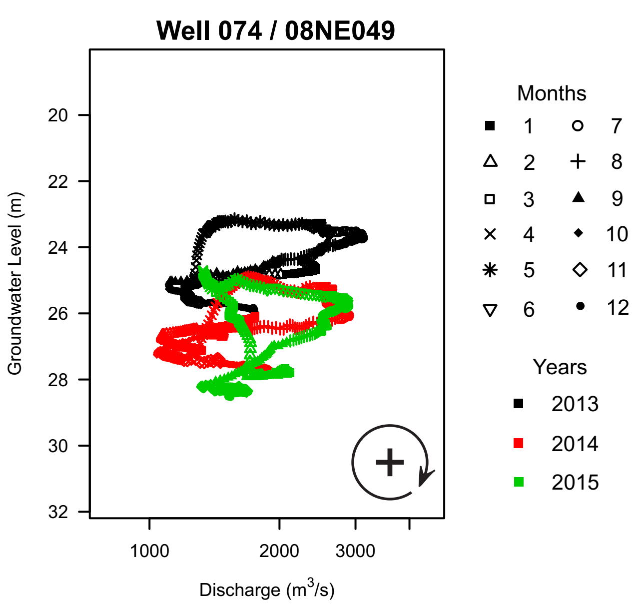
South Natural Resource Area

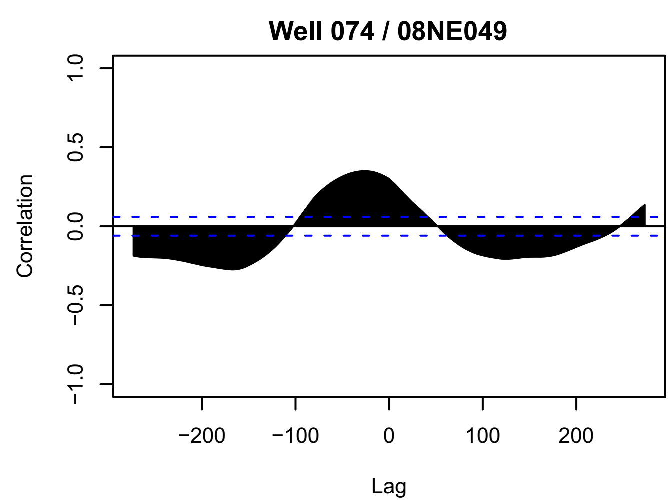




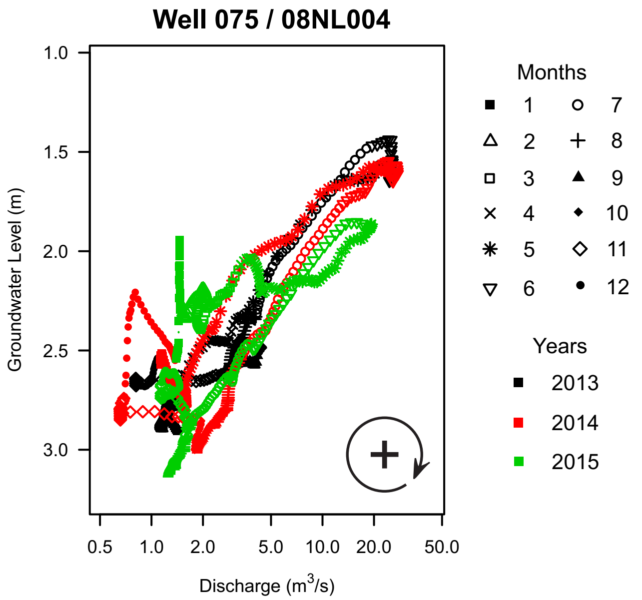


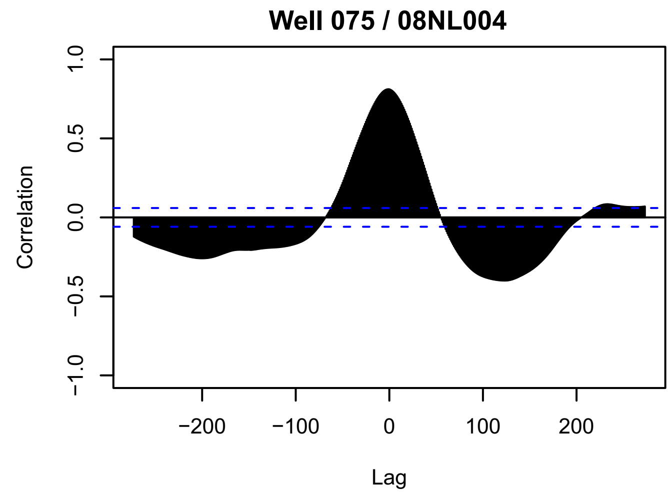


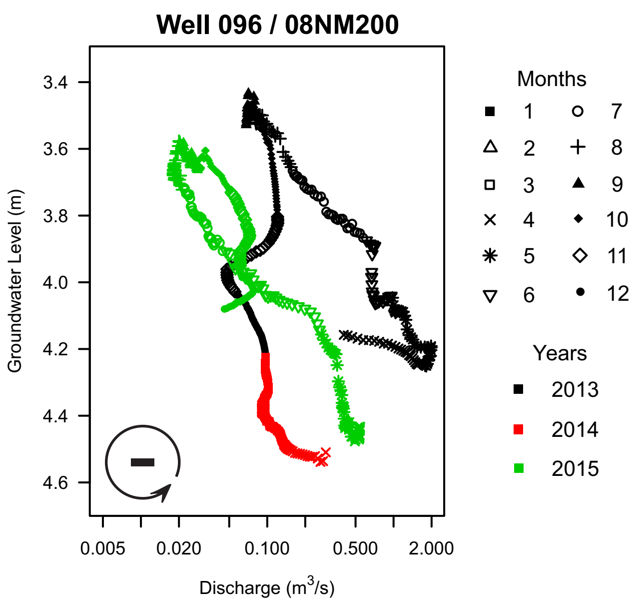


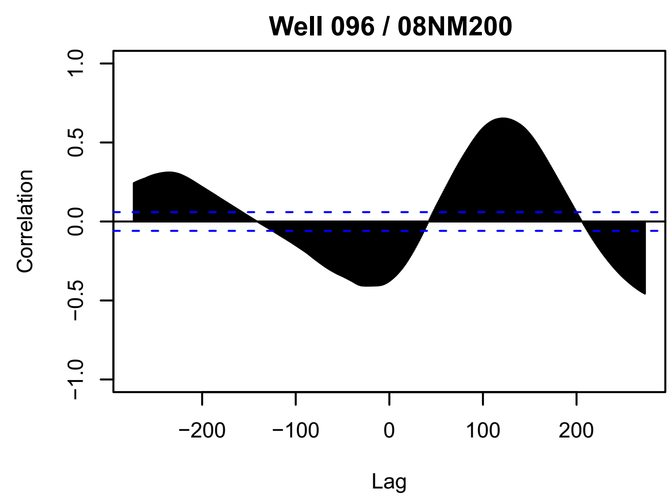


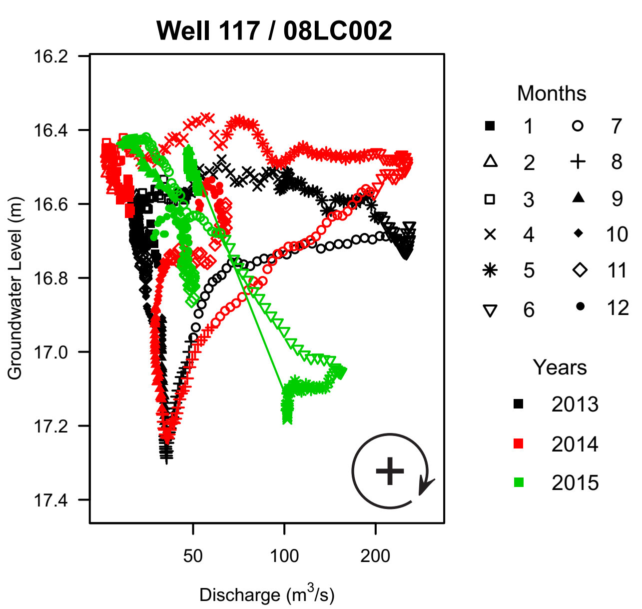
South Natural Resource Area

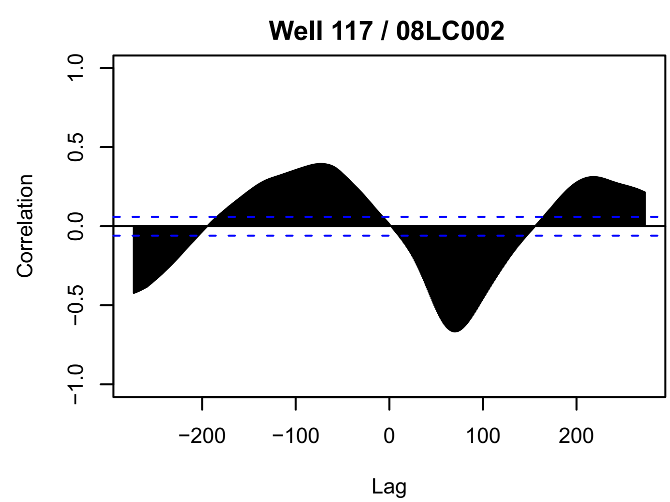




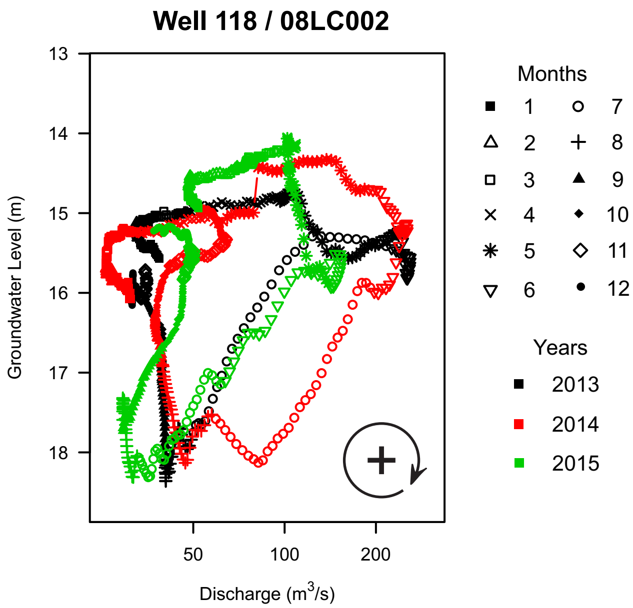


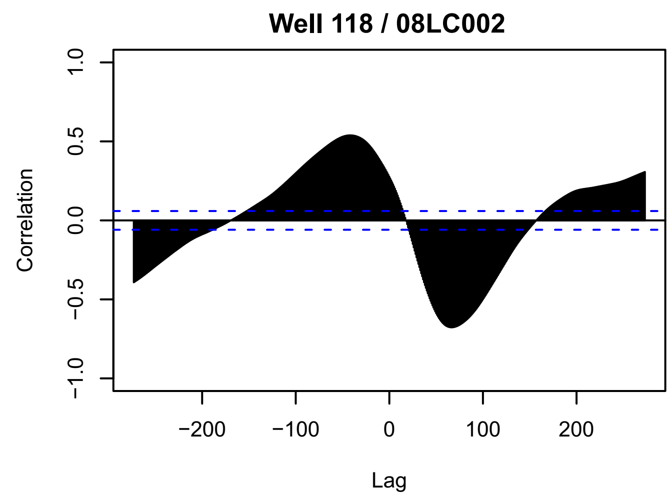


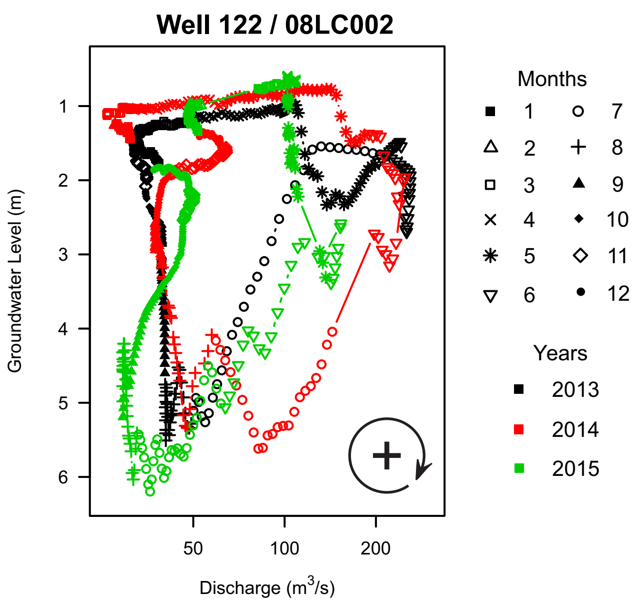


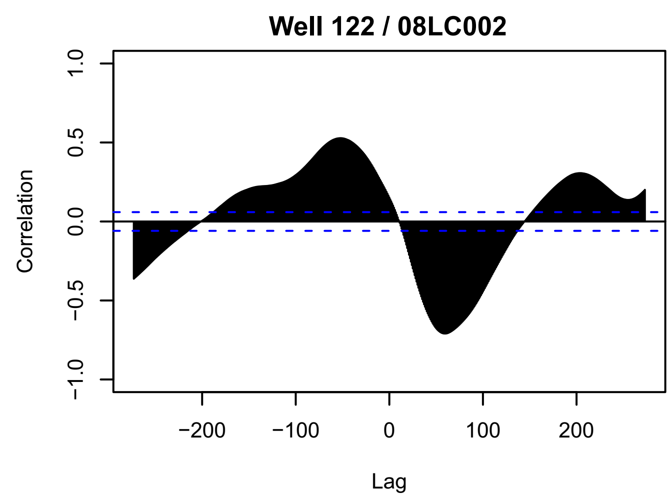


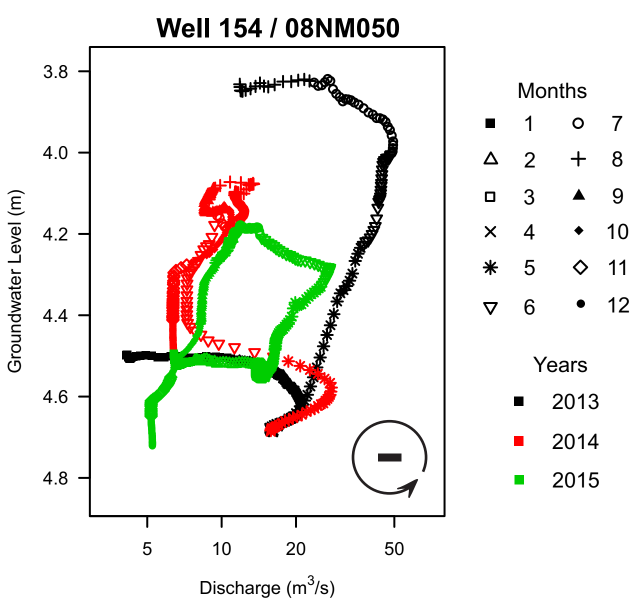
South Natural Resource Area

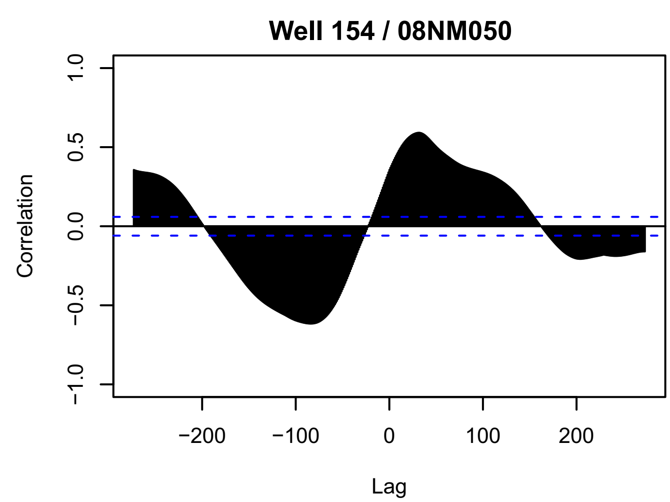




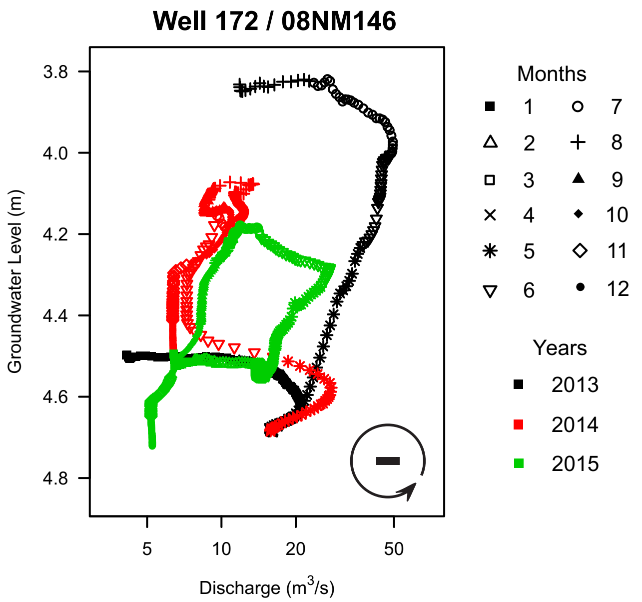


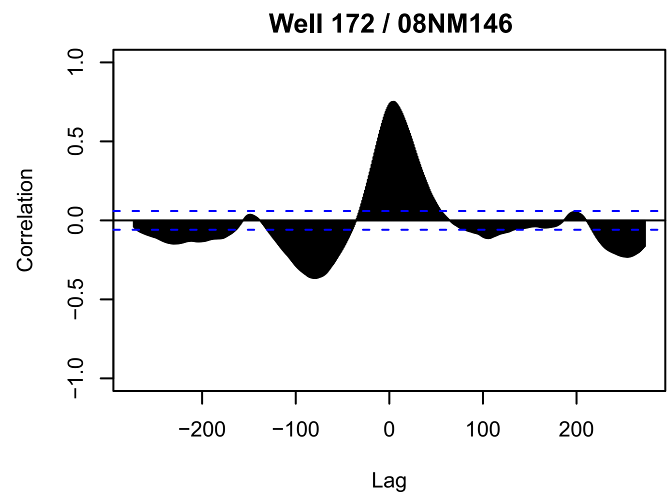


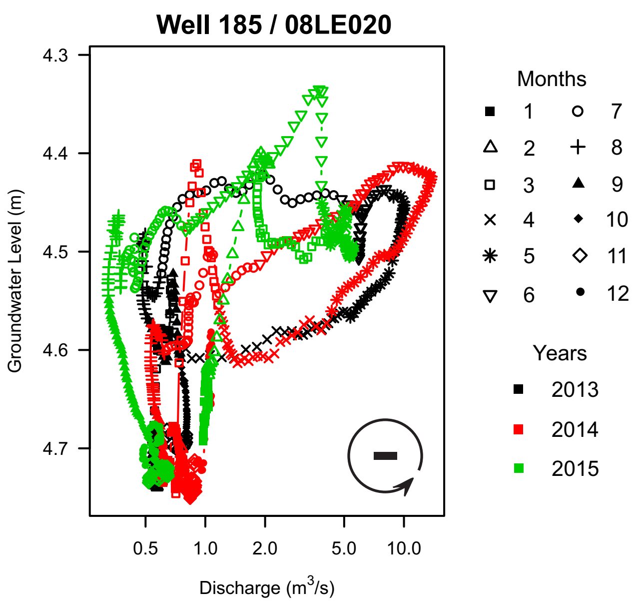


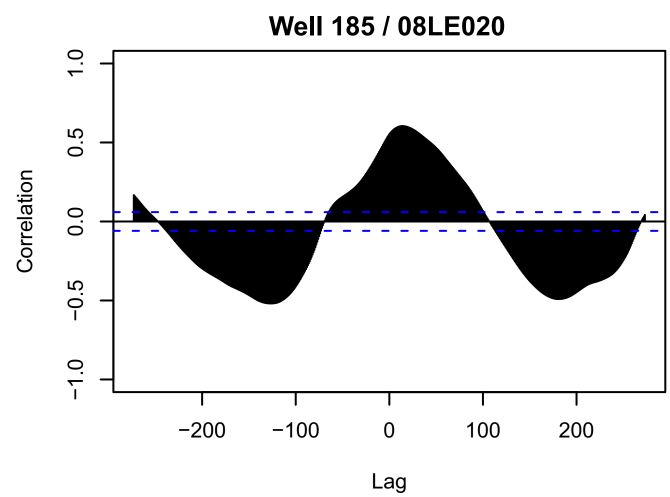


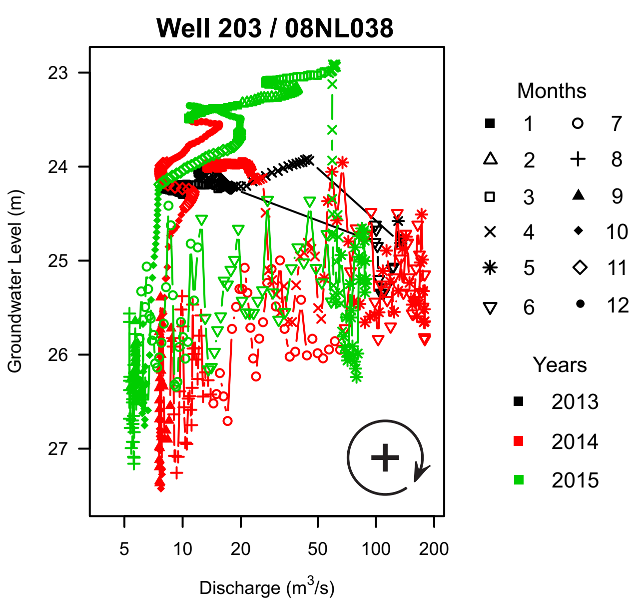
South Natural Resource Area

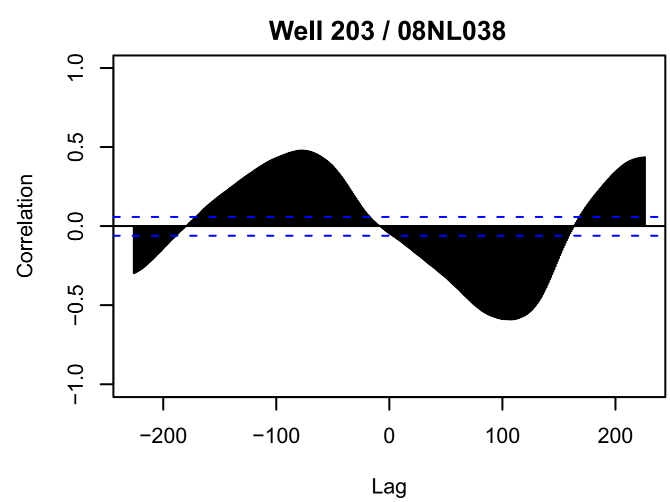






