Influence of groundwater residence time on biogeochemical transformations after legacy sediment removal from a headwater stream in Lancaster County, Pennsylvania

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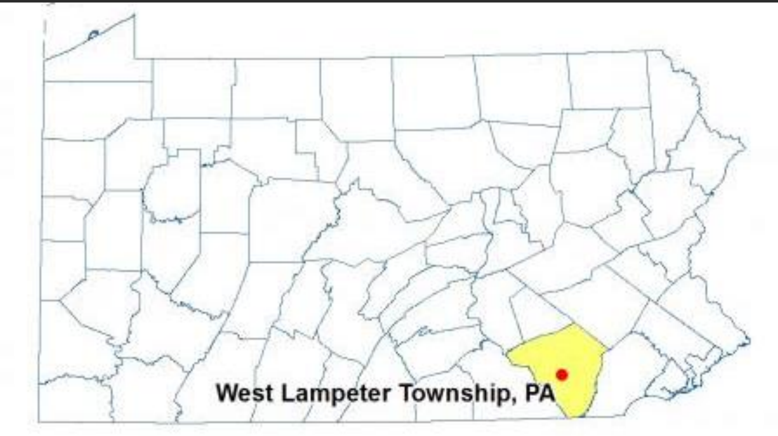
Research problem

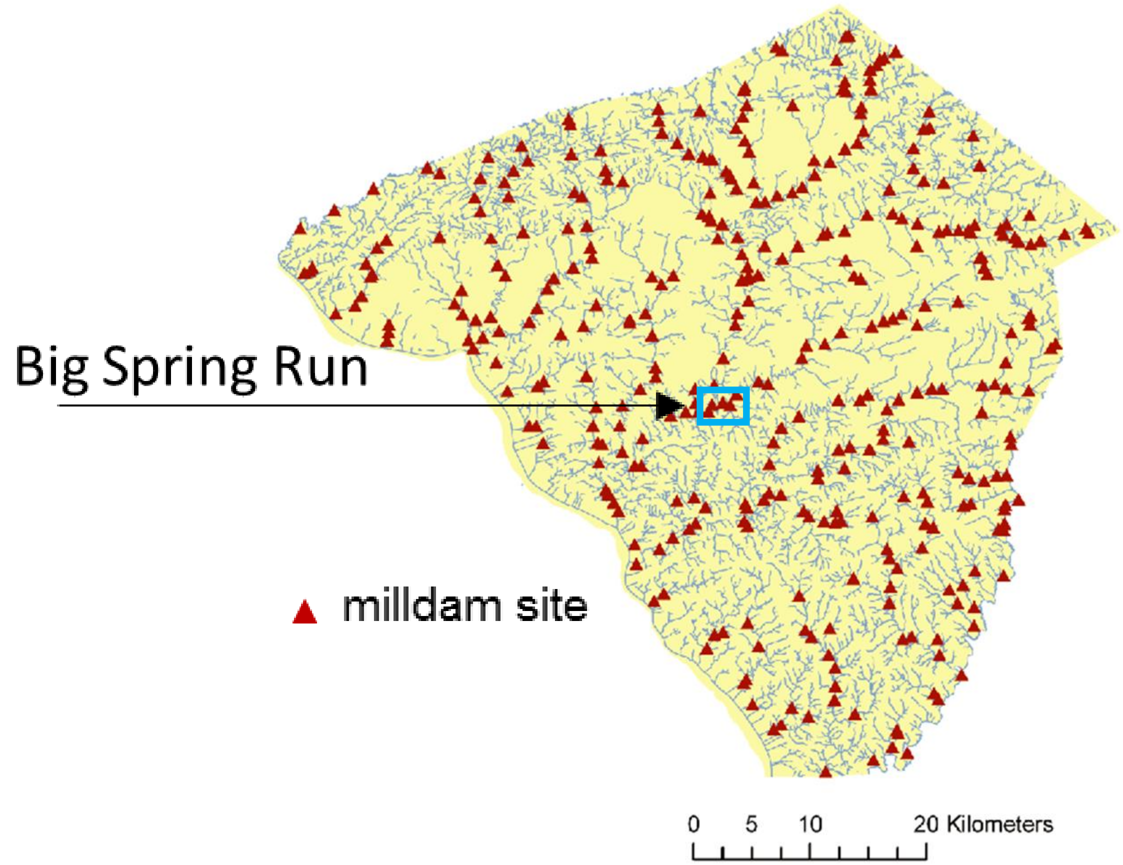


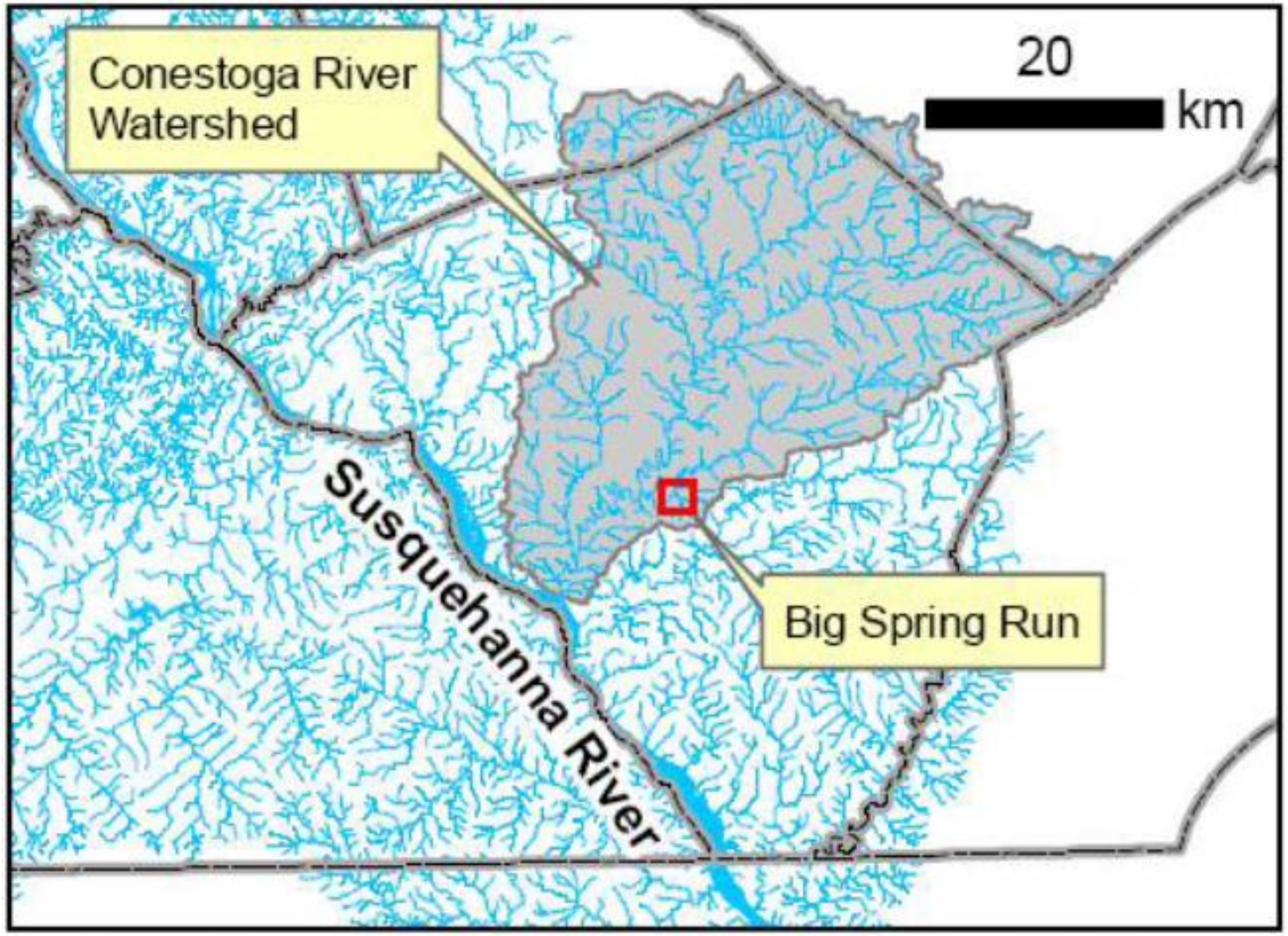
- Mounting evidence suggests that concurrent, widespread deforestation and milldam construction between the 18th and 20th centuries blanketed mid-Atlantic Piedmont valley bottoms with a thick (~1.5 m - >10 m) accumulation of fine-grained legacy sediment.
- Banks of numerous 1st- to 3rd-order streams became incised as dams were breached. Consequentially, hydrological and biogeochemical processes between the former floodplain and active stream channel were decoupled. Given the ubiquity of milldam-impacted streams in the Chesapeake Bay, it is critical to understand:

How does a restored hydrologic connection in this milldam-impacted landscape influence biogeochemical processing of nitrogen and carbon?