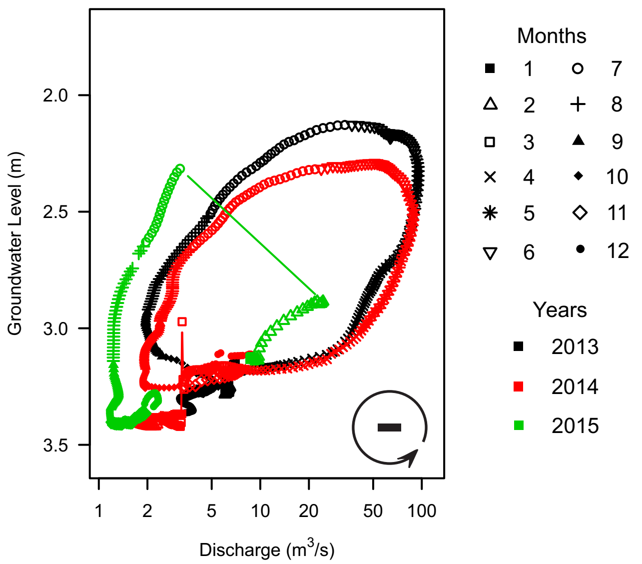




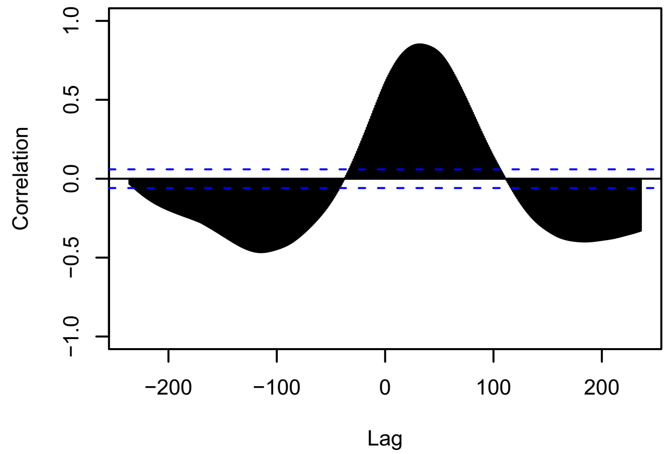


South Natural Resource Area

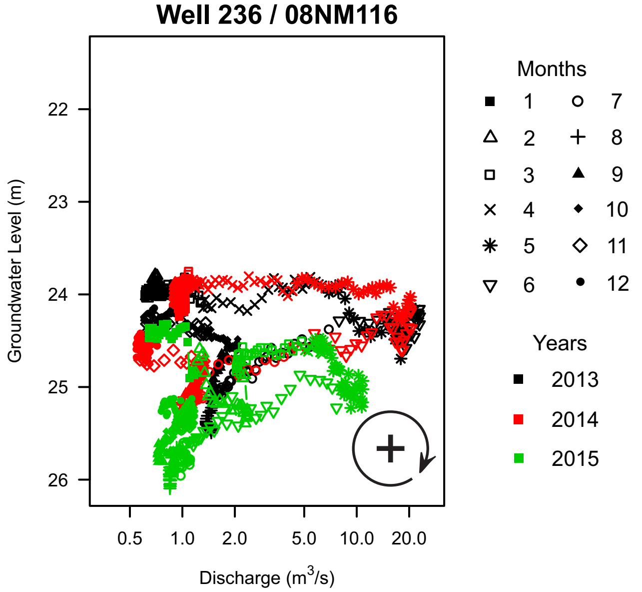
Well 217 / 08NN002



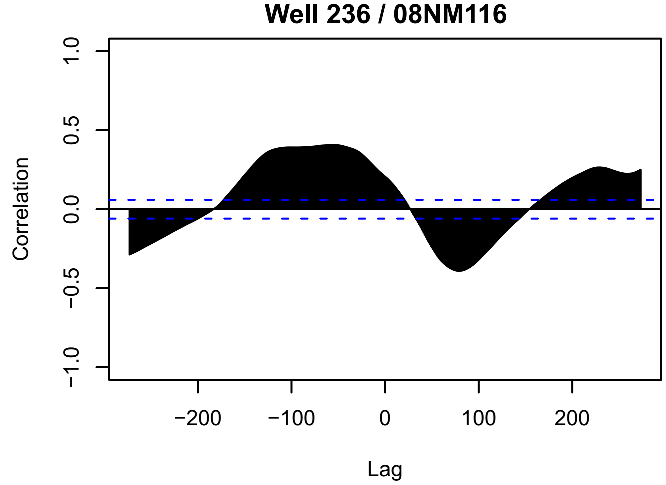
Well 217 / 08NN002



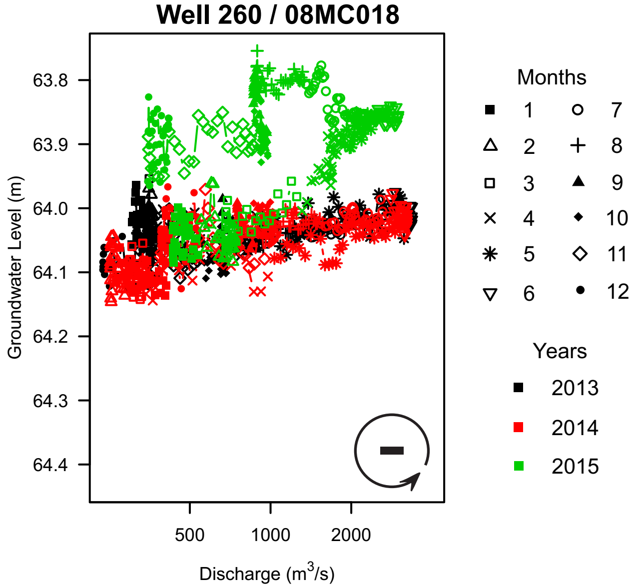
Well 236 / 08NM116



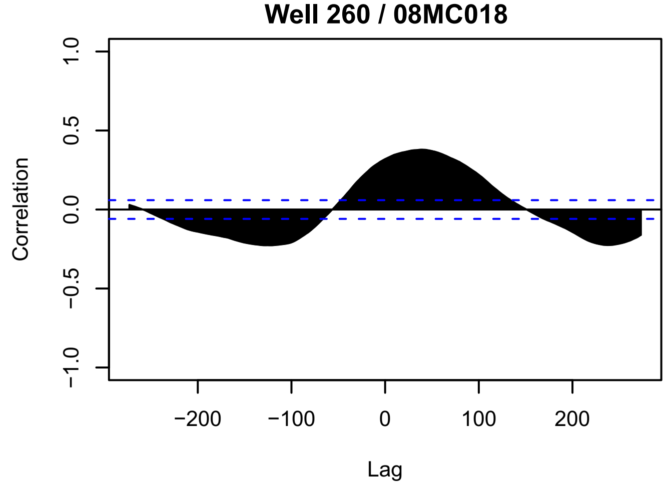
Well 236 / 08NM116



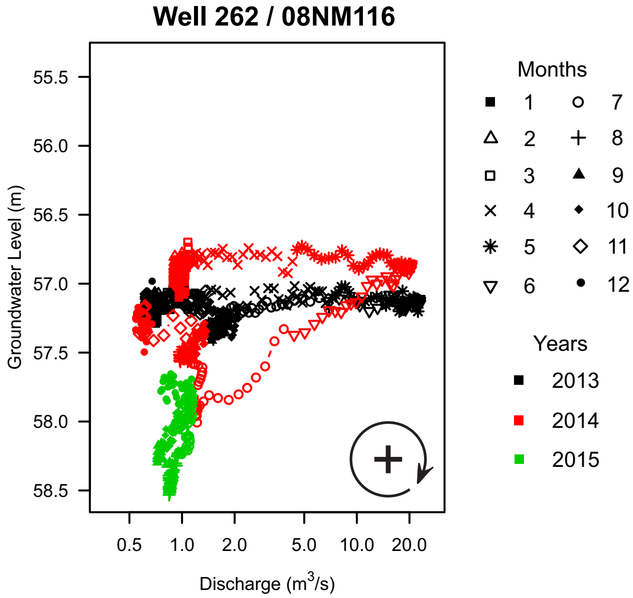
Well 260 / 08MC018

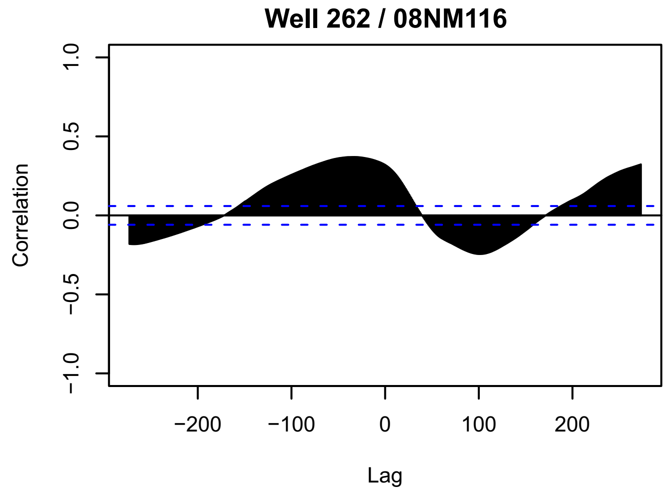


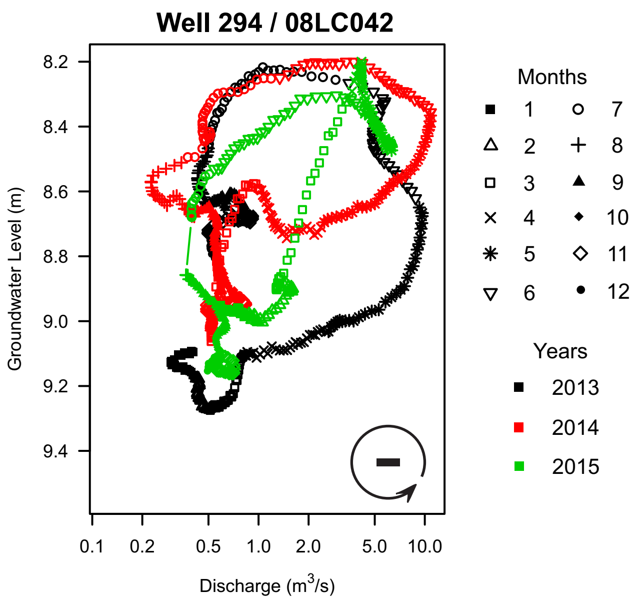
Well 260 / 08MC018

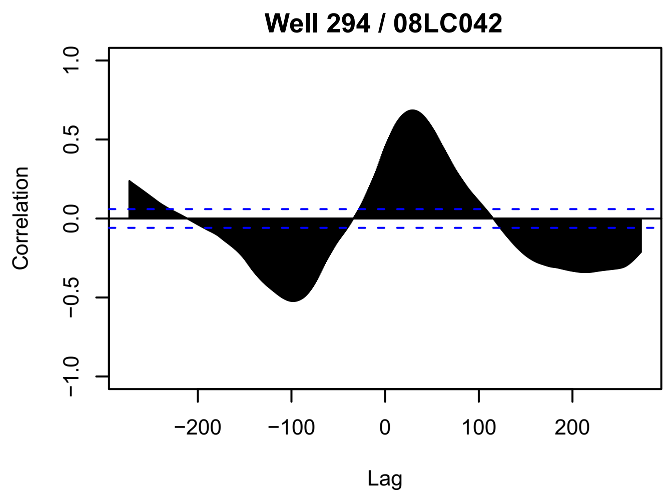


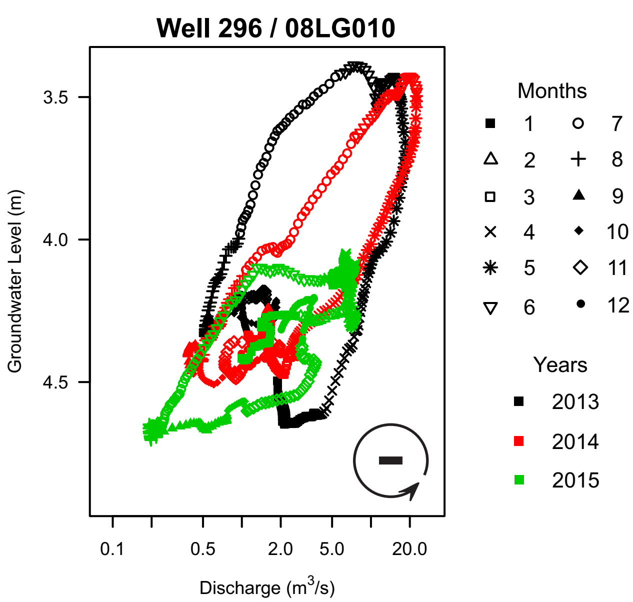
South Natural Resource Area

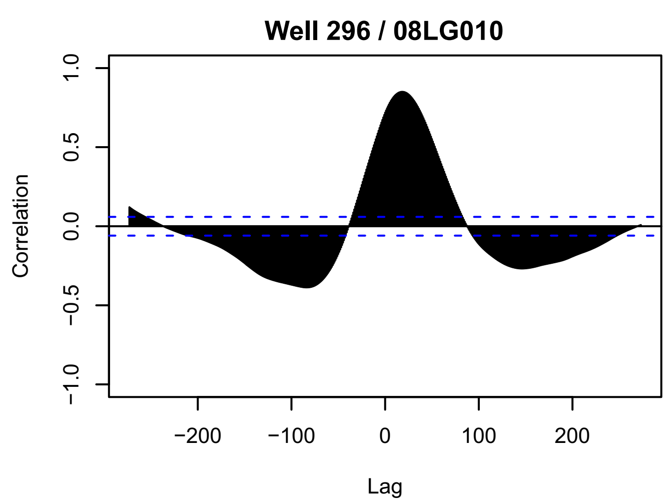






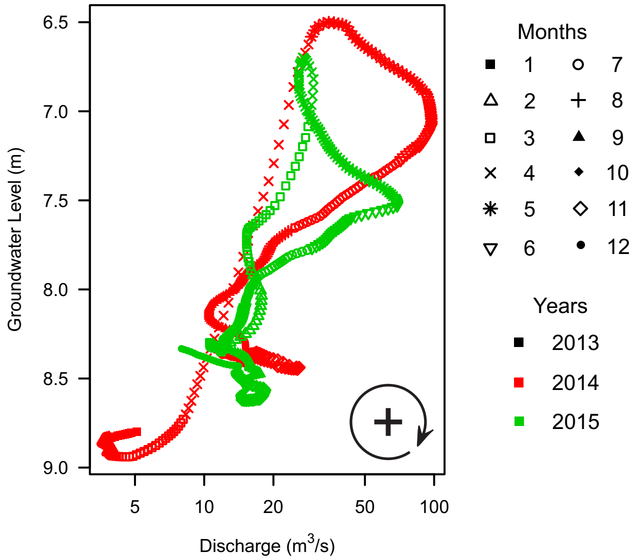




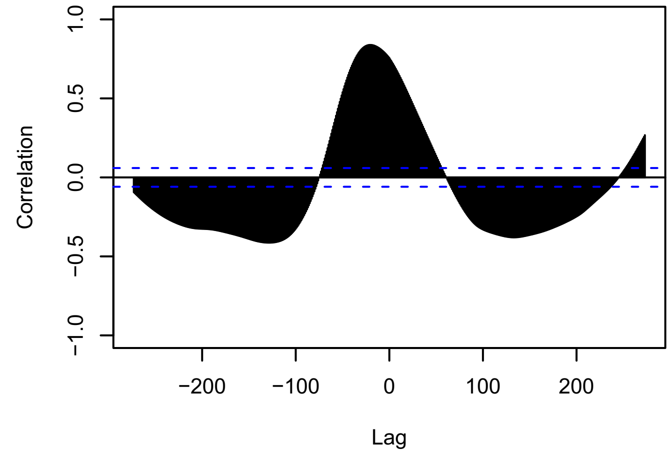


South Natural Resource Area

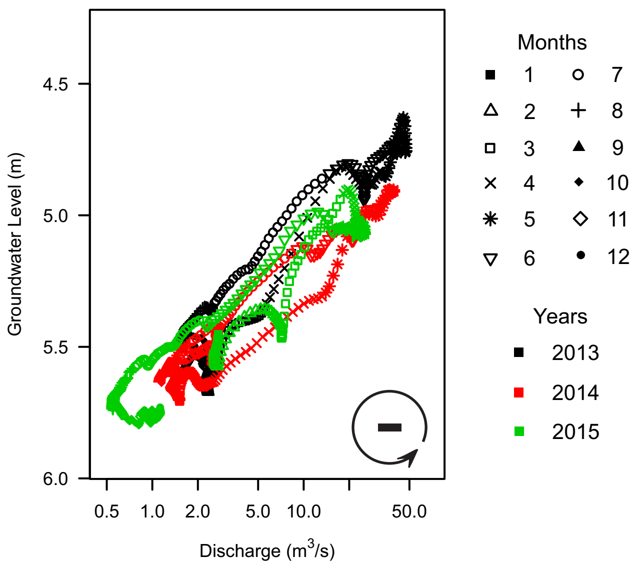
Well 302 / 08LE024



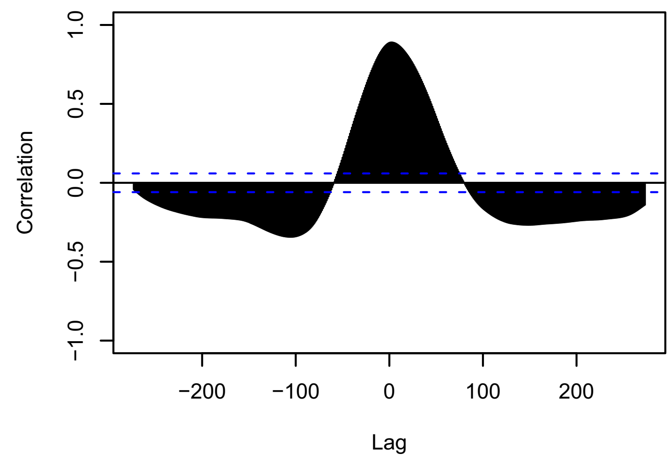
Well 302 / 08LE024



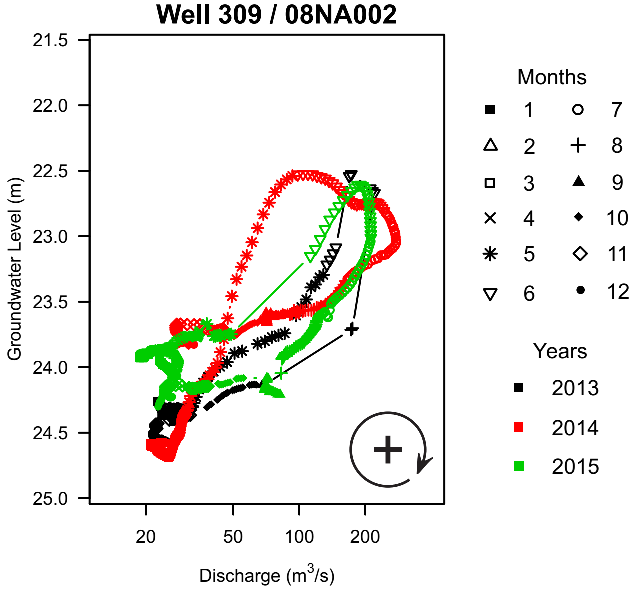