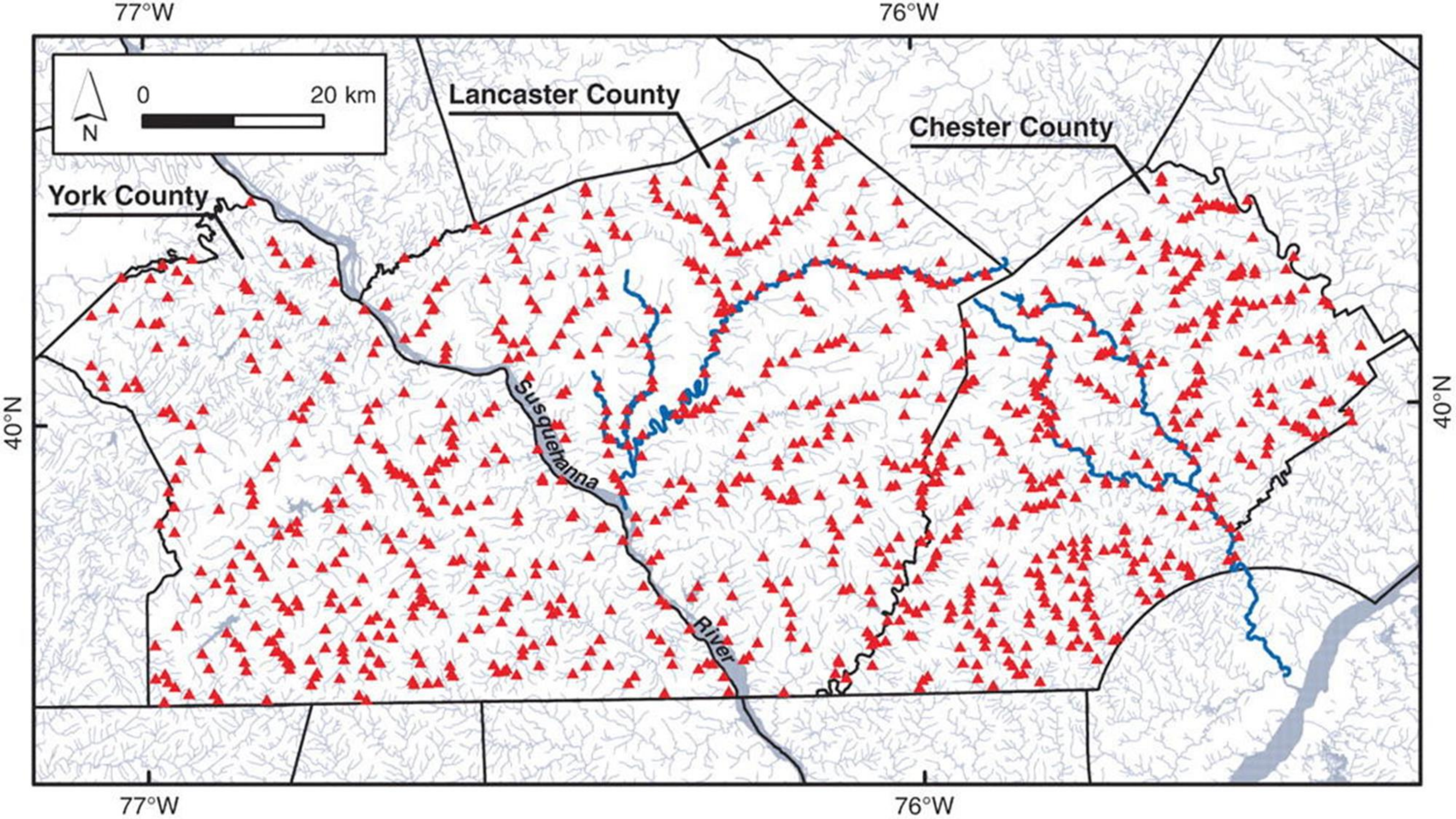
- We present findings from an 8-year, pre- and post-restoration study conducted at Big Spring Run, Lancaster, Pennsylvania where we evaluated variability in the oxygen isotope composition of catchment waters to examine how groundwater contact times and flowpaths influence seasonal nitrate (NO_3-NO_2-N) and dissolved organic carbon (DOC) dynamics.

LOCATION OF 383 HISTORIC MILL DAMS, LANCASTER COUNTY, PA





Equals 1 mill every 2.4 km of stream length in County


77°W
76°W
0
20 km
N
Lancaster County
Chester County
York County
Susquehanna
River
40°N
40°N
77°W
76°W

Big Spring Run - Wetland Restoration

Bank erosion in the upper reaches of BSR, made worse during high water events (Wolman 1959; Merritts *et al.* 2010) and freeze-thaw cycles (Merritts *et al.* 2011; Inamdar *et al.* 2017; Walter *et al.* 2018), resulted in an **average annual release of 94 tons of fine suspended sediment between 2008 and 2011** (PA DEP 2013).

Typical incised channel, erosional banks

9/13/2011

PA DEP began discussion with landowners on two adjacent farms to designate a portion of the BSR catchment that would eventually become the site of an 8-year study to pilot a BMP designed to restore streams in the eastern US impacted by historic milldams to a close approximation of their natural stream morphology (Hartranft *et al.* 2011).