Well 306 / 08NN003



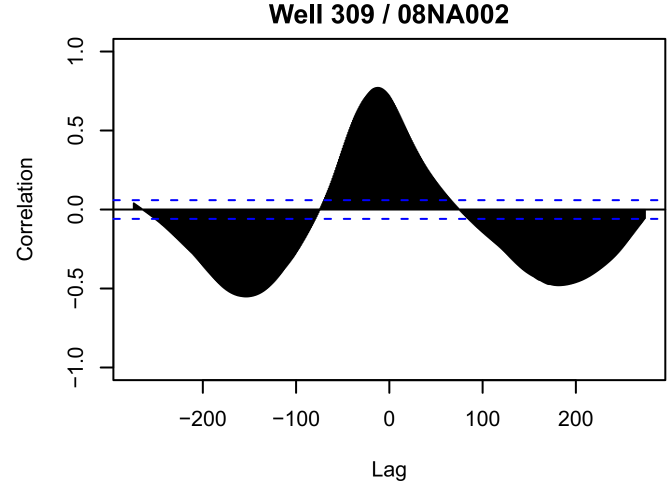
Well 306 / 08NN003



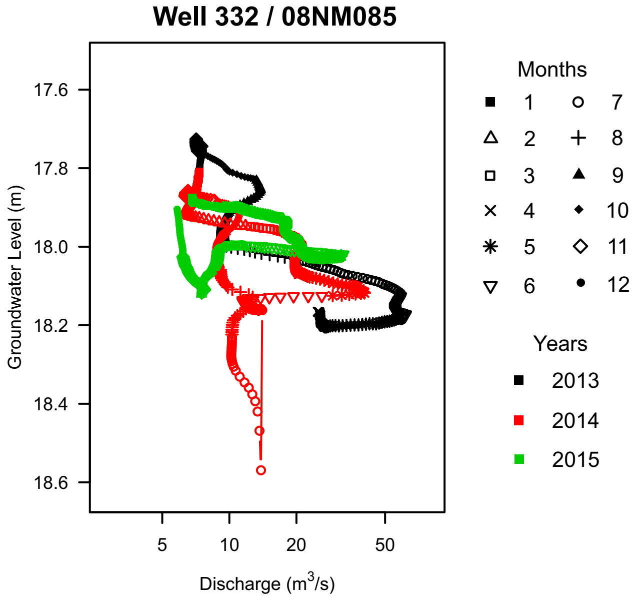
Well 309 / 08NA002

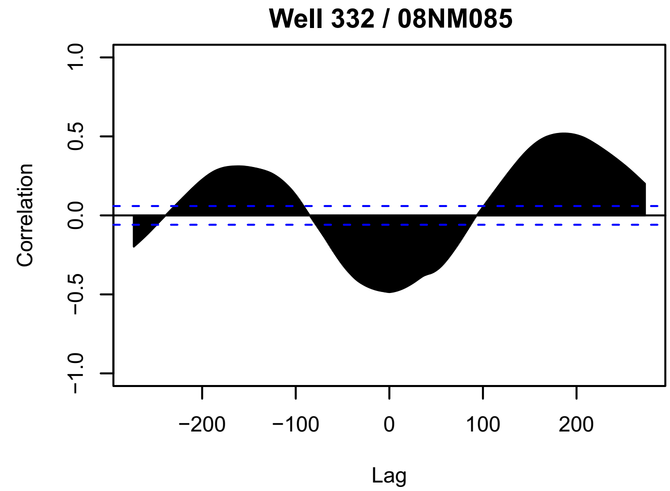


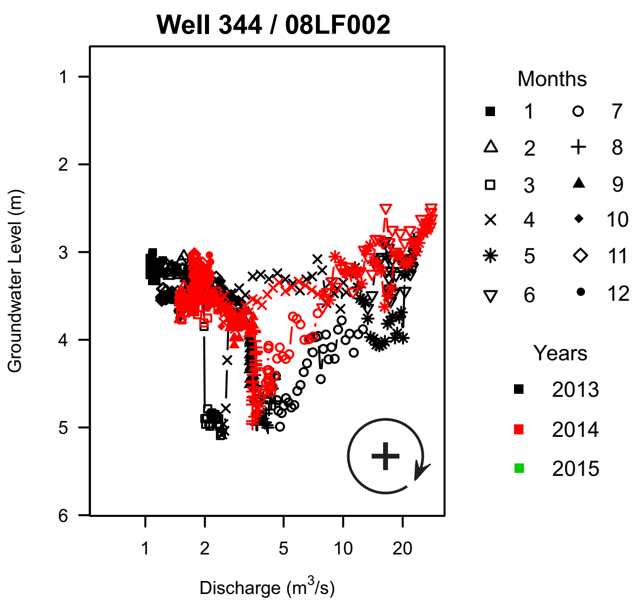
Well 309 / 08NA002

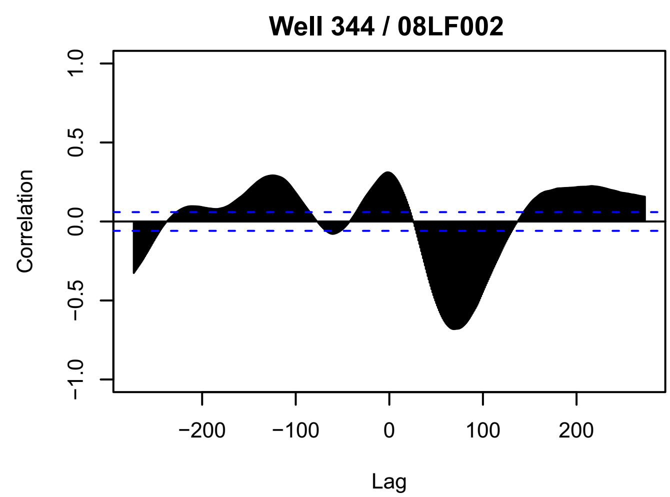


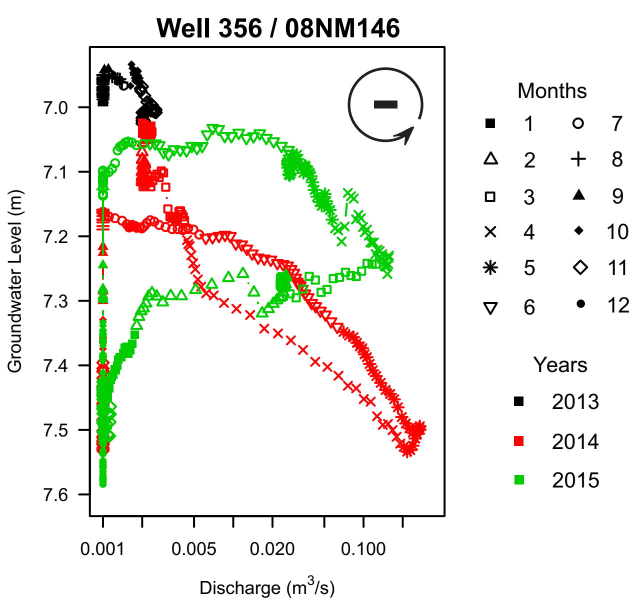
South Natural Resource Area

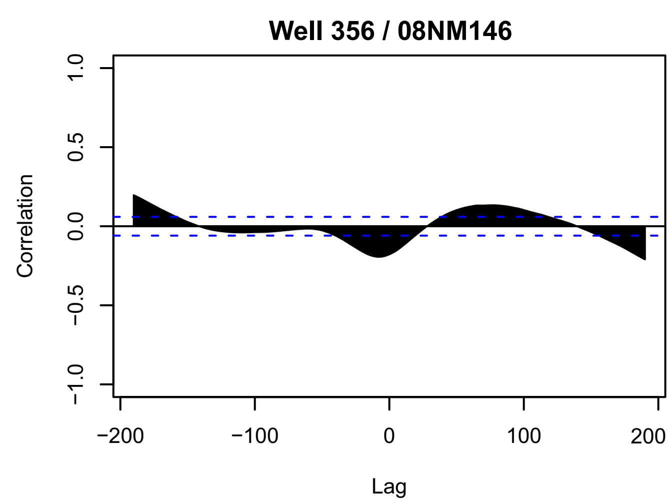




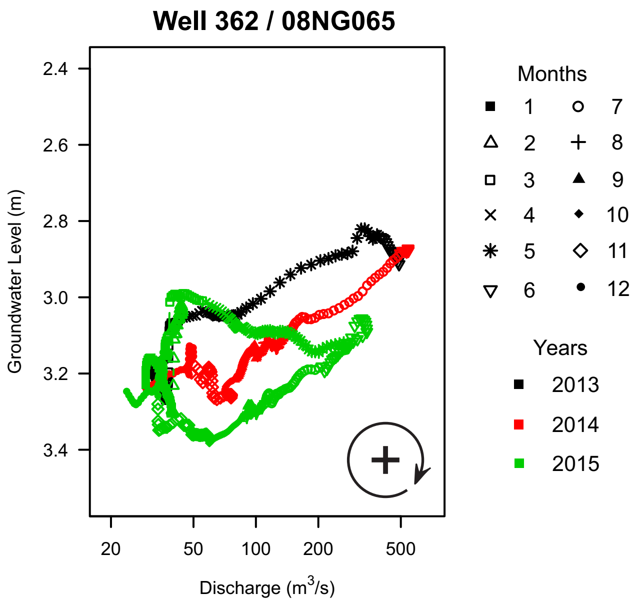


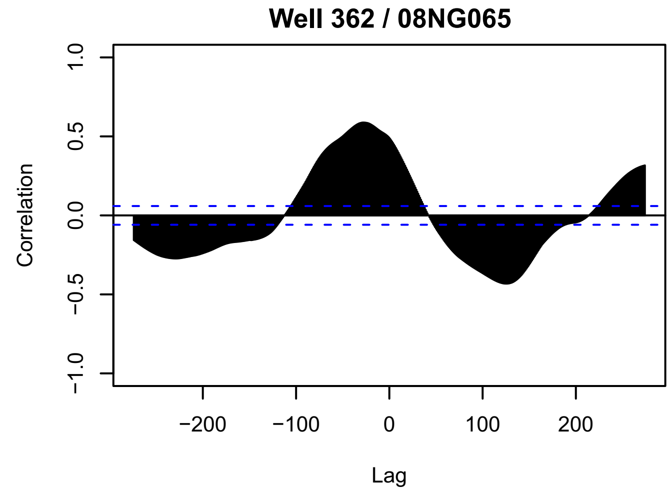


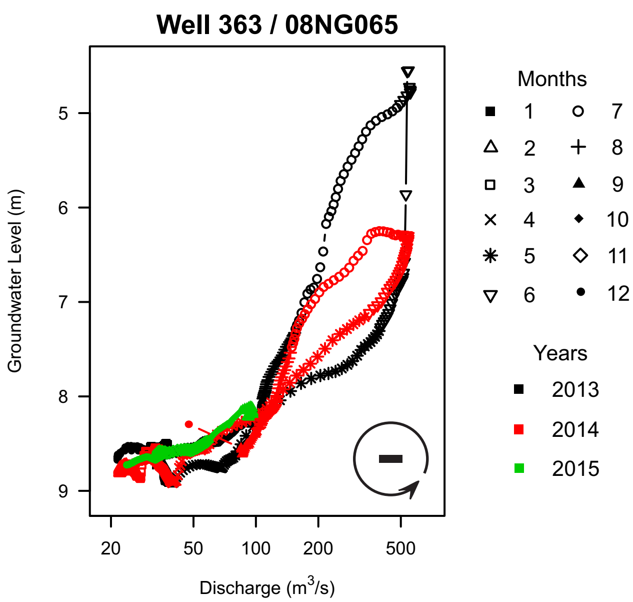


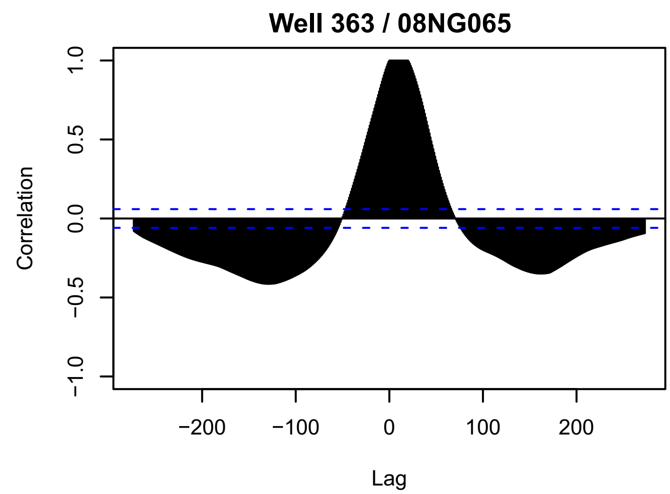


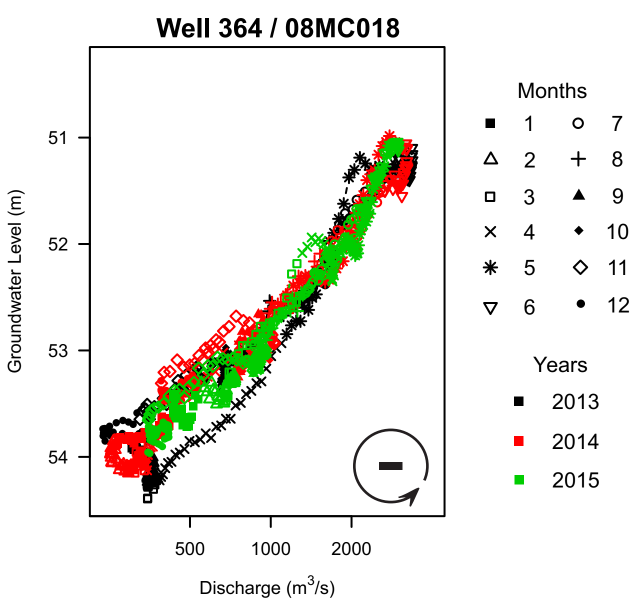
South Natural Resource Area

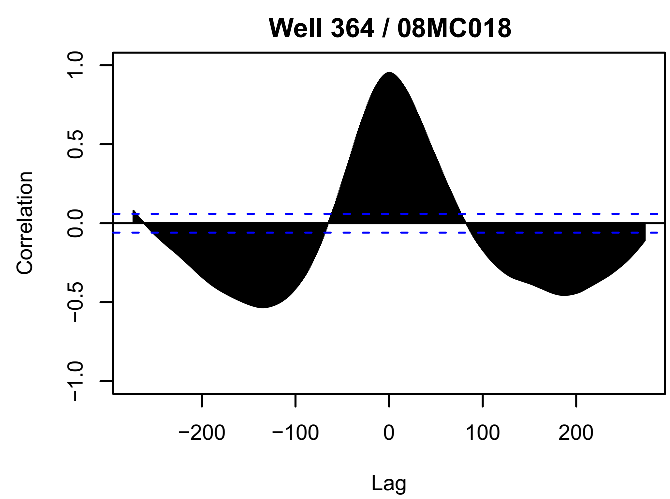




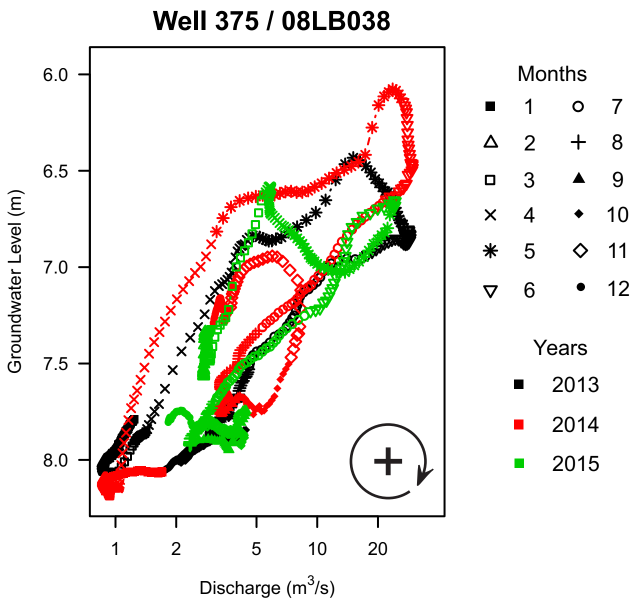


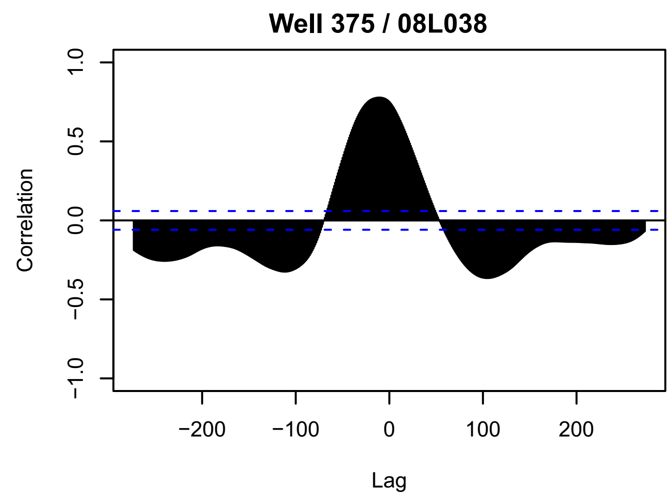


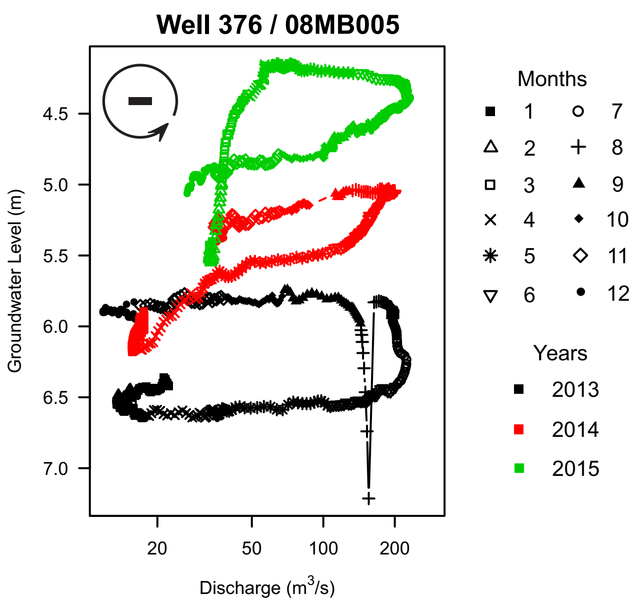


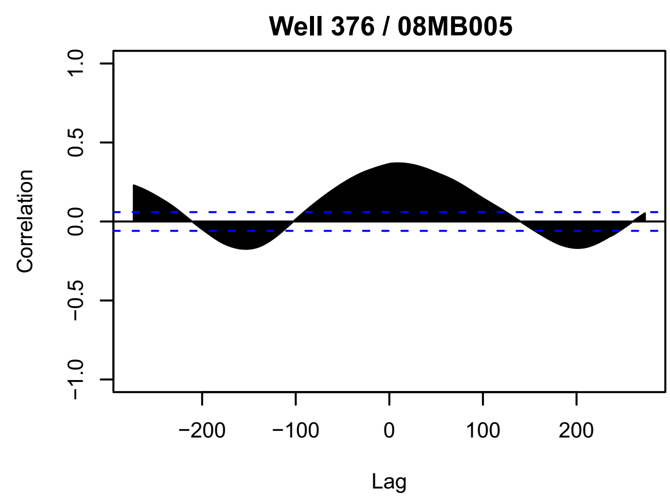


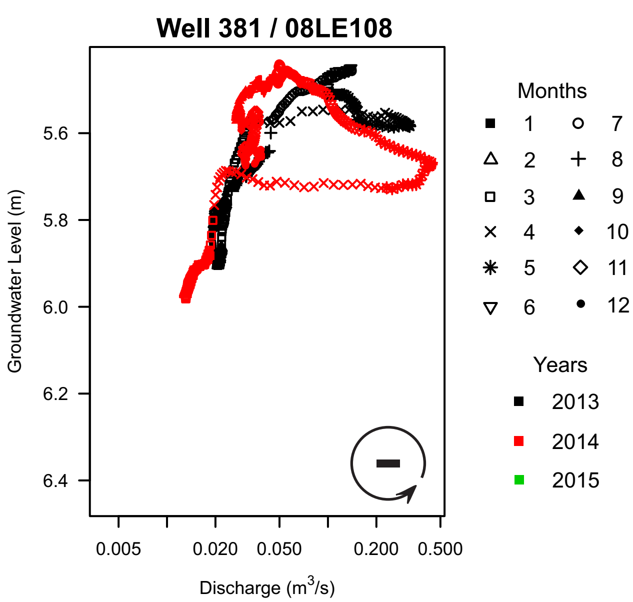
South Natural Resource Area

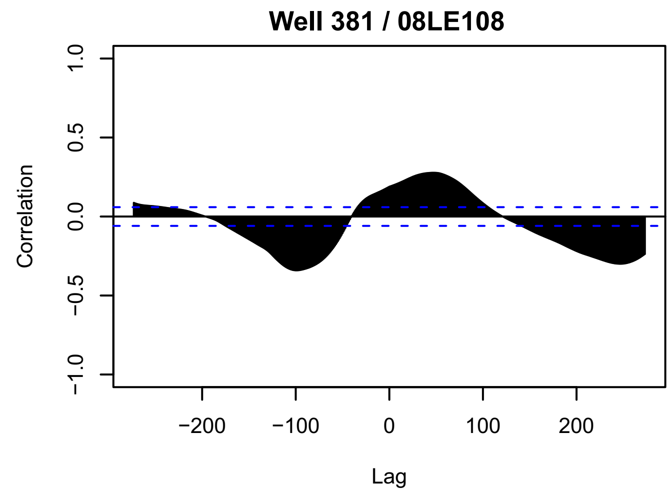