Natural valley morphology

07/27/2012

The restoration

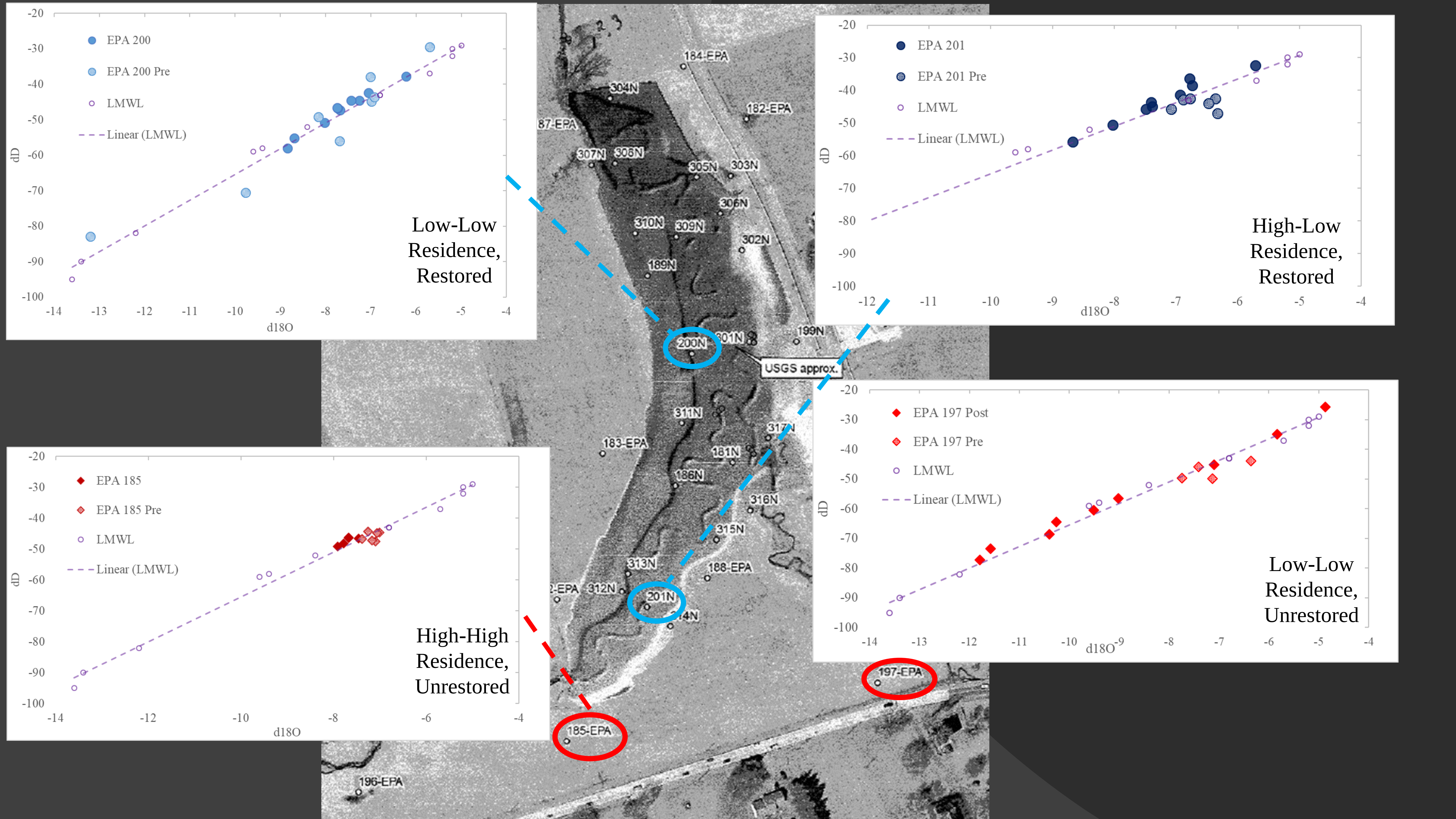
- LandStudies, a local engineering firm based in Lancaster, began the restoration in October 2011
- 21,721 cubic feet of legacy sediment was removed from a 4 km^2 portion of the catchment
- 1,479 linear feet of stream valley and 3,074 linear feet of stream channel was restored

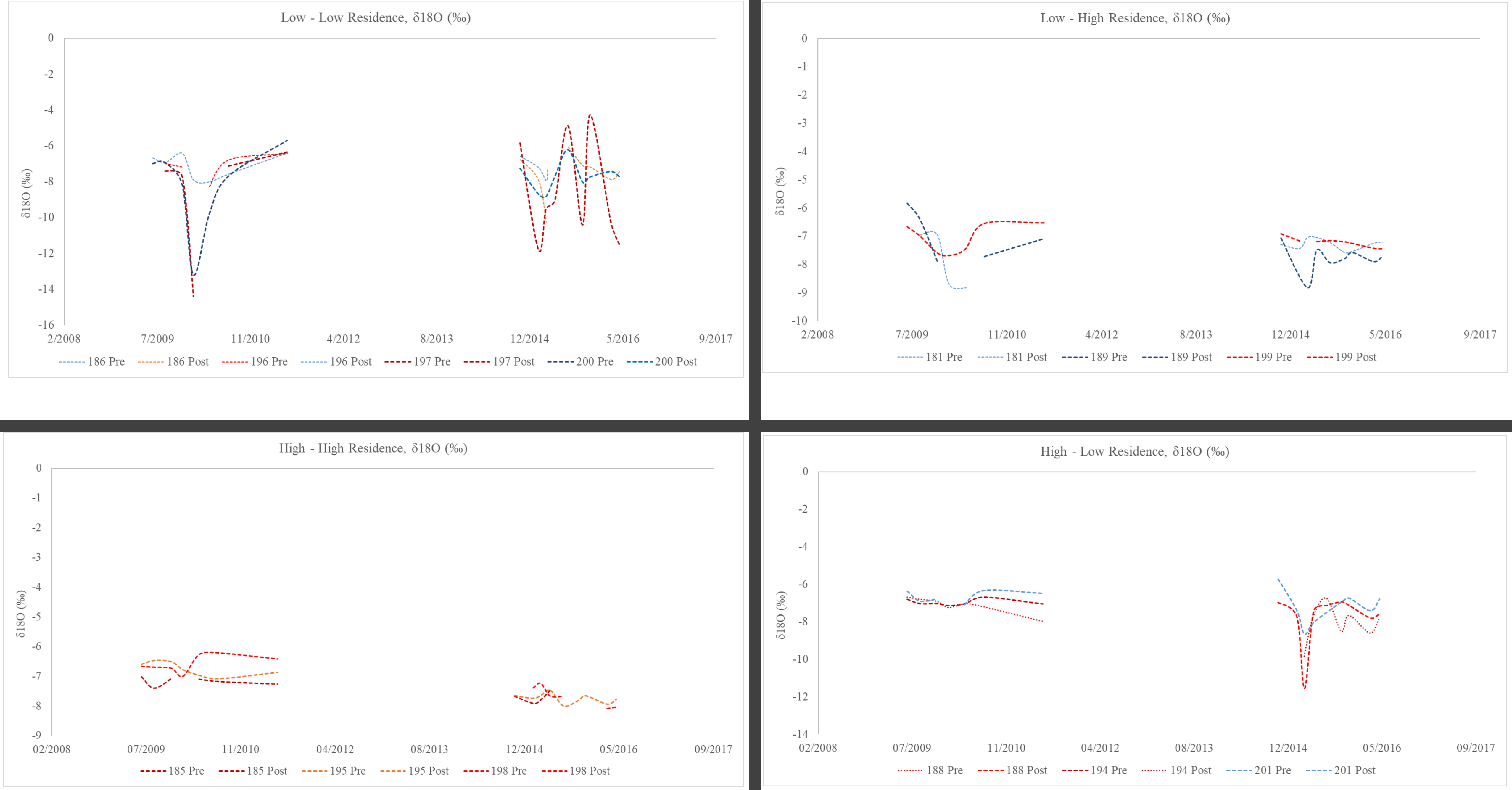
Isotope theory

- We utilized the variance in the stable isotope ratio ($^{18}O/^{16}O$) in water to determine a relative ranking of groundwater residence time for 13 wells in the catchment pre- and post-restoration

$$\delta^{18}O = \left(\frac{\left(\frac{^{18}O}{^{16}O}\right)_{\text{sample}}}{\left(\frac{^{18}O}{^{16}O}\right)_{\text{standard}}} - 1 \right) \times 1000 \text{ ‰}$$

- Water samples were taken on a bi-monthly basis for 2 years pre-restoration (2009-2011) and post-restoration (2014-2016)
- Greater variance in $\delta^{18}O$ infers shorter groundwater contact times and a more active flow path


EPA 200
EPA 200 Pre
LMWL
Linear (LMWL)
dD
d18O
Low-Low Residence, Restored
EPA 201
EPA 201 Pre
LMWL
Linear (LMWL)
dD
d18O
High-Low Residence, Restored
EPA 185
EPA 185 Pre
LMWL
Linear (LMWL)
dD
d18O
High-High Residence, Unrestored
EPA 197 Post
EPA 197 Pre
LMWL
Linear (LMWL)
dD
d18O
Low-Low Residence, Unrestored
184-EPA
304N
182-EPA
87-EPA
307N
308N
305N
303N
306N
310N
309N
302N
189N
200N
201N
199N
USGS approx.
311N
317N
183-EPA
181N
186N
316N
315N
313N
188-EPA
312N
201N
185-EPA
197-EPA
196-EPA


Low - Low Residence, δ18O (‰)
δ18O (‰)
0
-2
-4
-6
-8
-10
-12
-14
-16
2/2008
7/2009
11/2010
4/2012
8/2013
12/2014
5/2016
9/2017
186 Pre
186 Post
196 Pre
196 Post
197 Pre
197 Post
200 Pre
200 Post
Low - High Residence, δ18O (‰)
δ18O (‰)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
2/2008
7/2009
11/2010
4/2012
8/2013
12/2014
5/2016
9/2017
181 Pre
181 Post
189 Pre
189 Post
199 Pre
199 Post
High - High Residence, δ18O (‰)
δ18O (‰)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
02/2008
07/2009
11/2010
04/2012
08/2013
12/2014
05/2016
09/2017
185 Pre
185 Post
195 Pre
195 Post
198 Pre
198 Post
High - Low Residence, δ18O (‰)
δ18O (‰)
0
-2
-4
-6
-8
-10
-12
-14
02/2008
07/2009
11/2010
04/2012
08/2013
12/2014
05/2016
09/2017
188 Pre
188 Post
194 Pre
194 Post
201 Pre
201 Post

Introduction: Low-Low Residence

Groundwater residence time at these wells remained *faster* than the catchment average pre- and post-restoration. **Groundwater at these locations assumes relatively *active flow paths***.