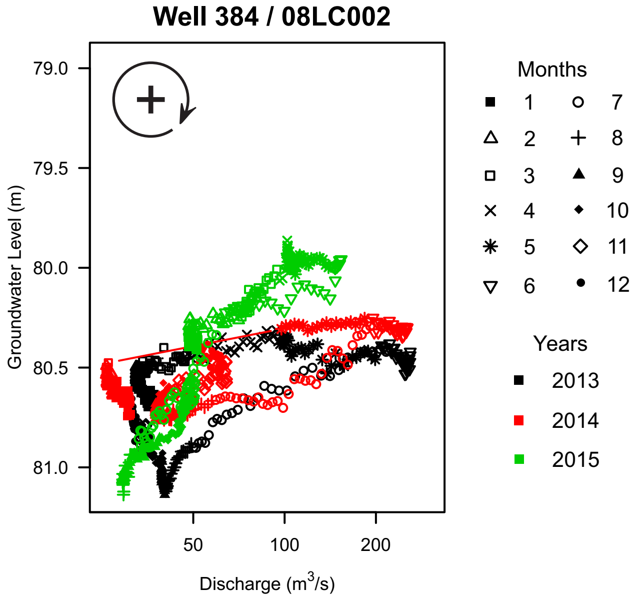


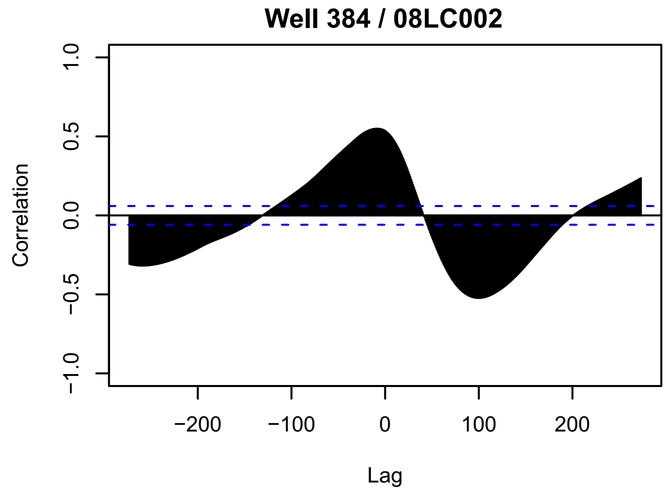


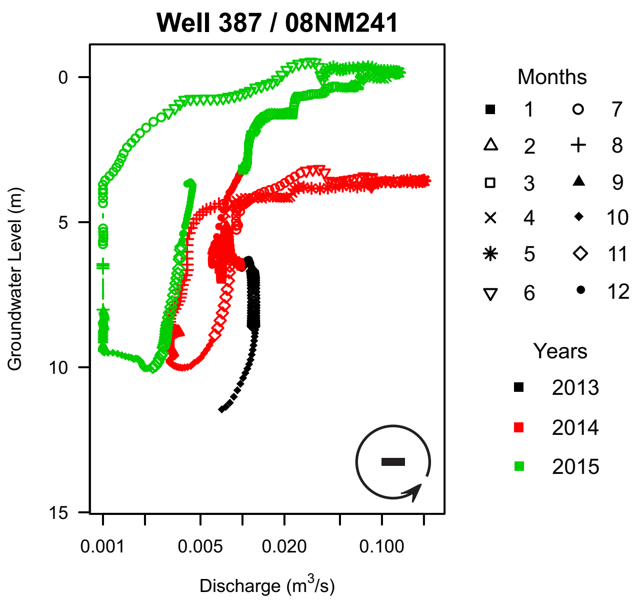


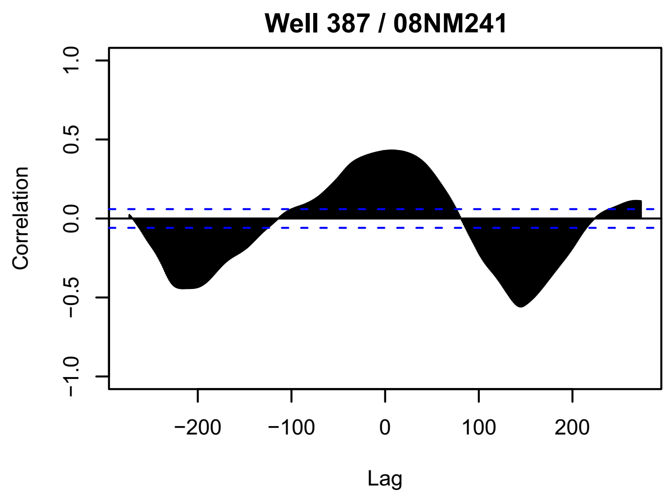


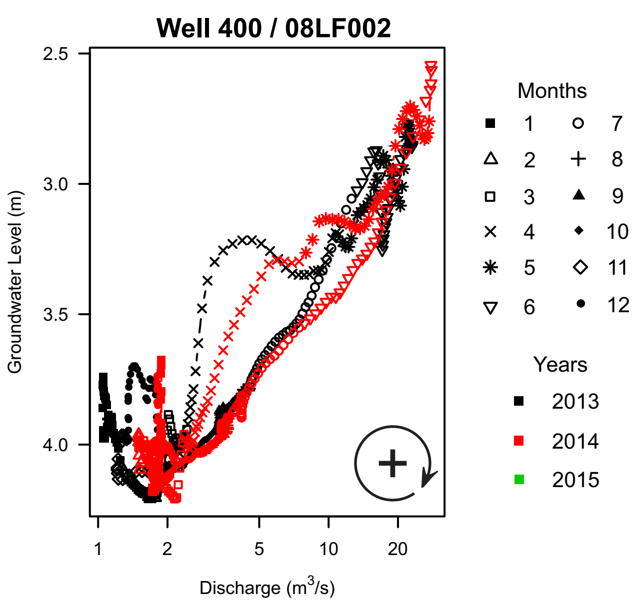
South Natural Resource Area

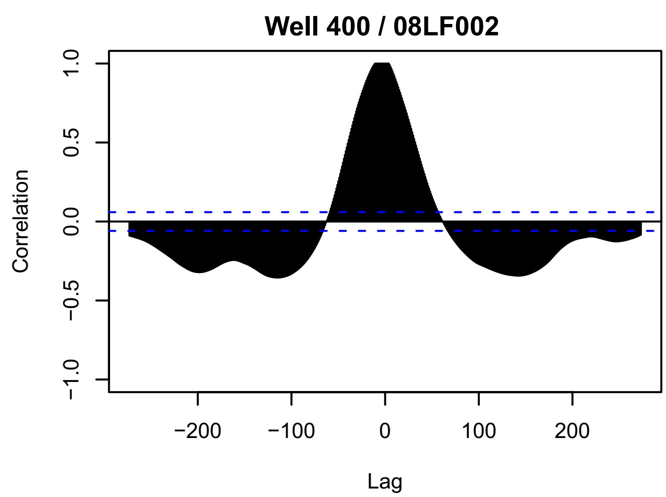




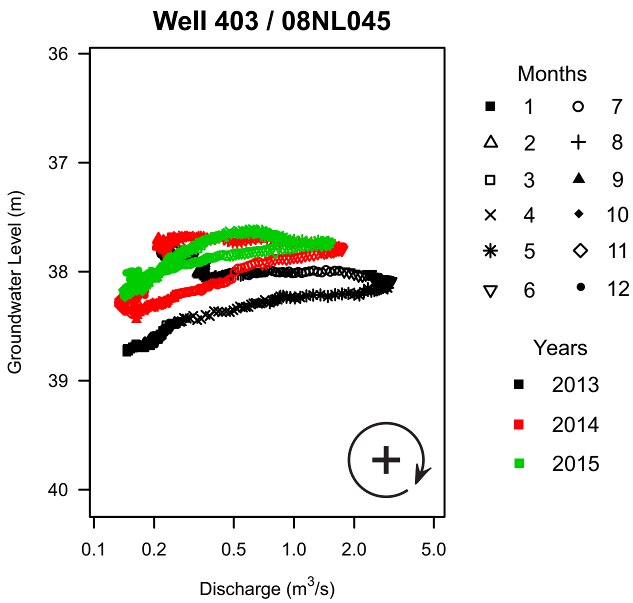


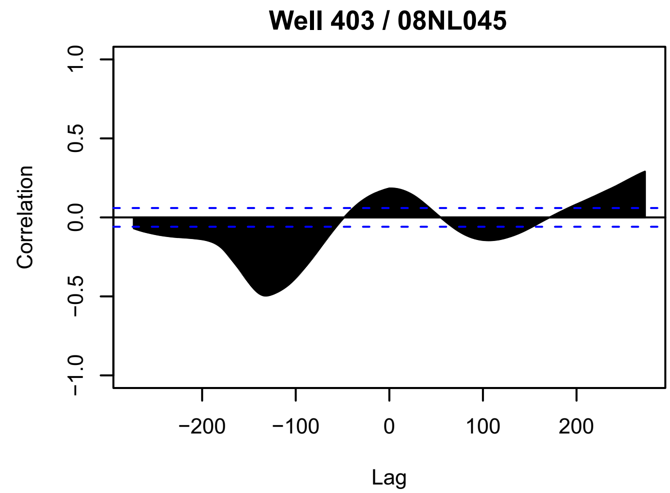


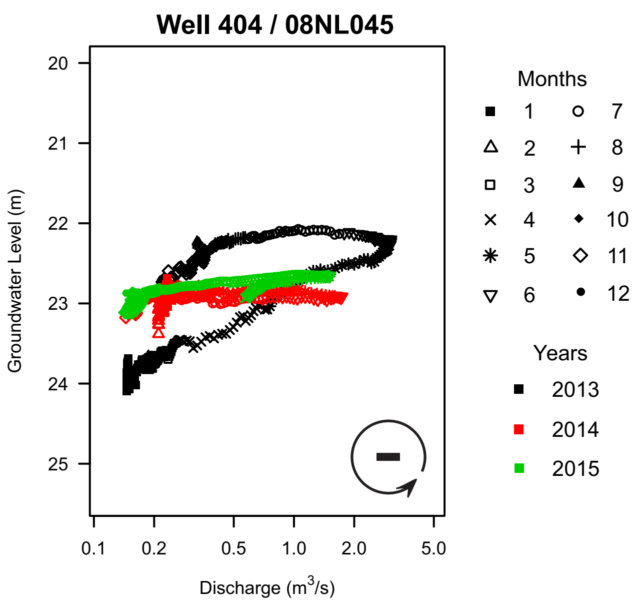


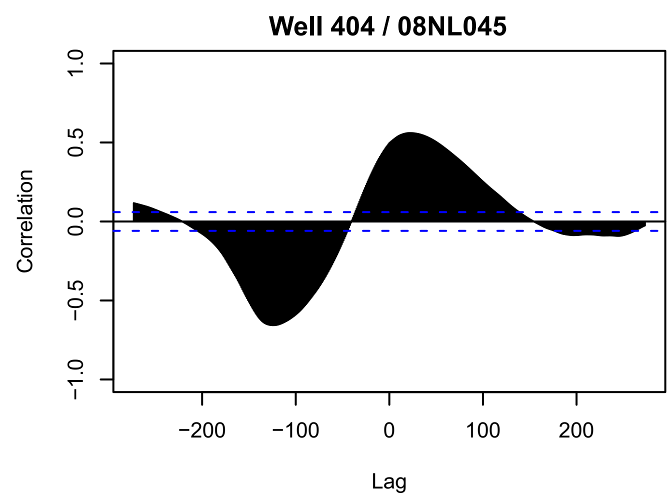


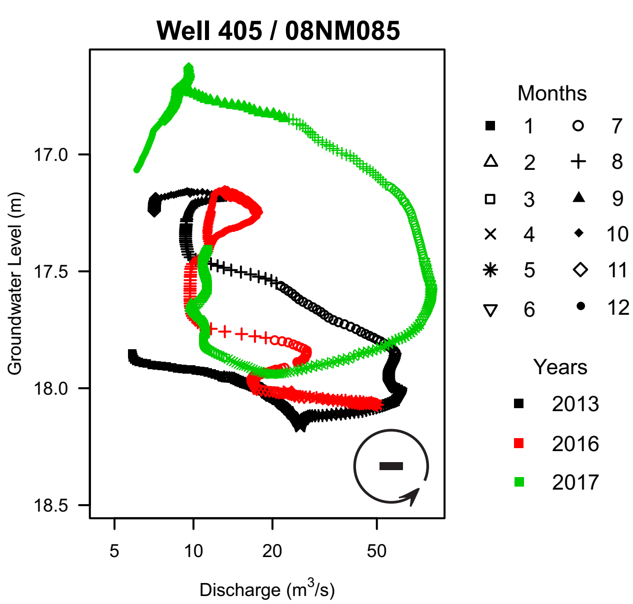
South Natural Resource Area

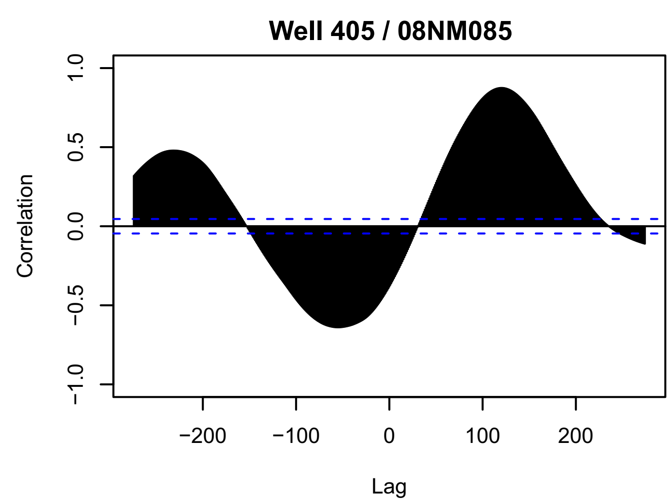












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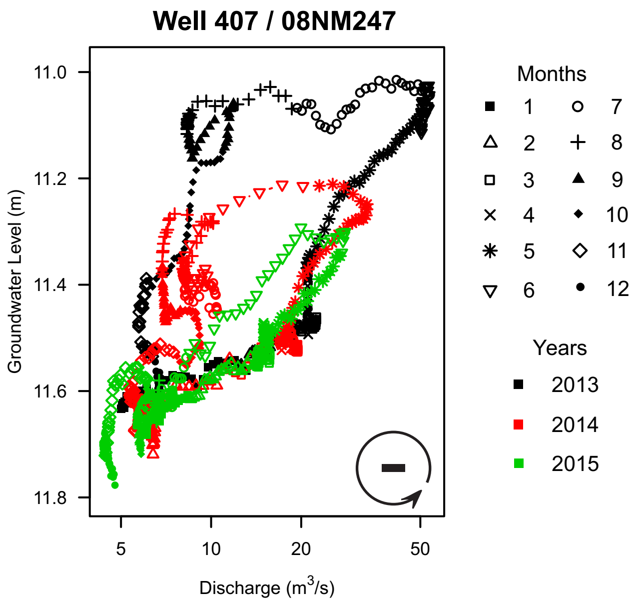

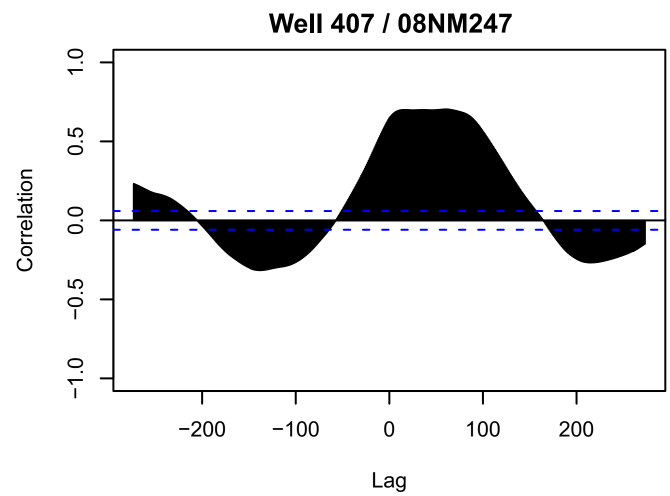

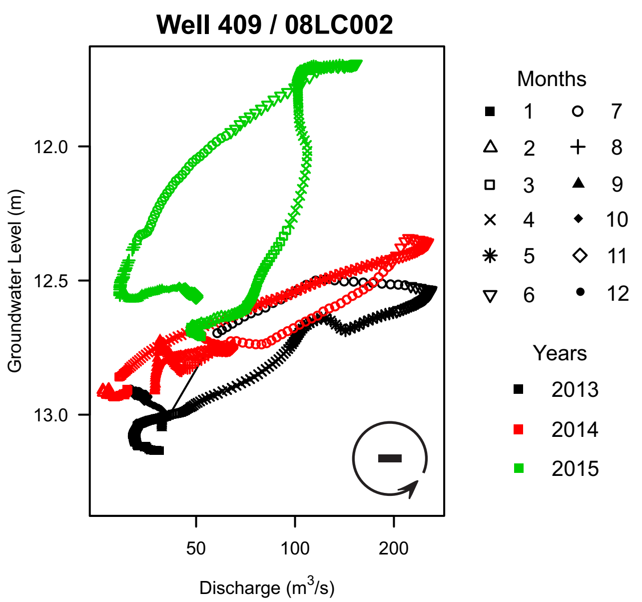

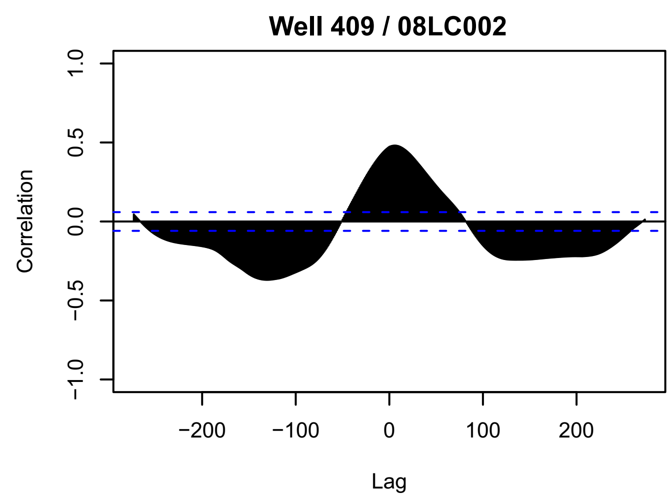

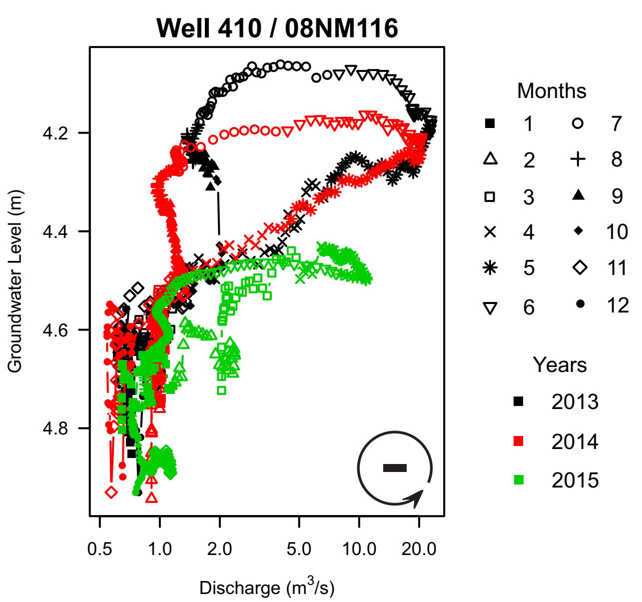

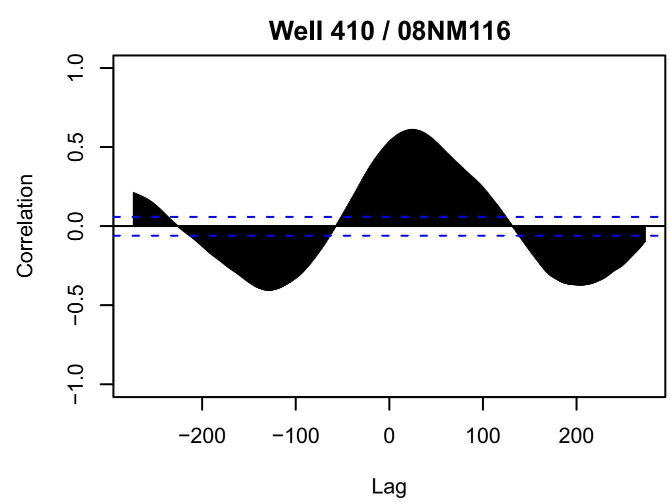

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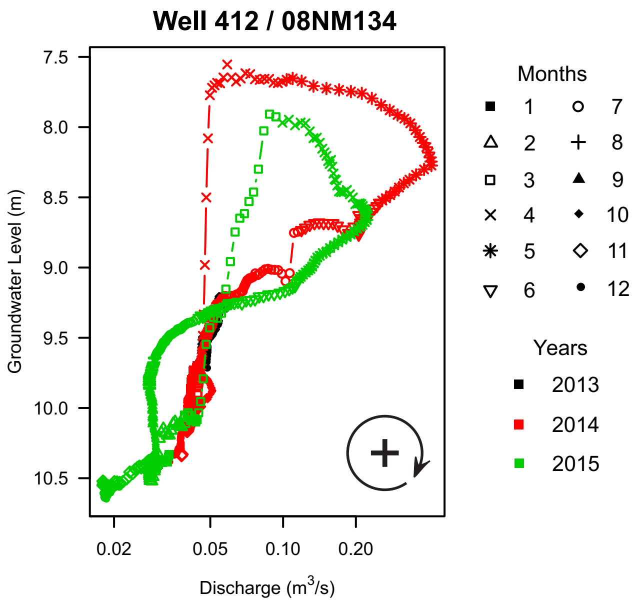