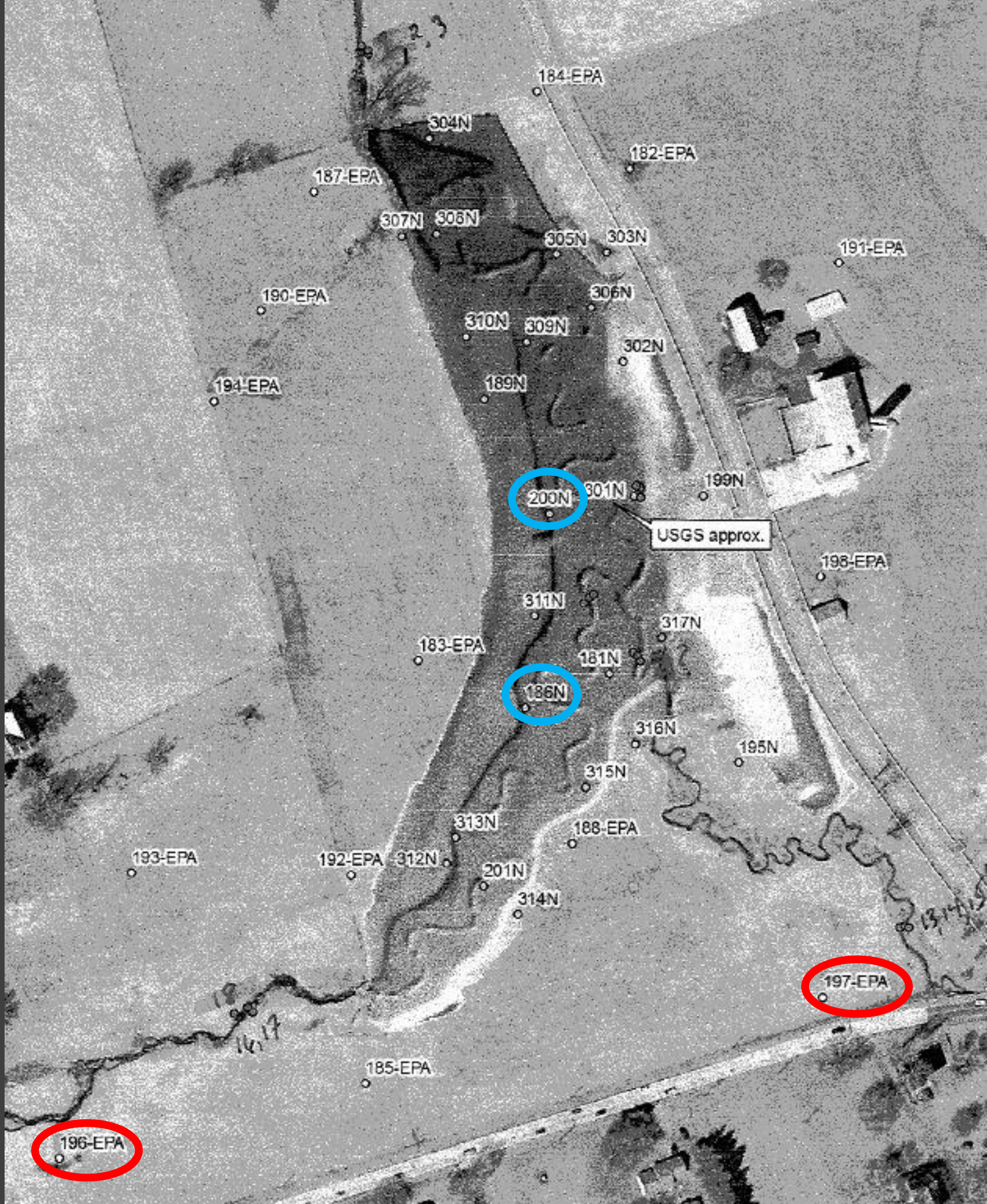
Wells **186** and **200** are both located inside the **restored area** whereas **196** and **197** are located **outside the restored area**.