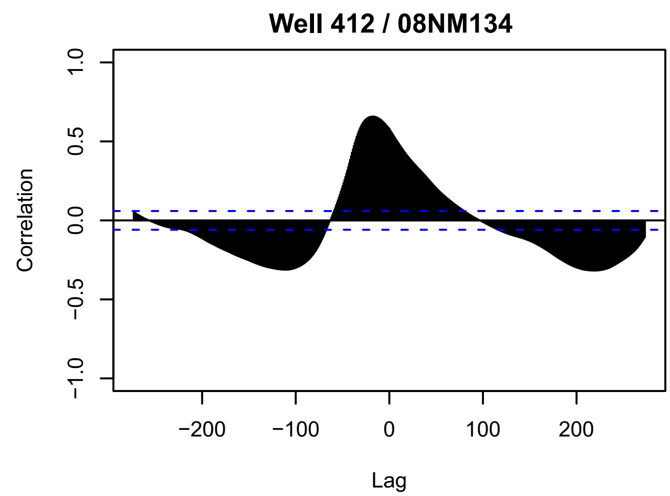

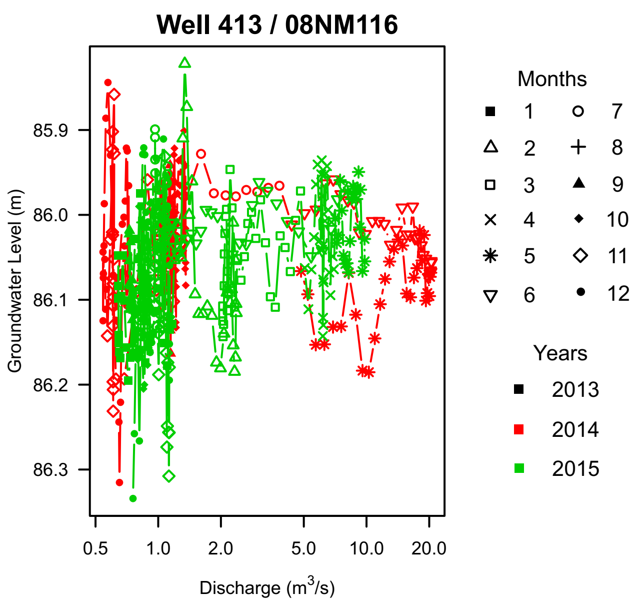

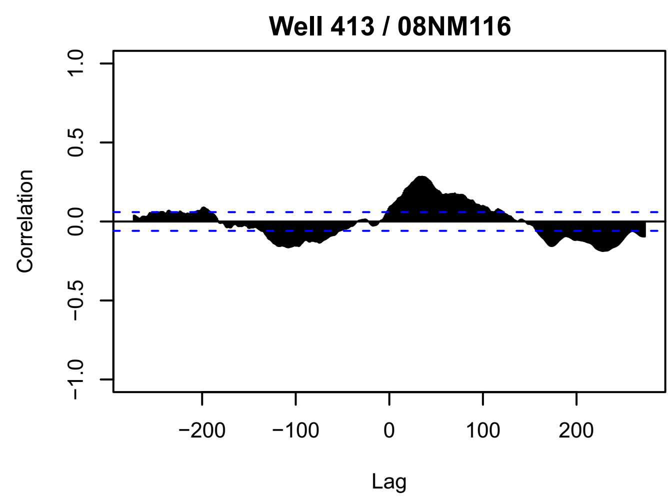

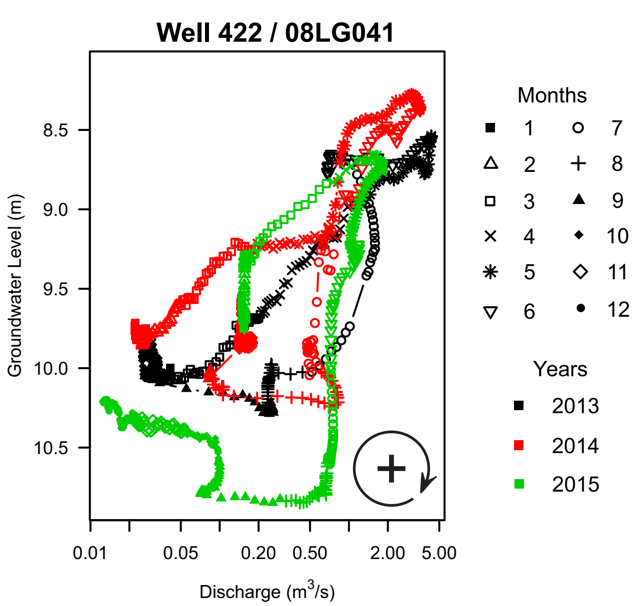

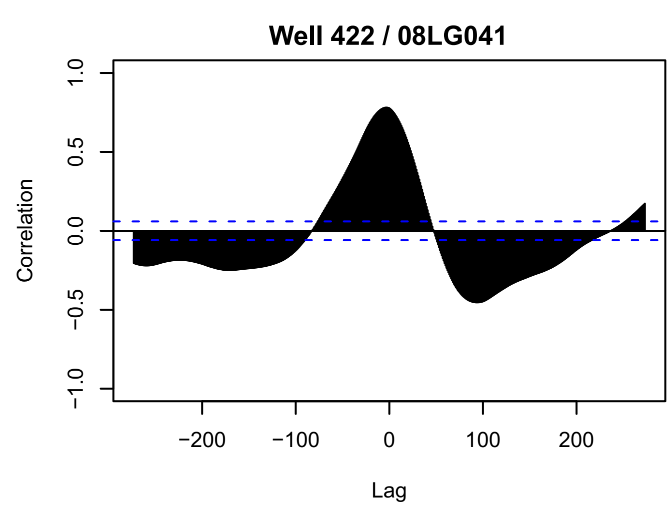

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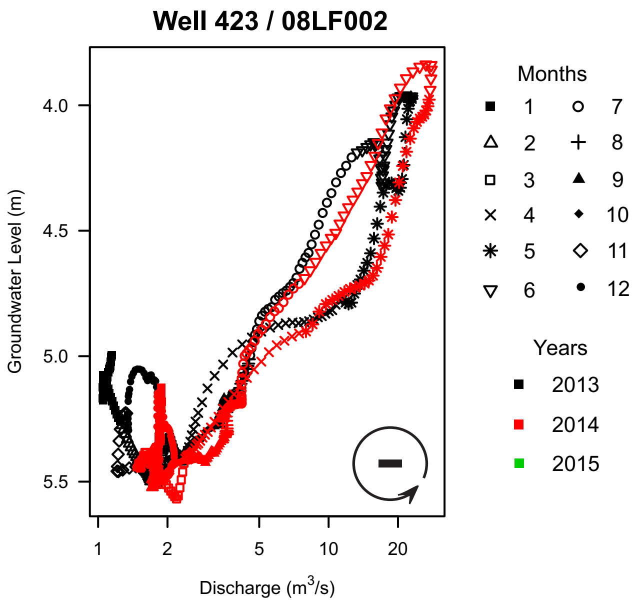

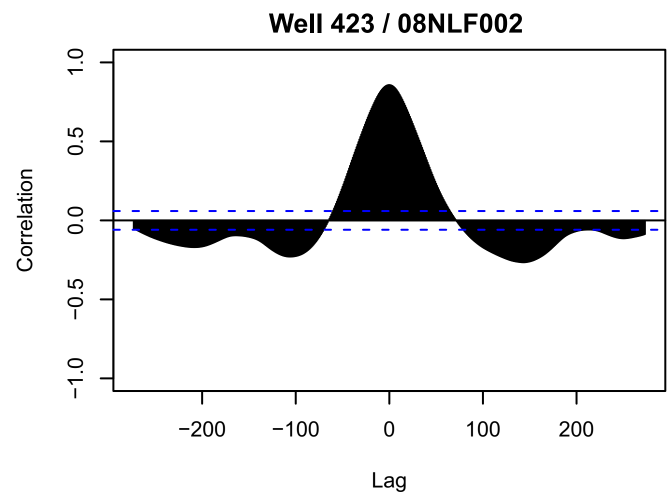

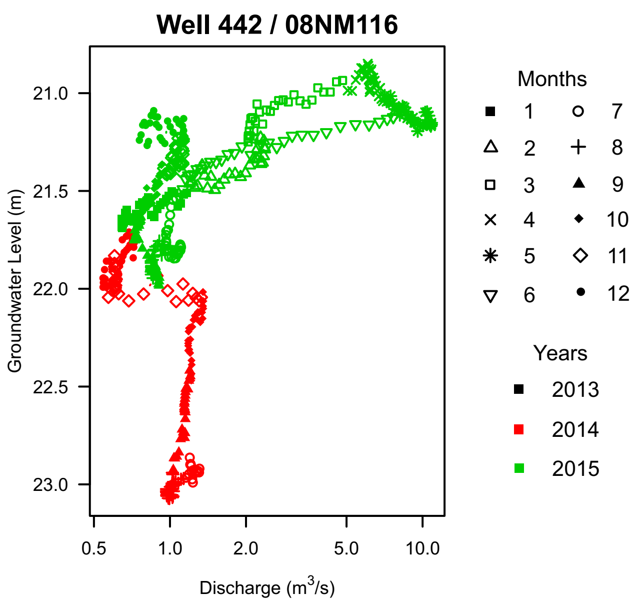

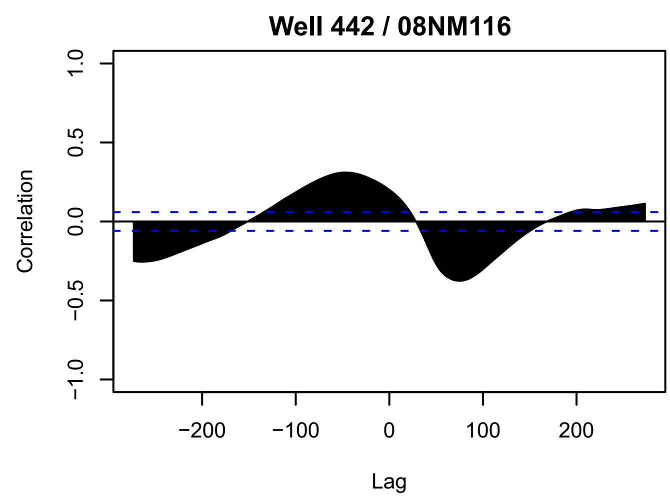

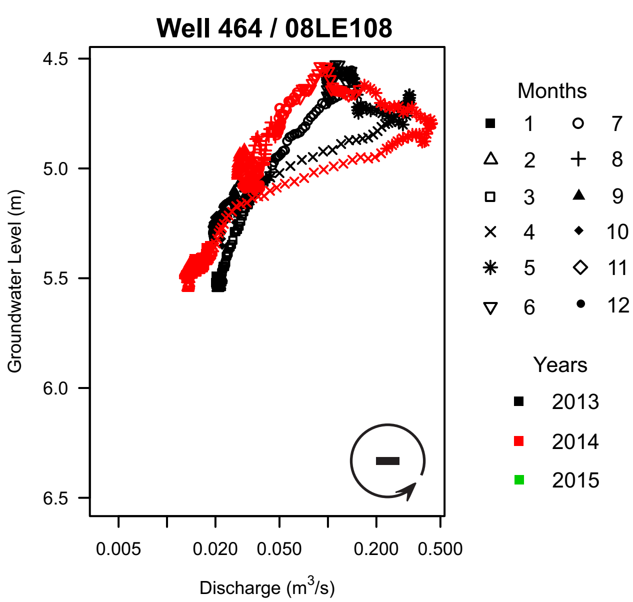

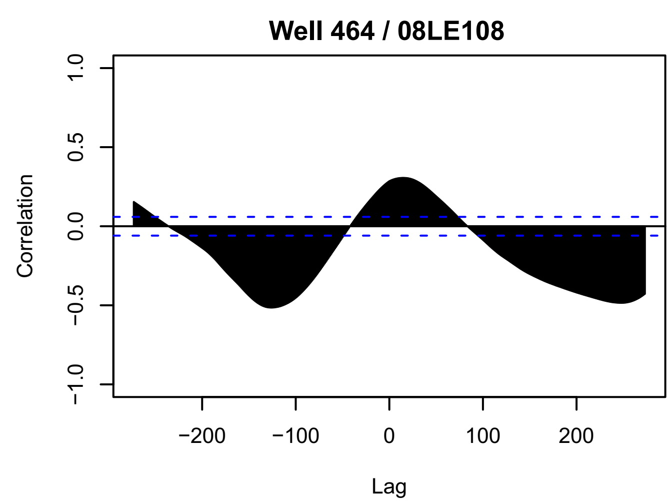

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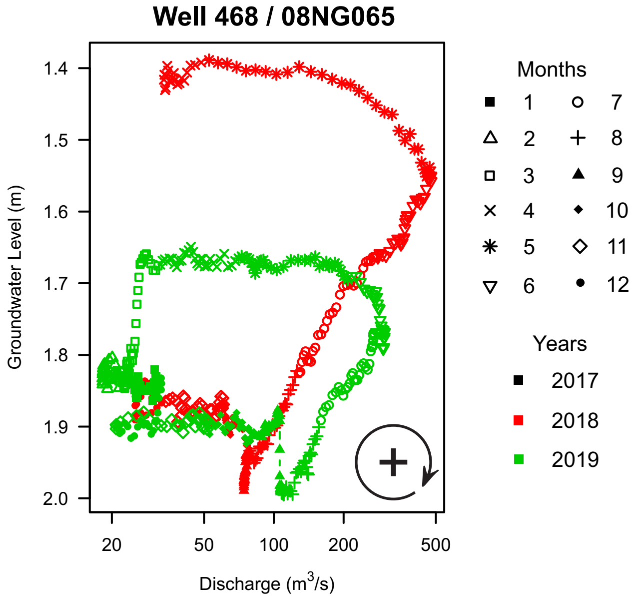

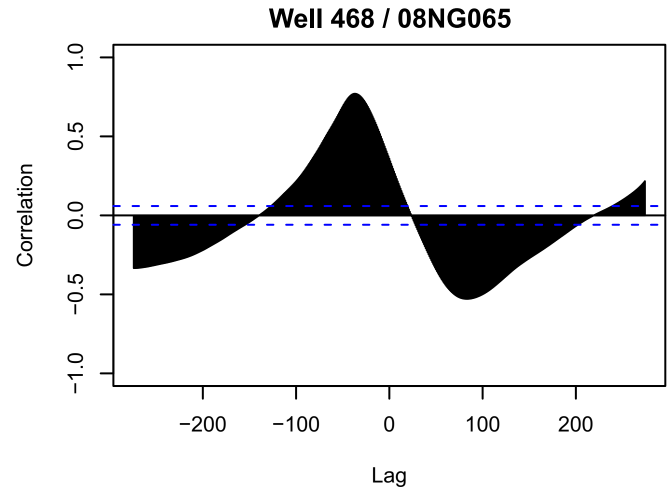

South Coast Region

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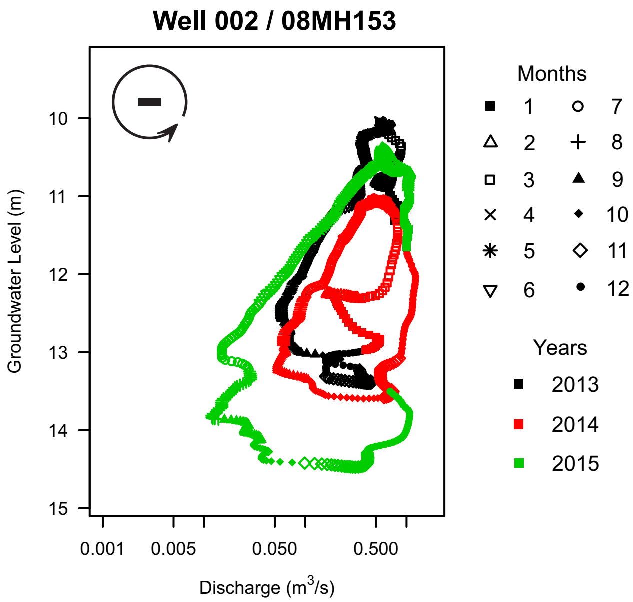

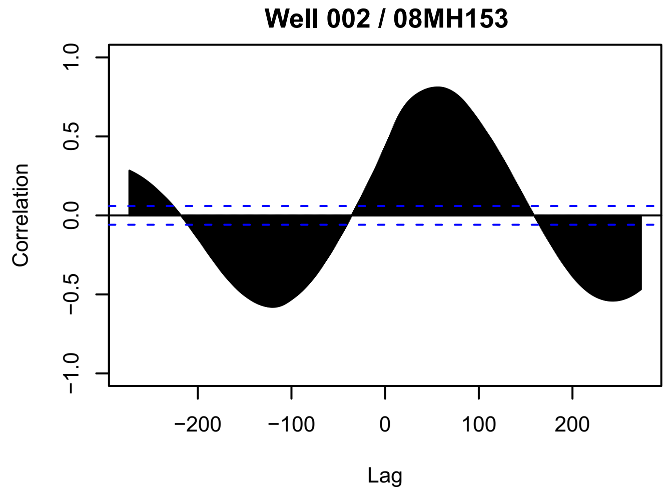

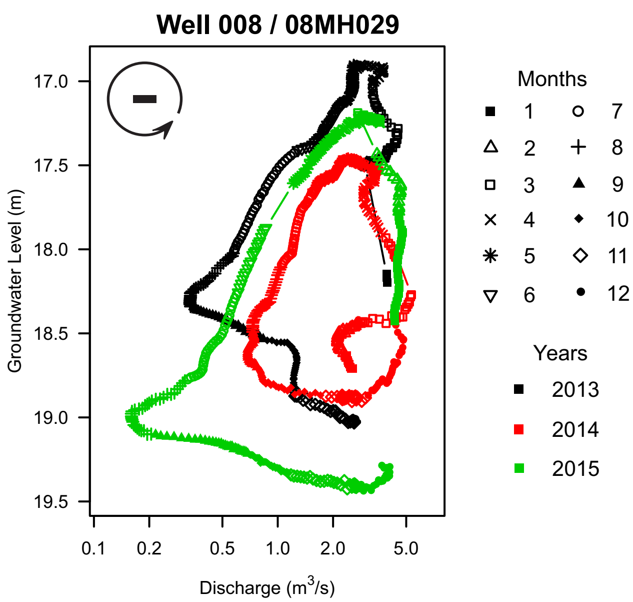

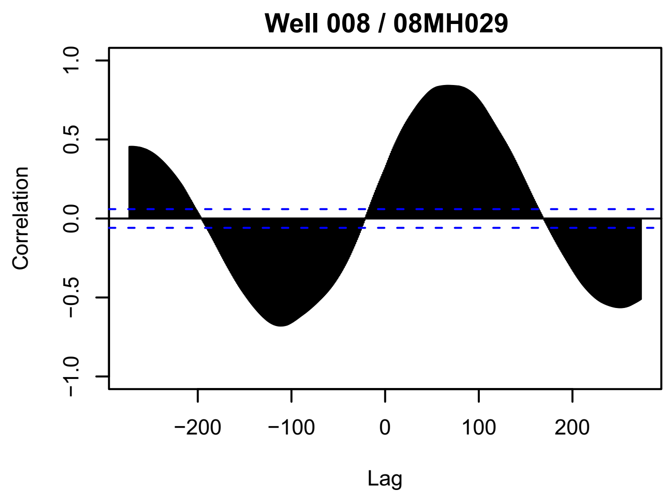

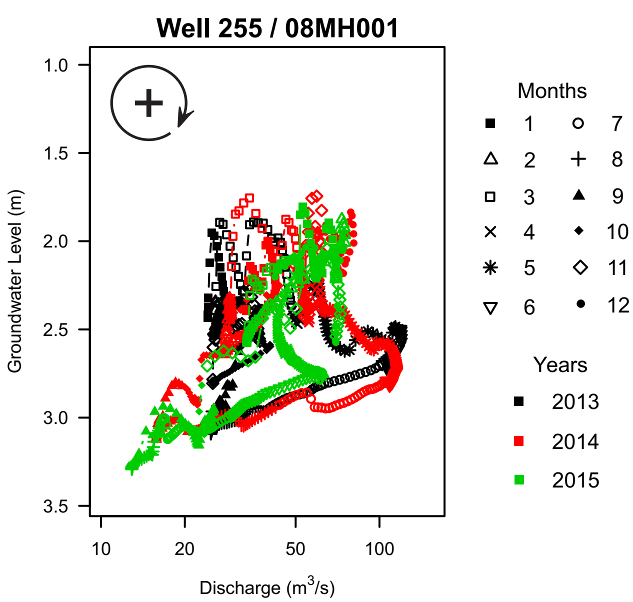

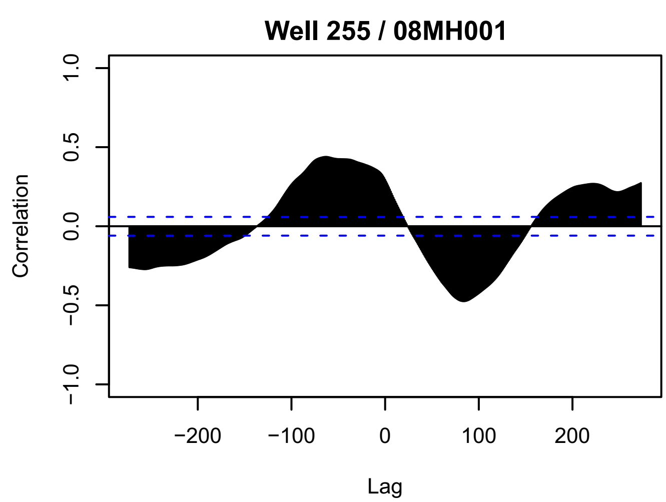

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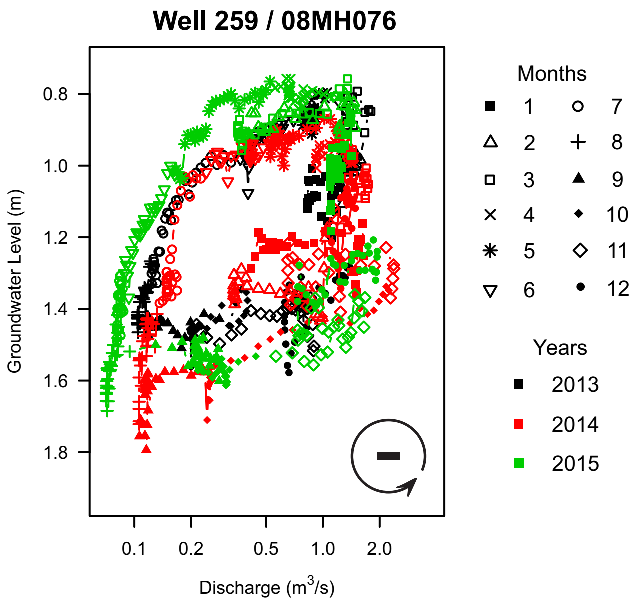

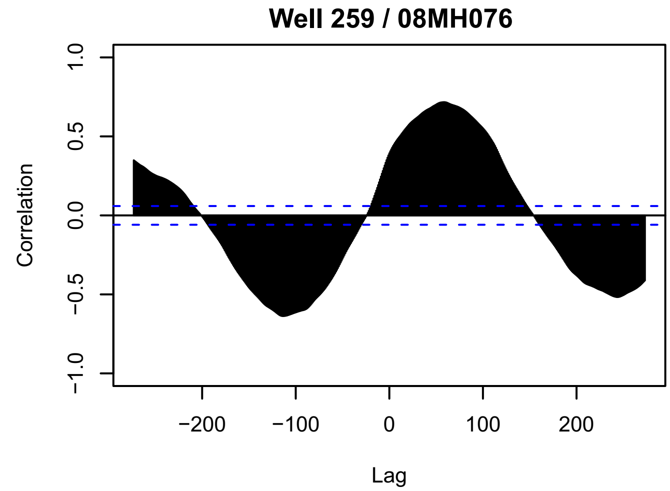

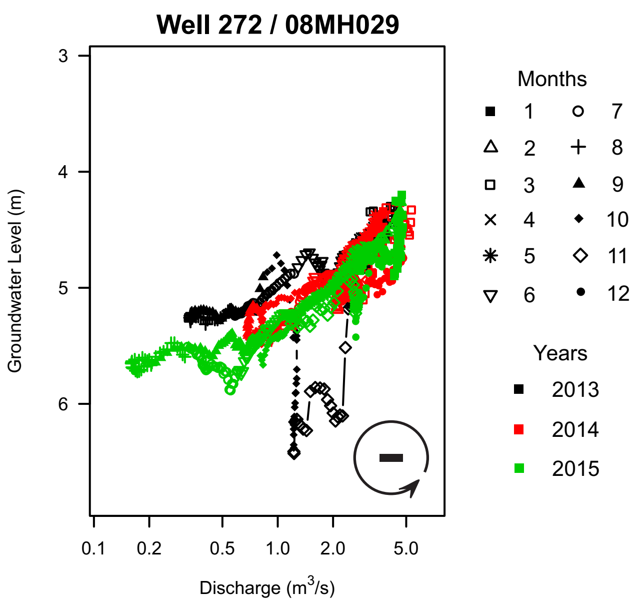

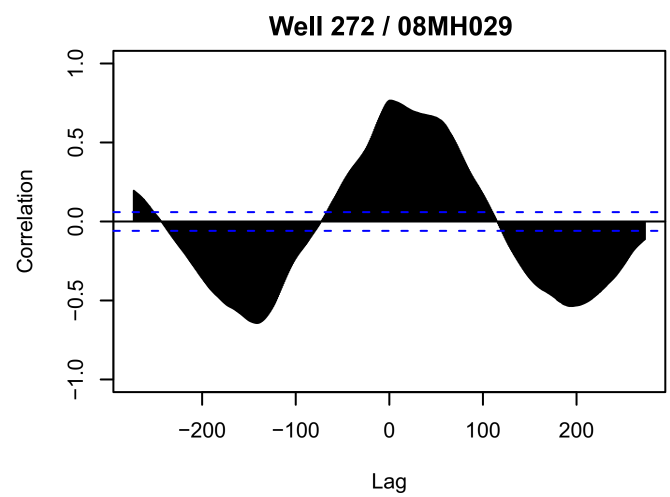

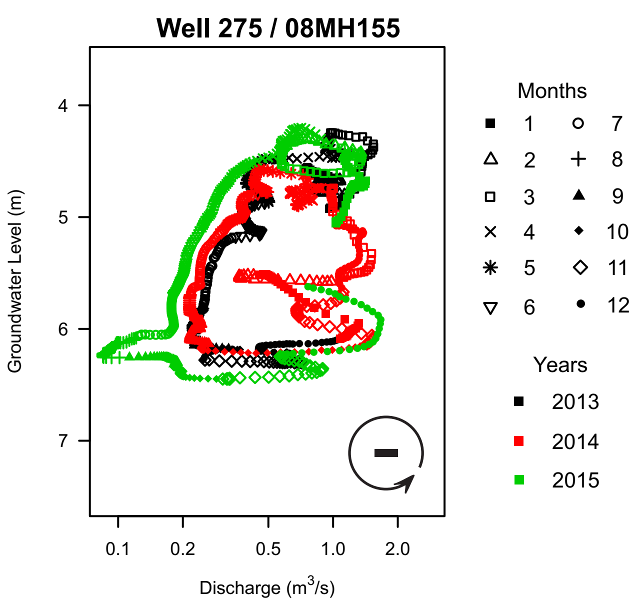

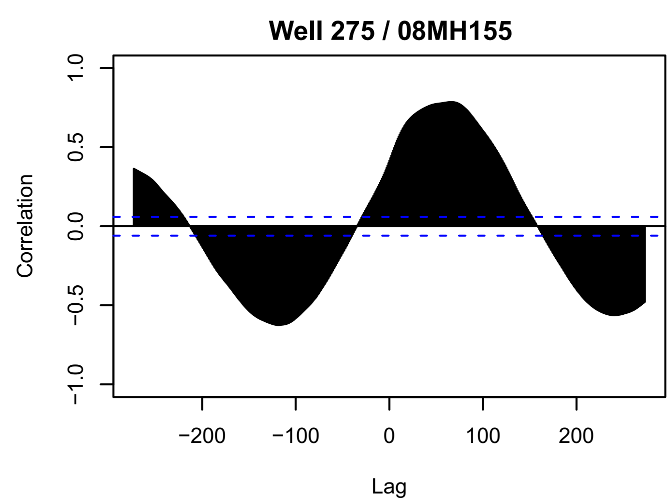

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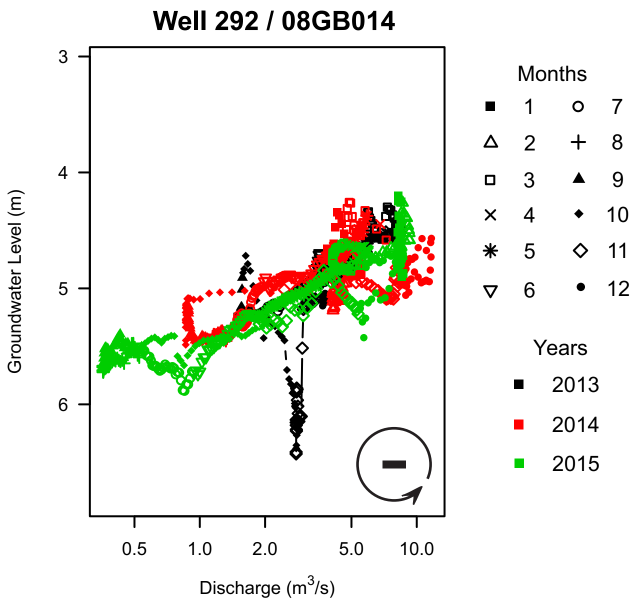

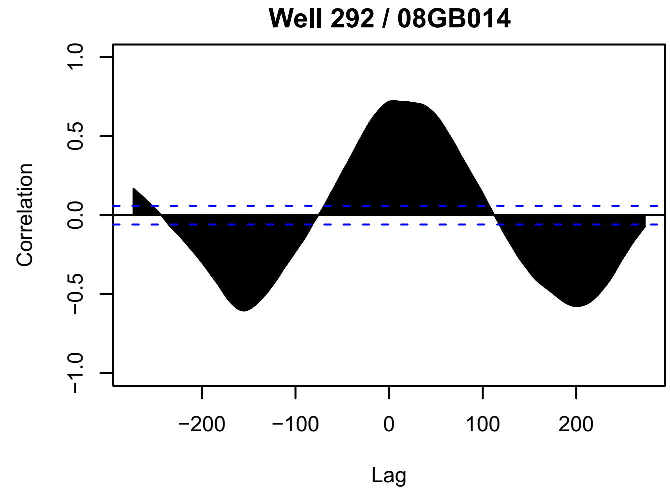

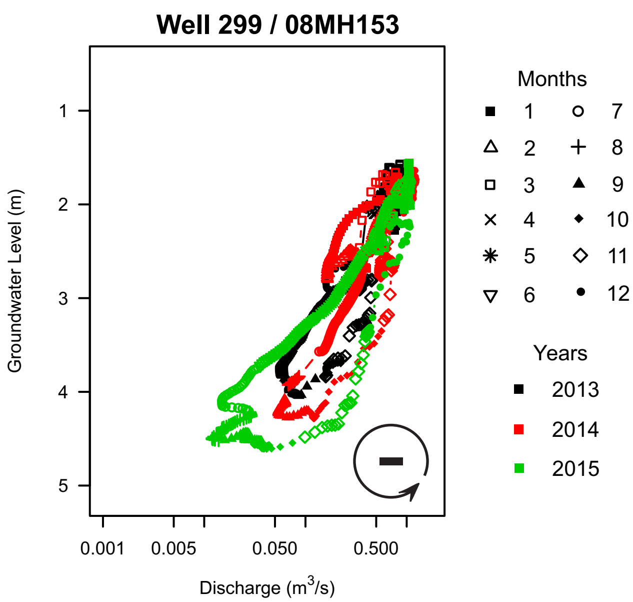

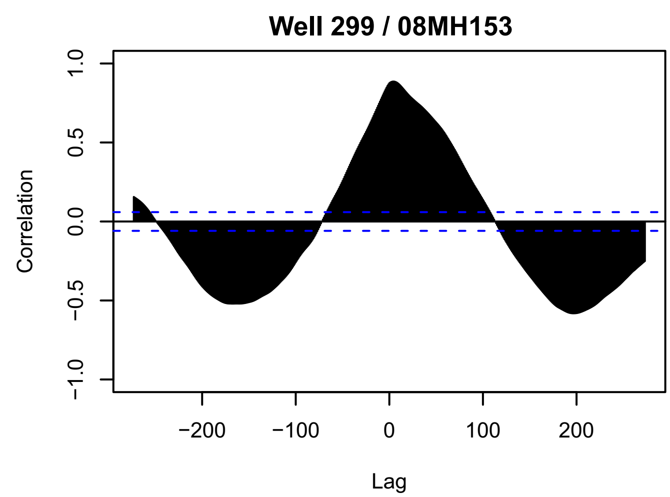

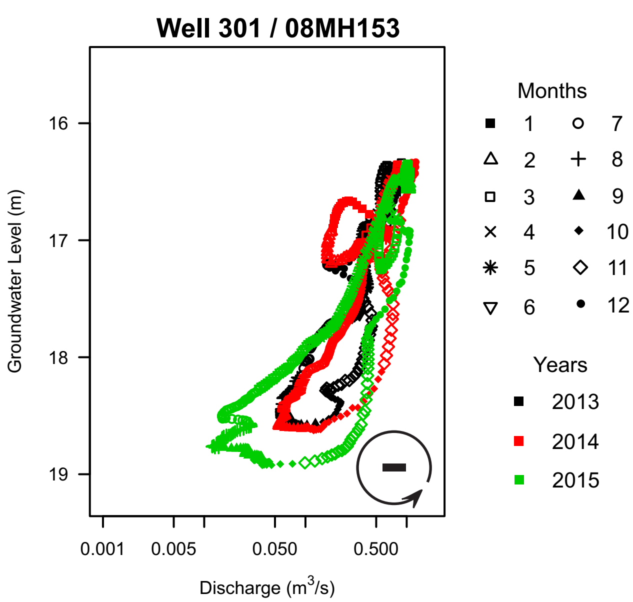

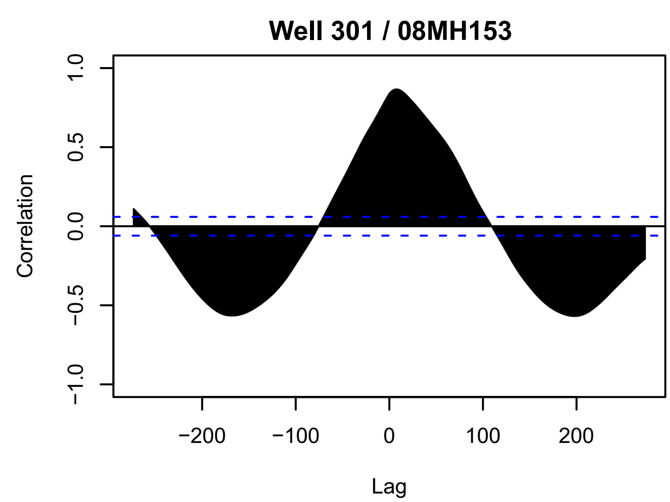

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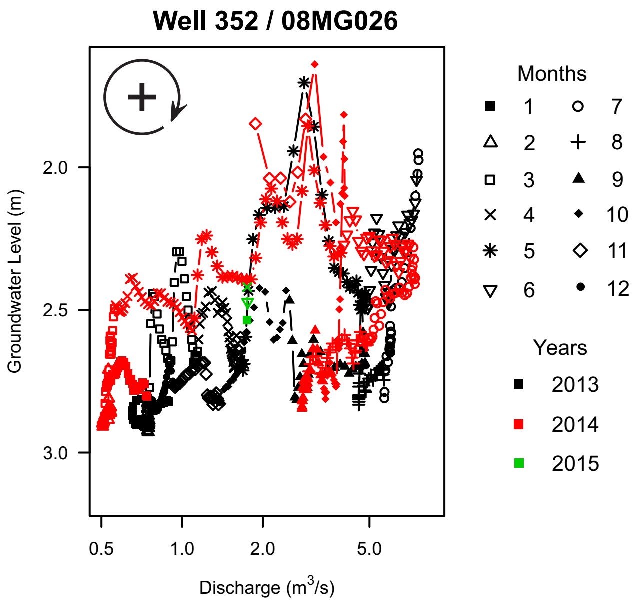

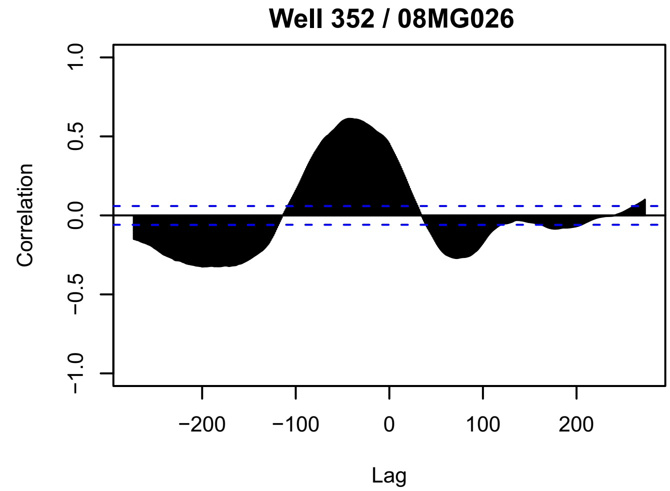

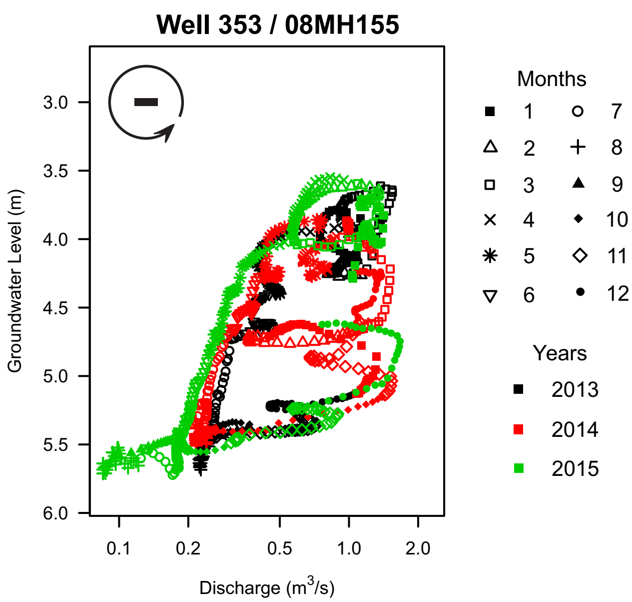

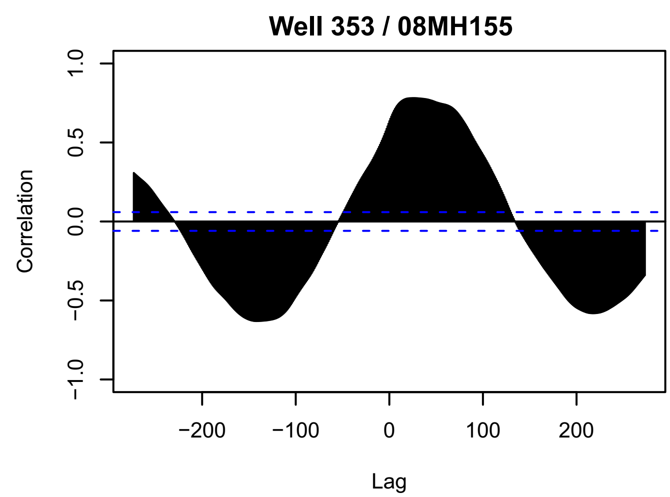

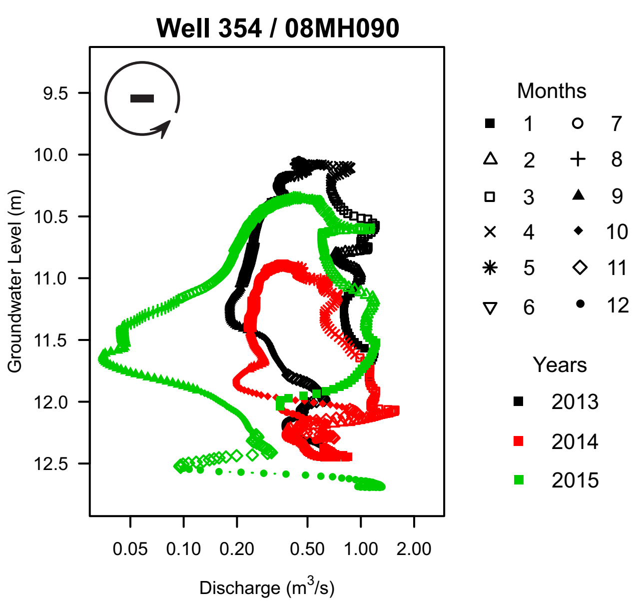

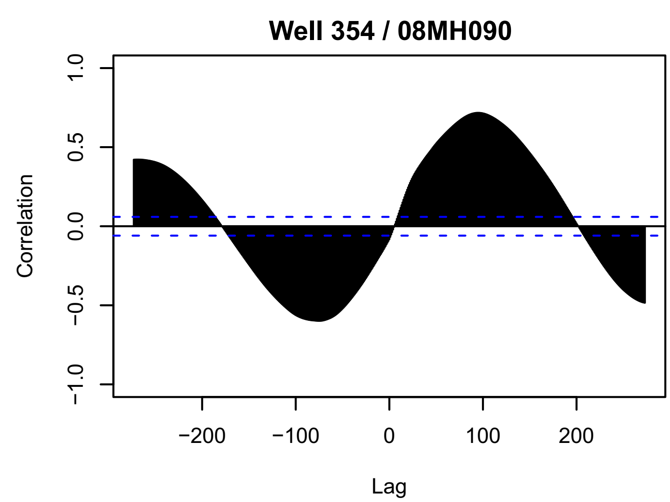

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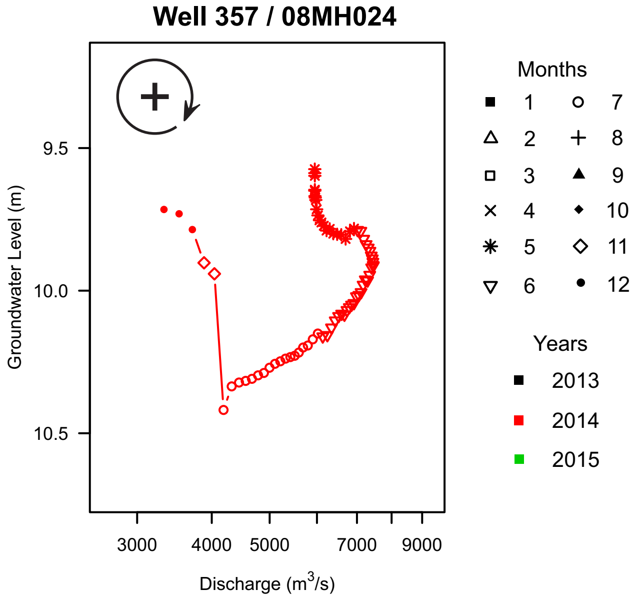