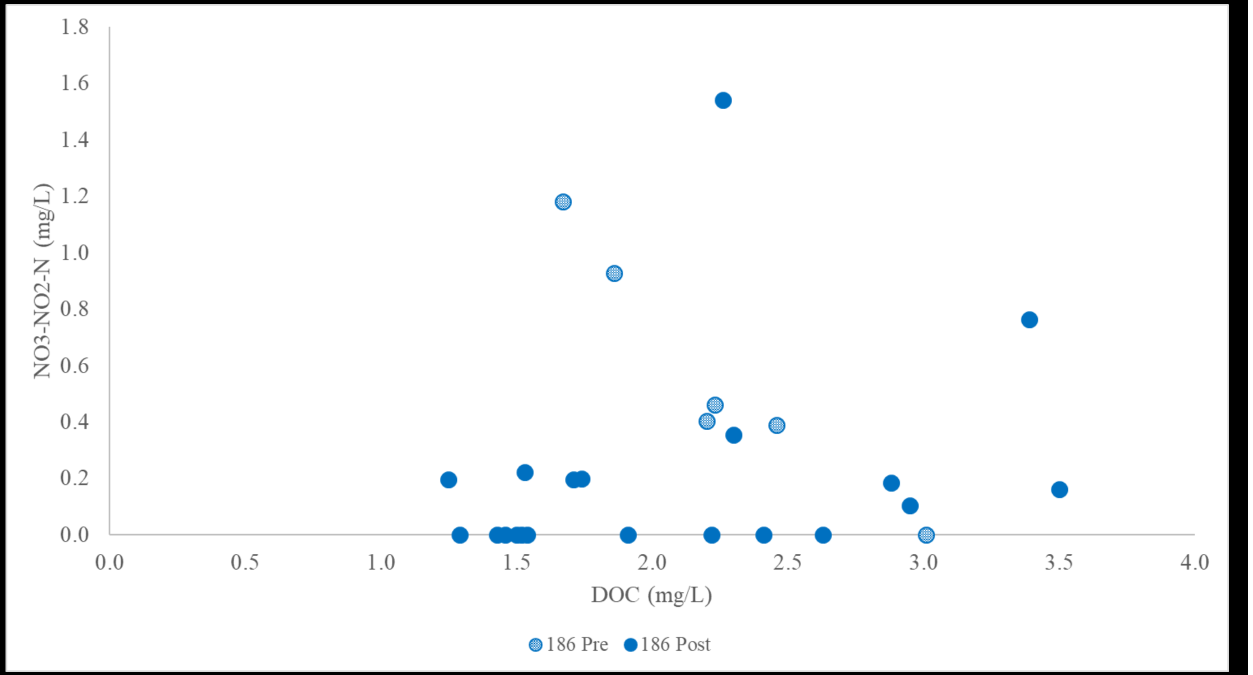
Well 186 had a depth of 7.2 ft, but was replaced post-restoration so the depth became 3.5 ft. The screened interval (SI) begins at 2.5 ft (relict) - The soil type is Newark.

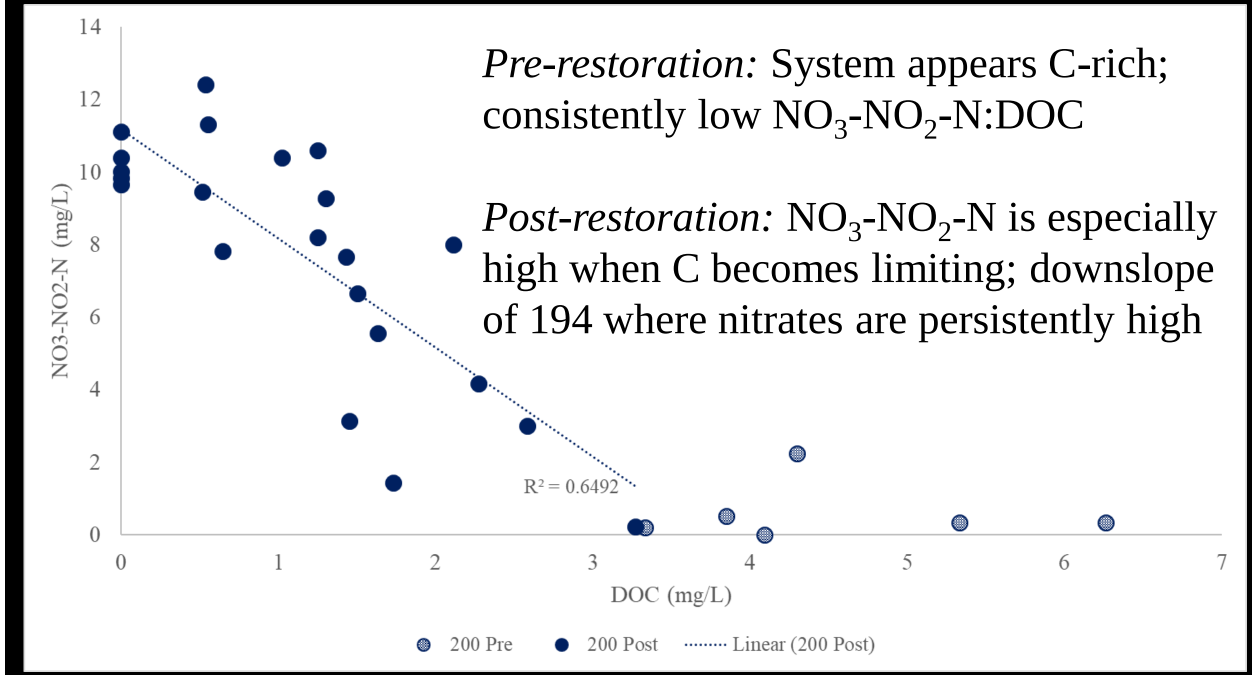
Well 200 had a pre-restoration depth of 3.5 ft but was re-drilled to 4.0 ft post-restoration. The SI begins at 3 ft (relict). The soil type is Newark.