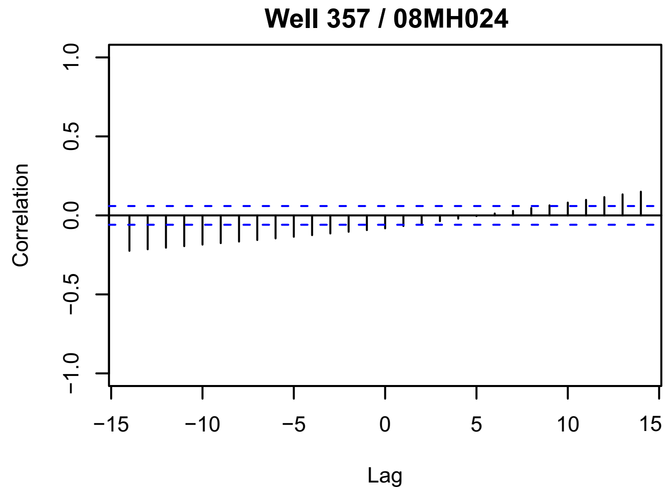

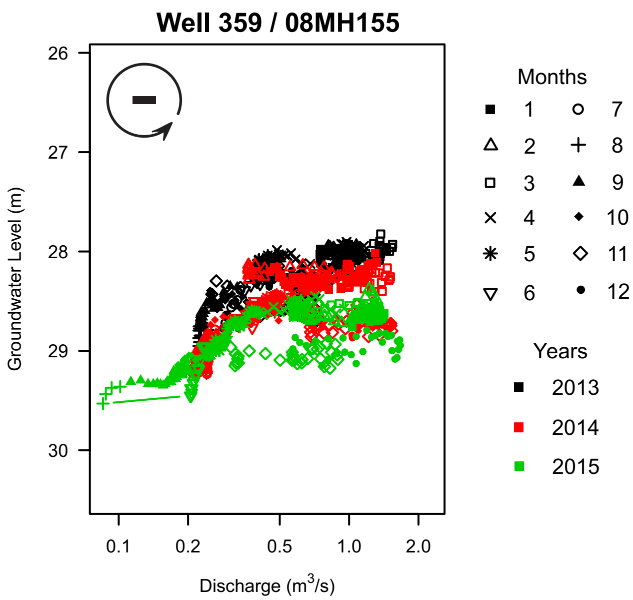

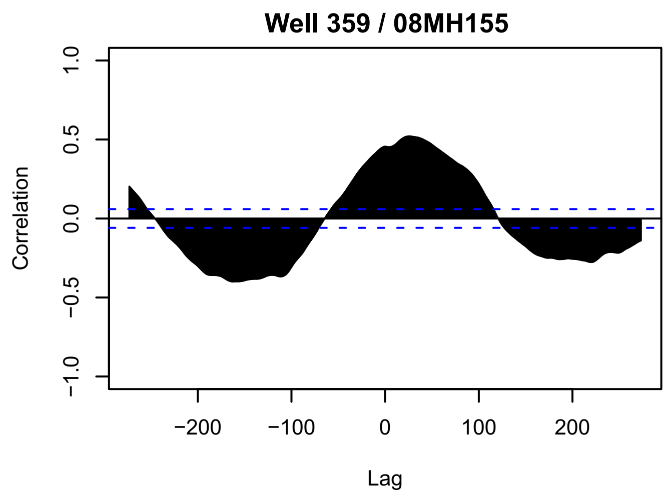

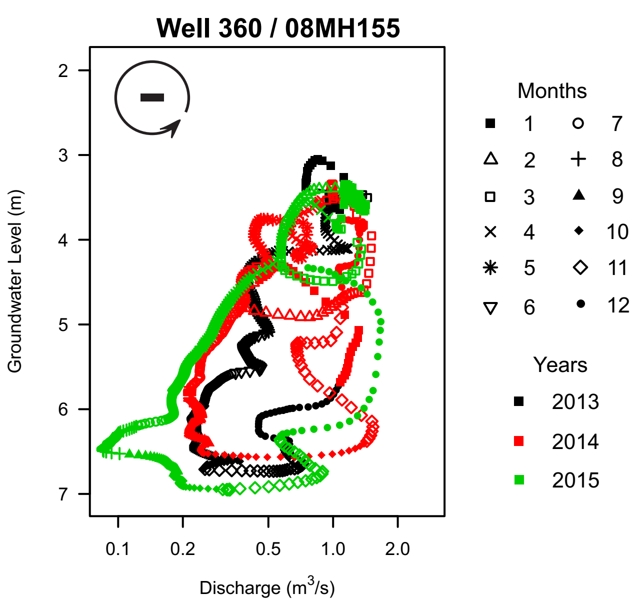

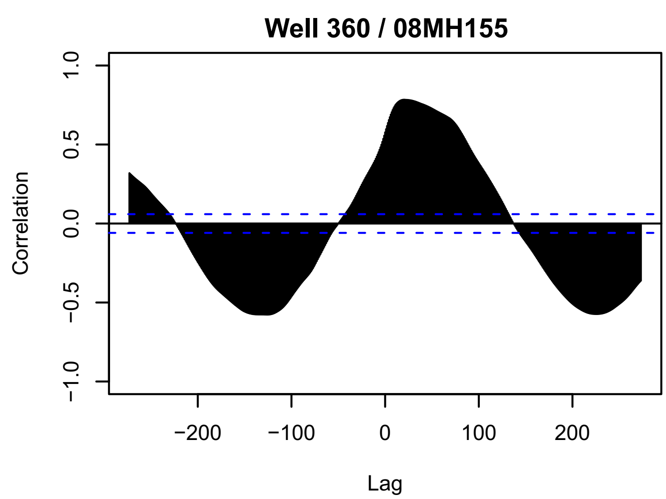

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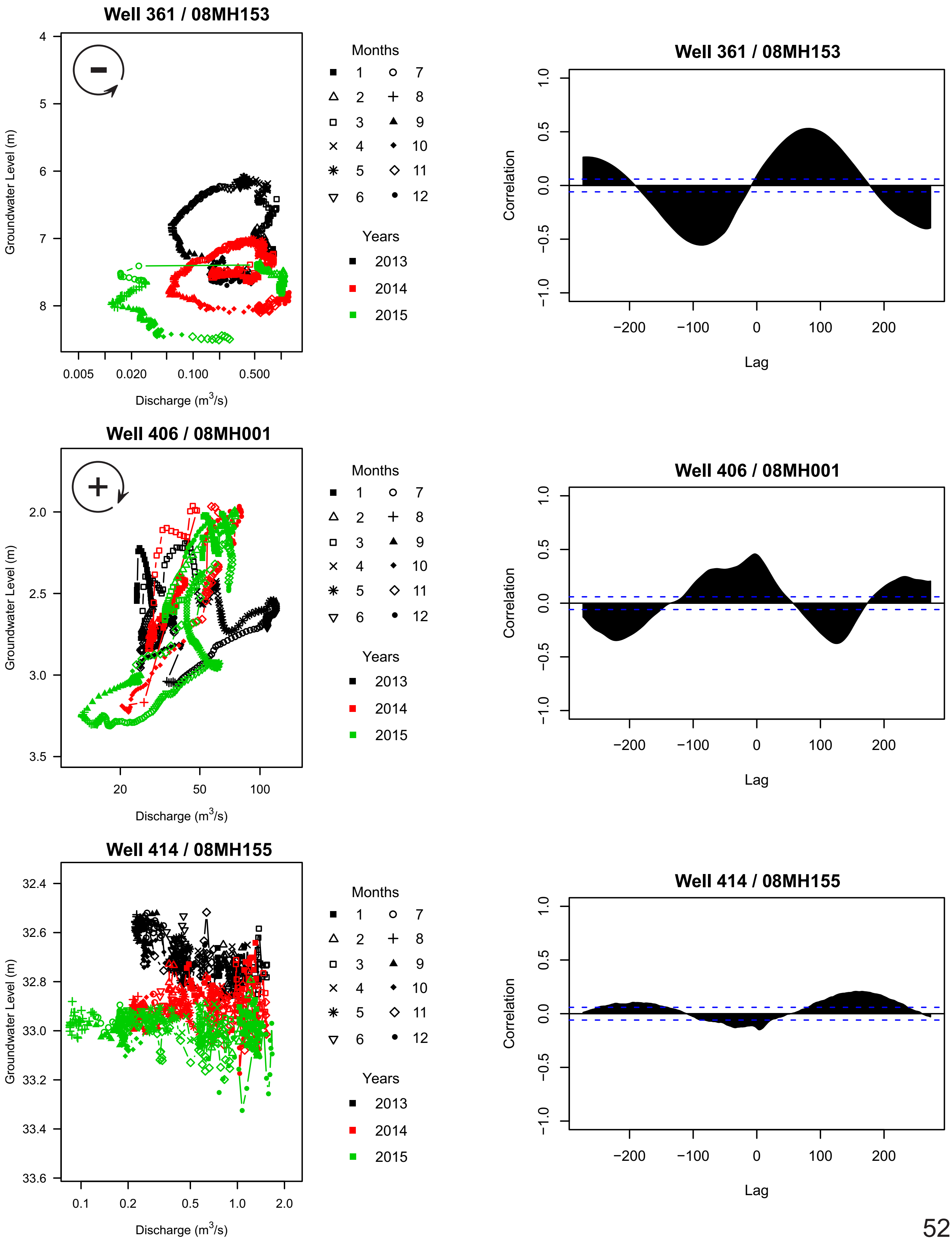

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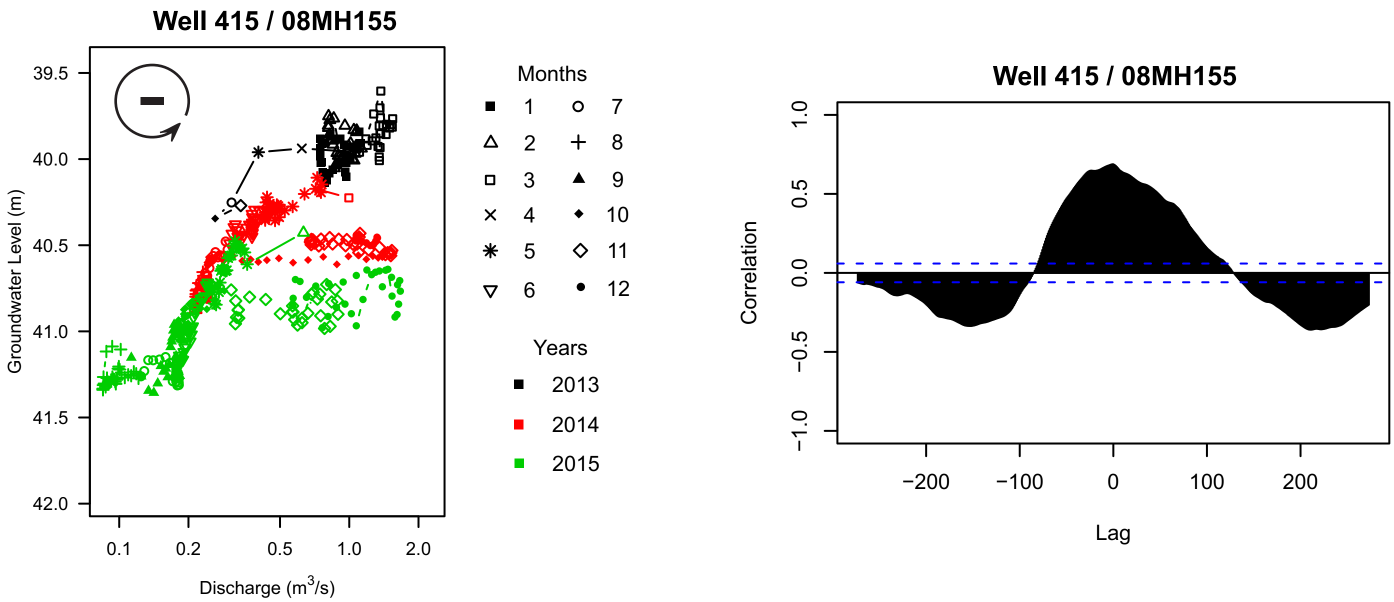

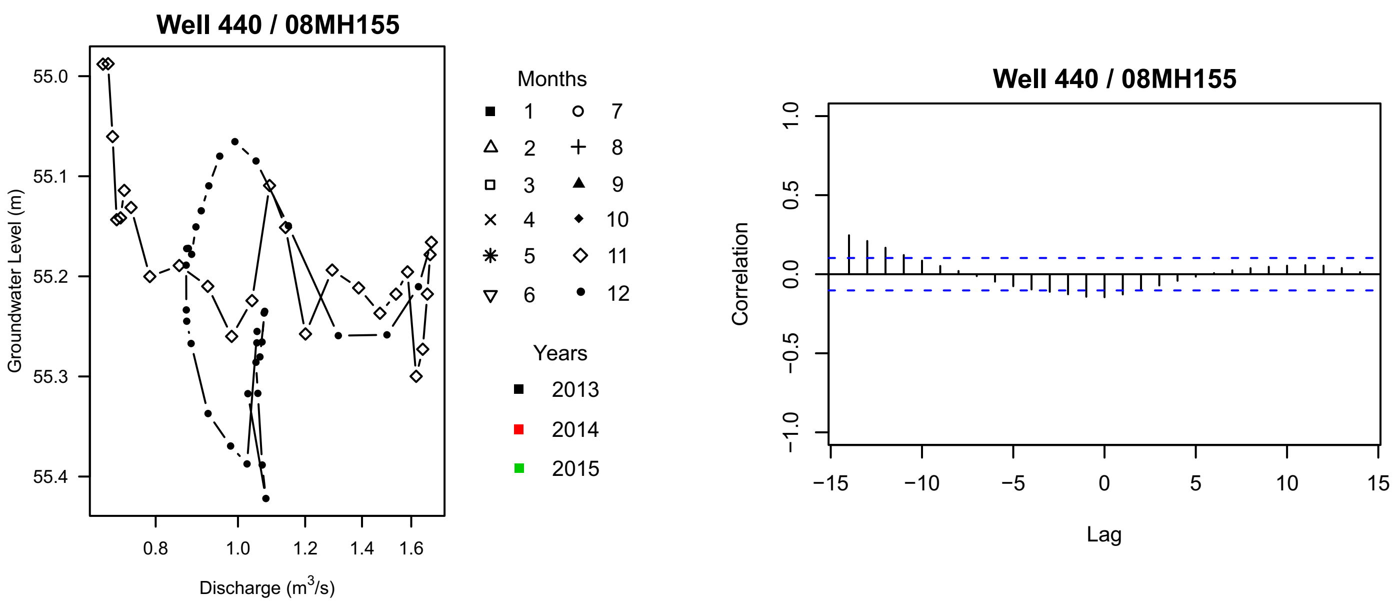

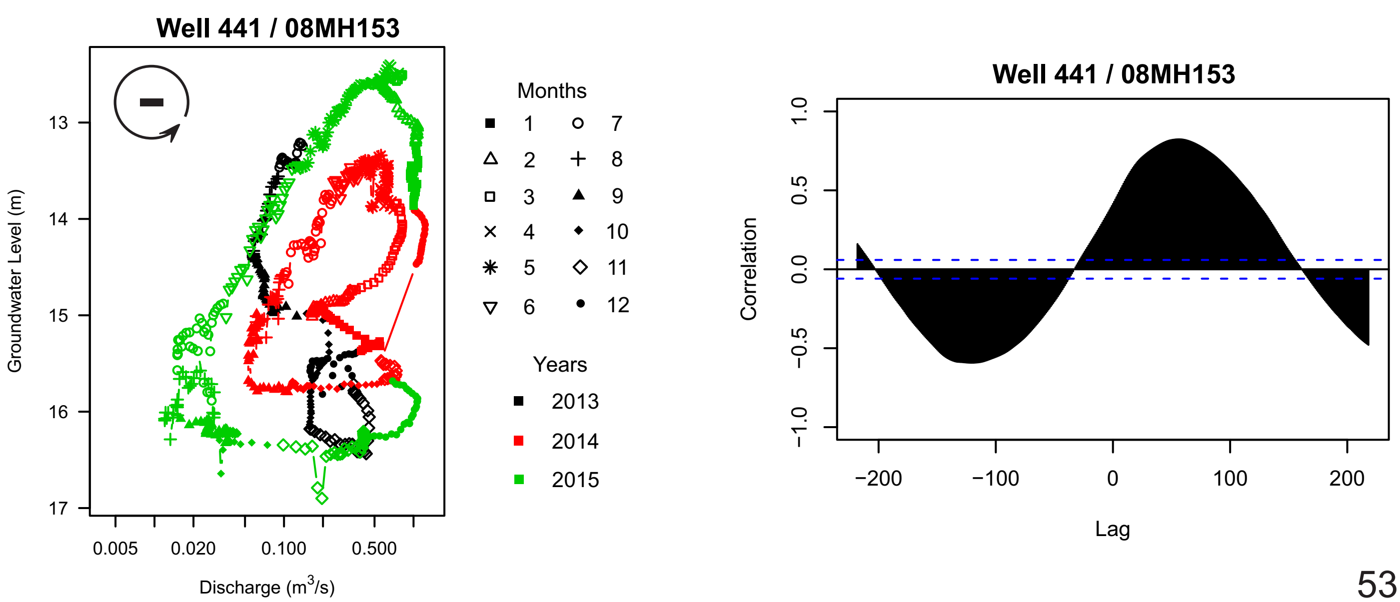

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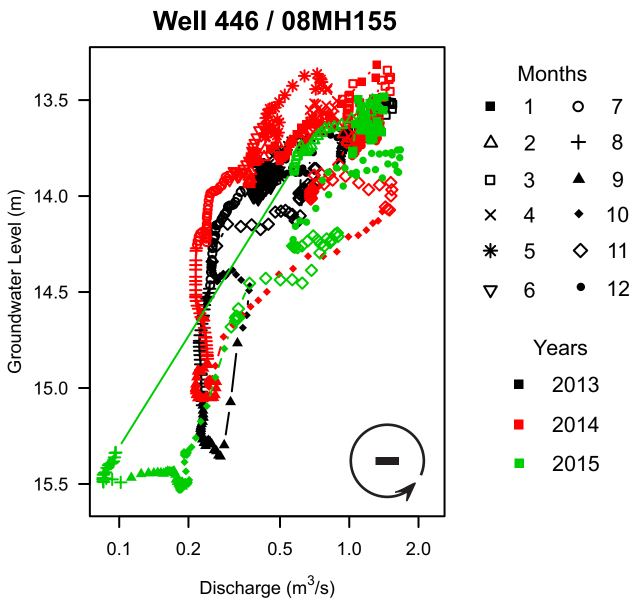

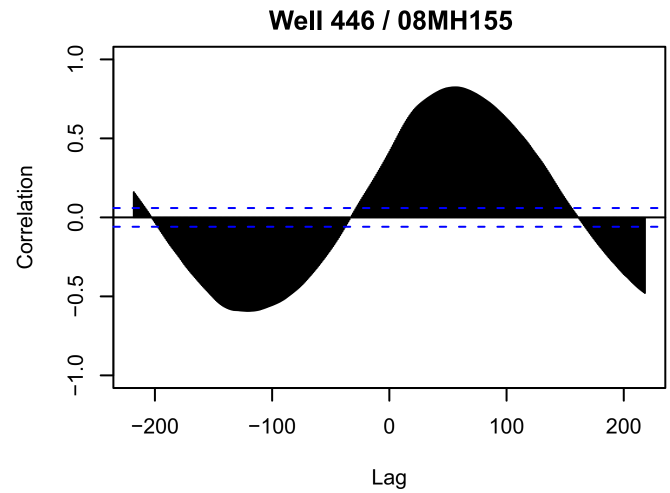

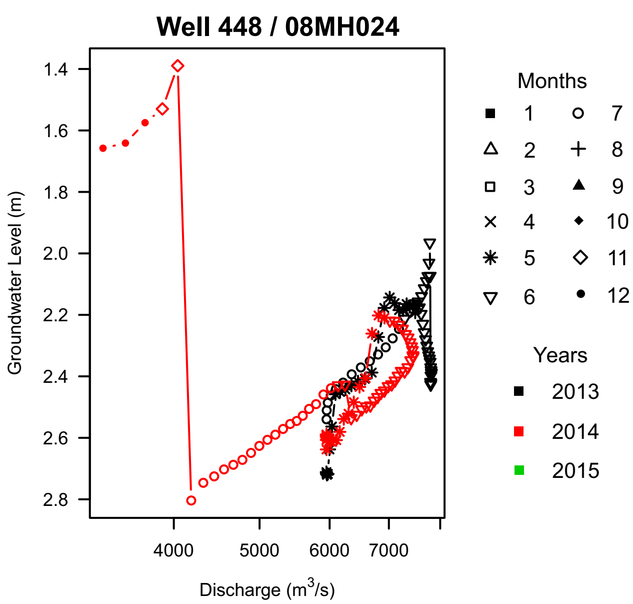

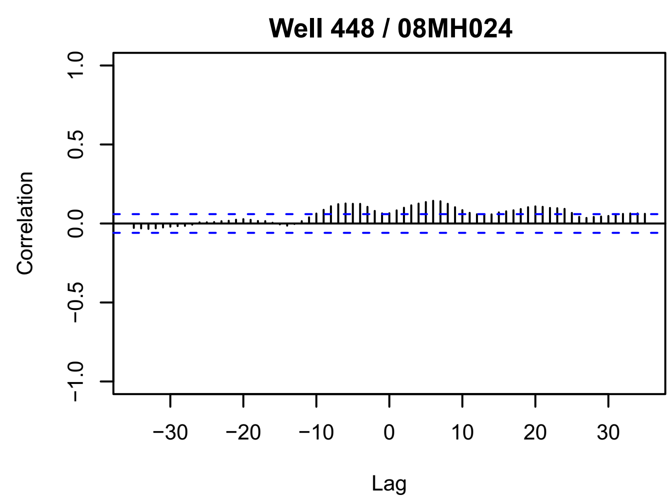

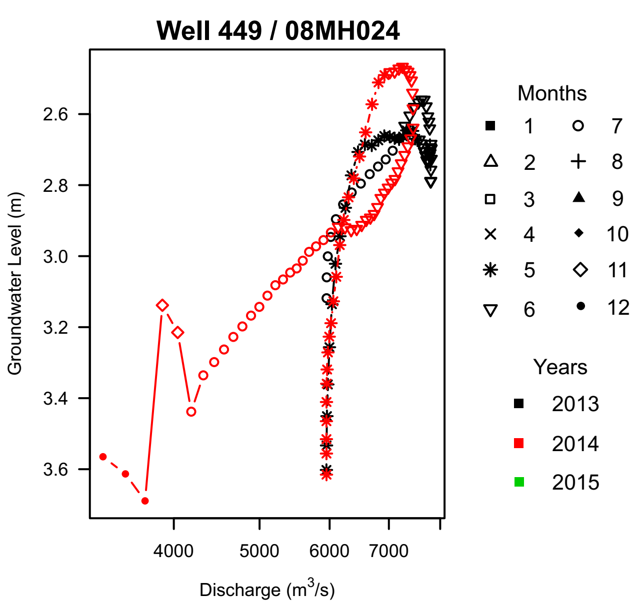

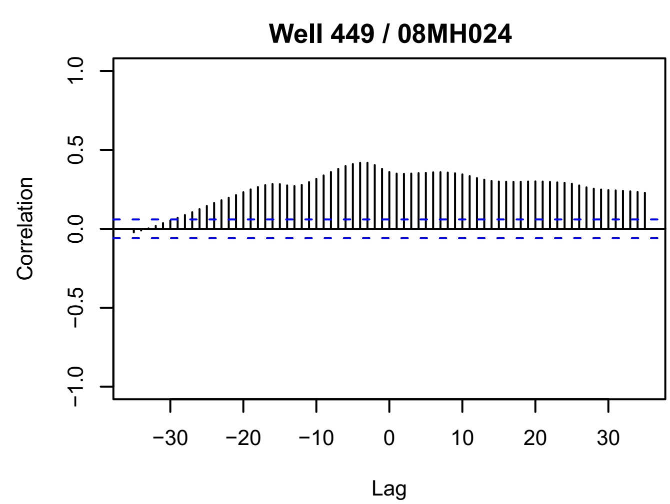

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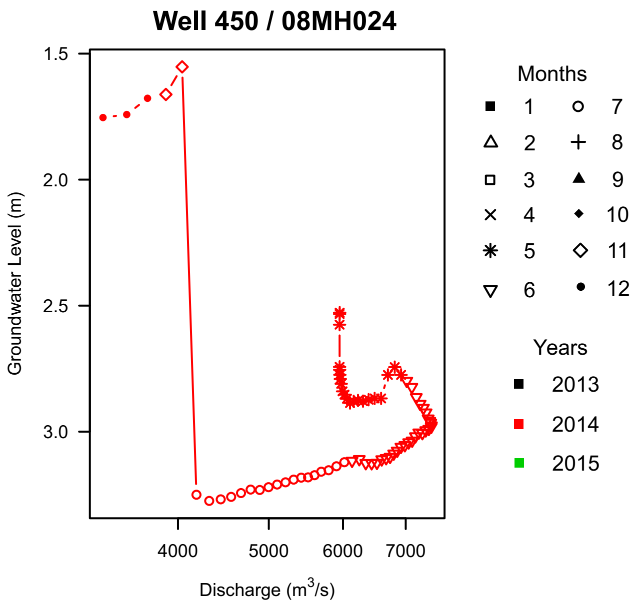

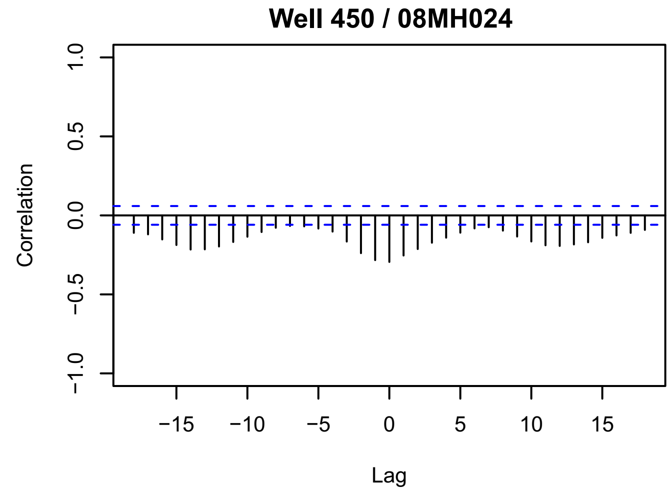

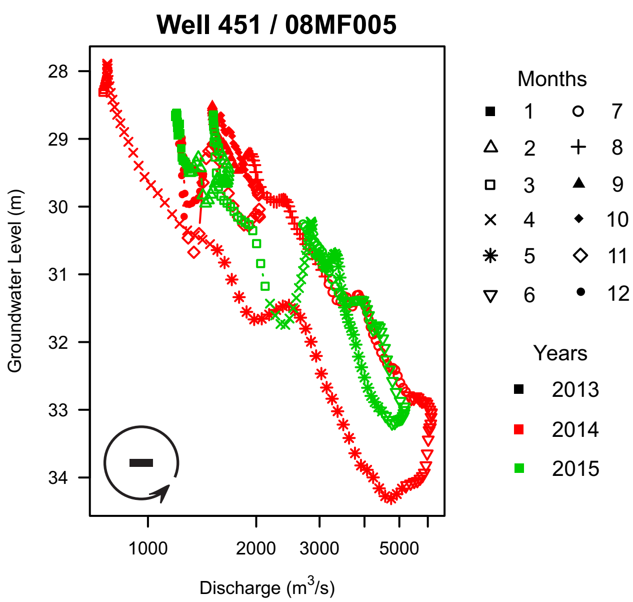

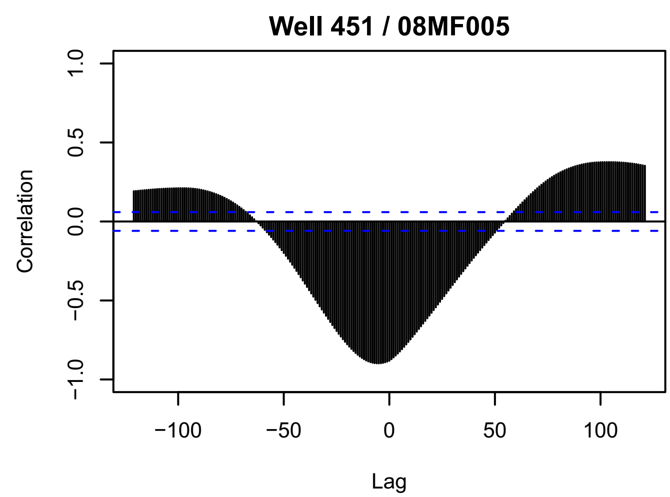

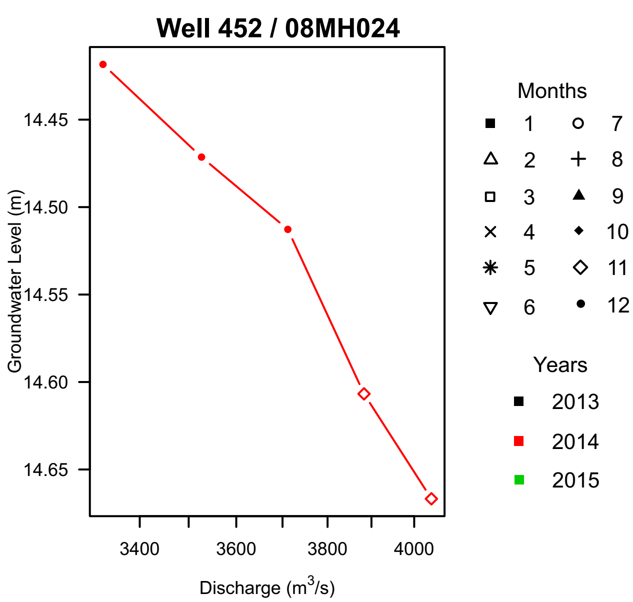

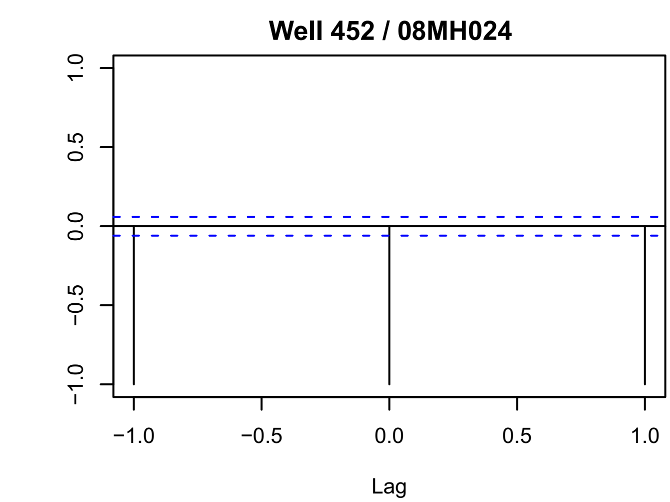

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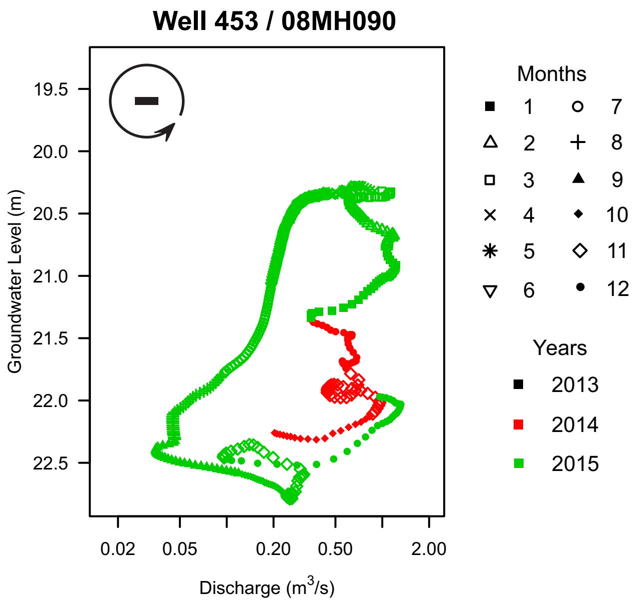

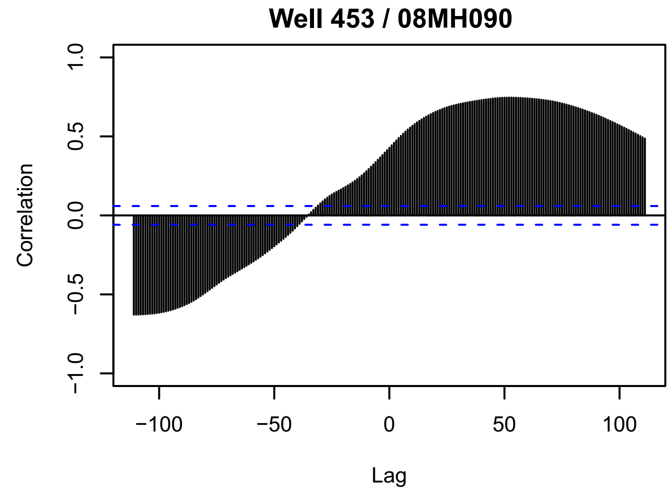

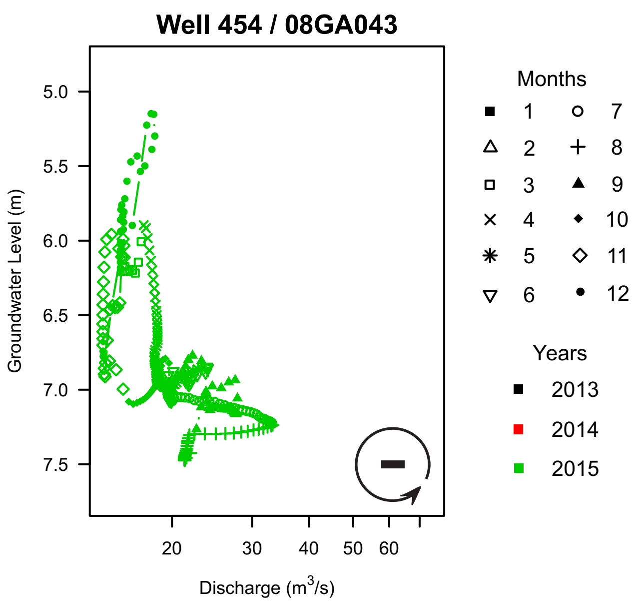

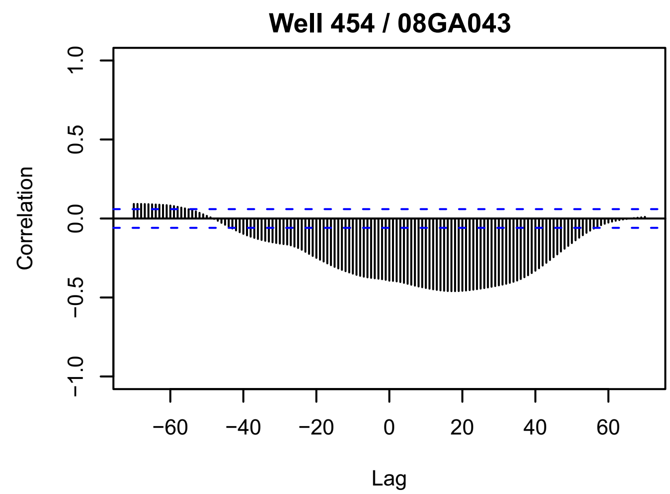

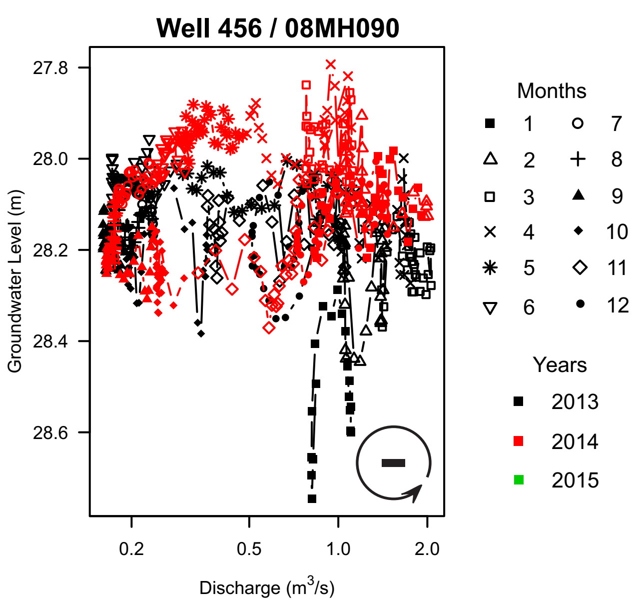

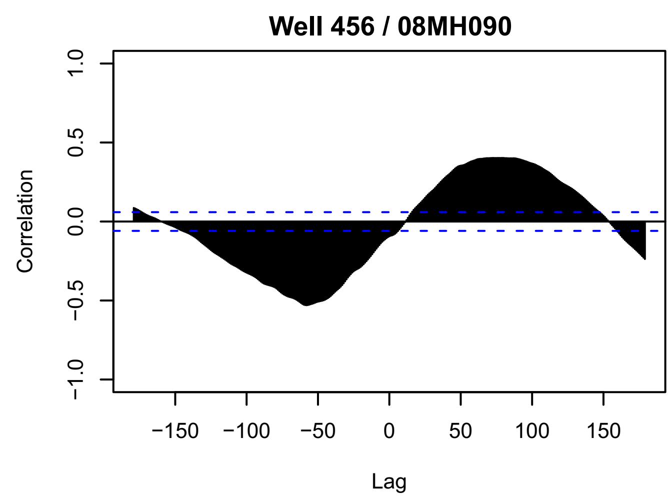

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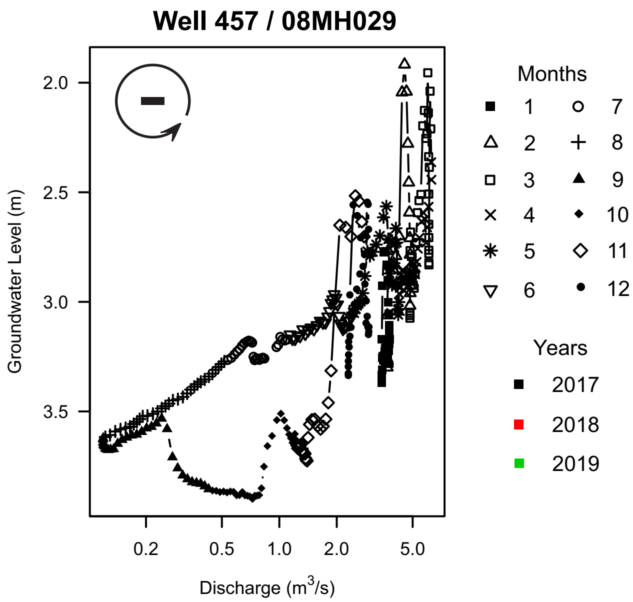

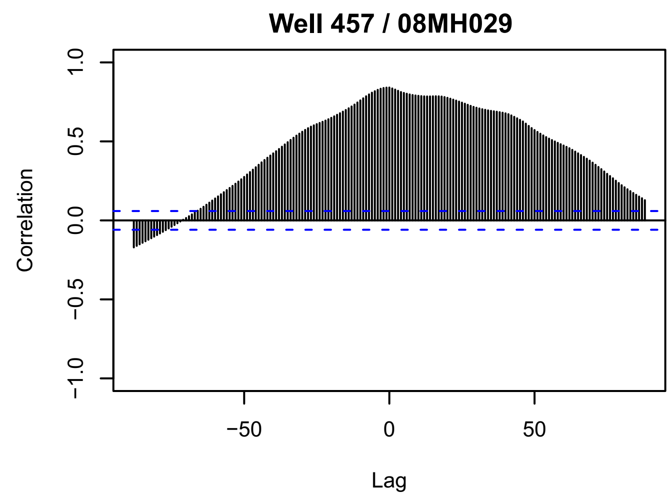

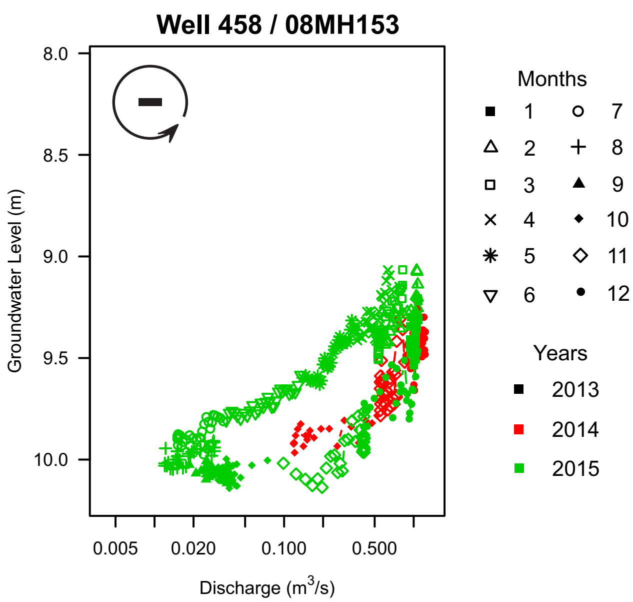

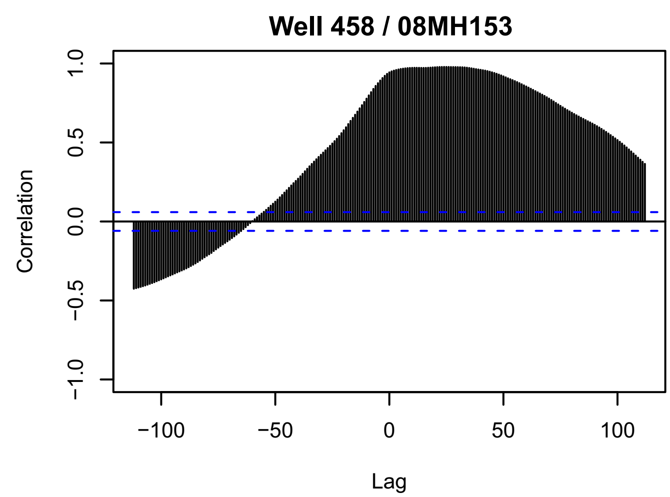

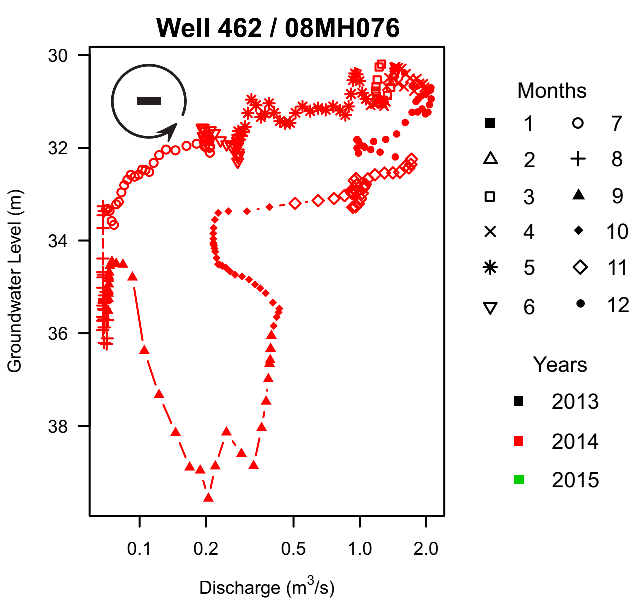

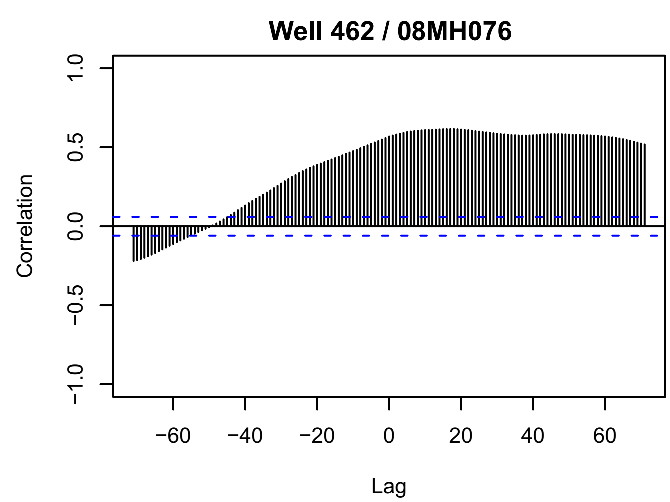

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