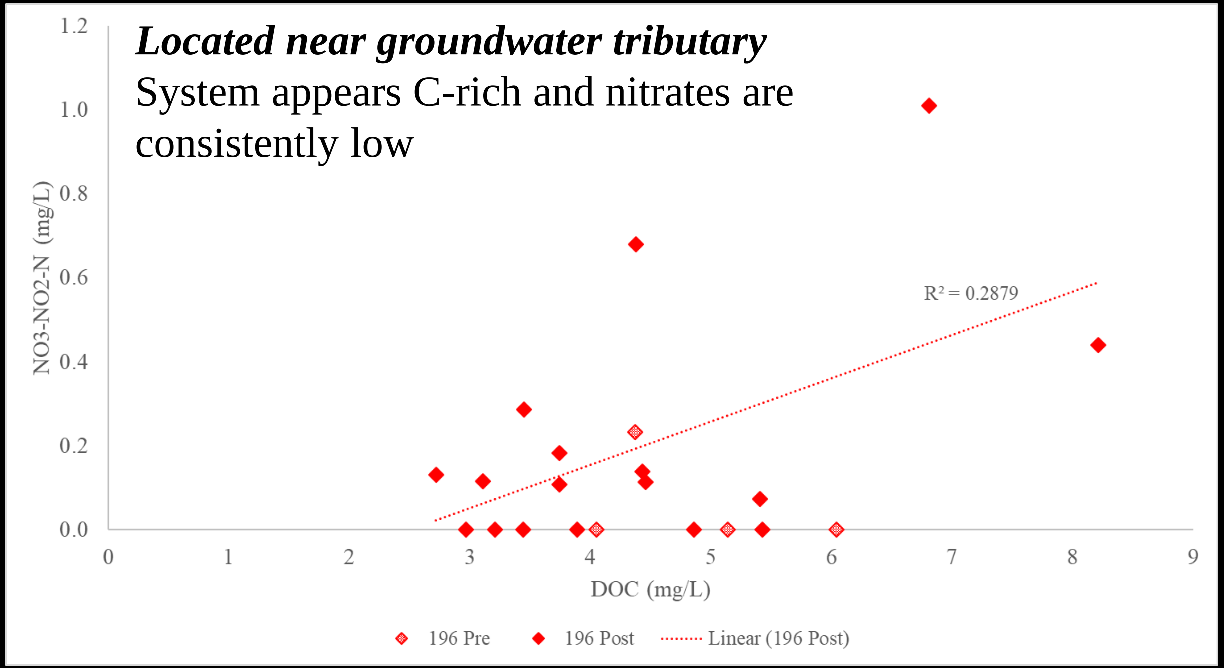
Well 197 may be seasonally influenced by road salts and/or leaf litter decomposition in stormwater runoff due to its roadside proximity. It is also located closer to trees than many other wells in the catchment. This well has a depth of 18.8 ft. The SI begins at 13.5 ft (bedrock). The overlying soil type is Newark.

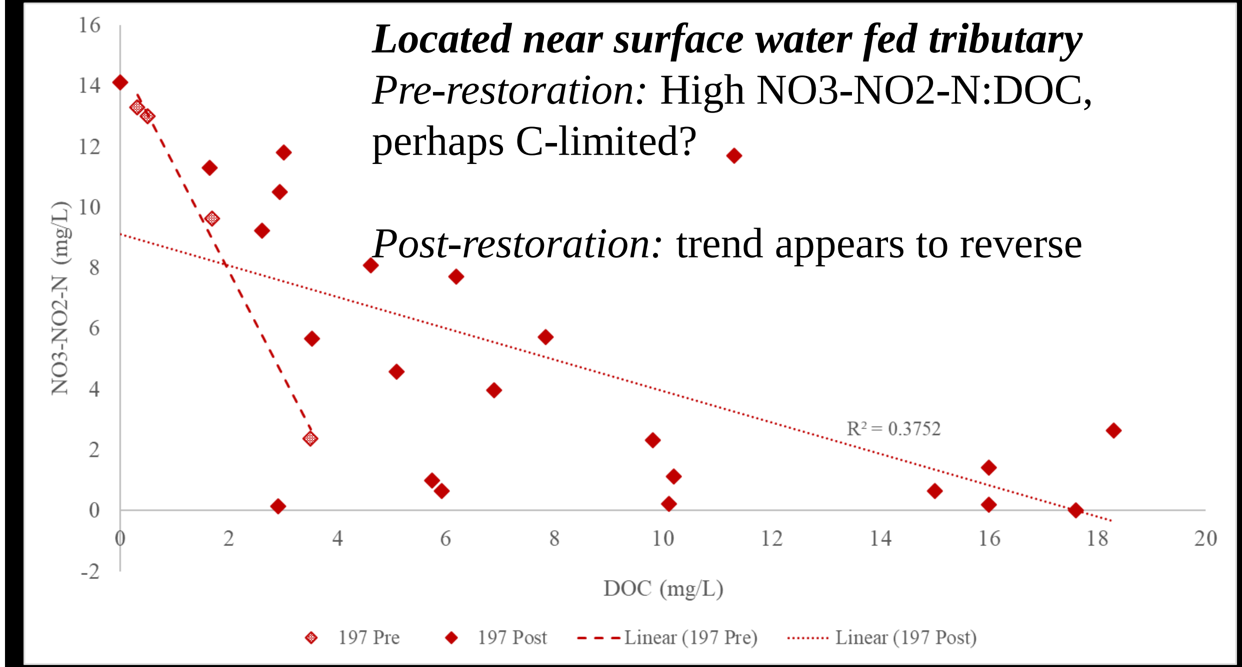
Well 196 has a depth of 8.3 ft (bedrock), SI at 5 ft and is located in close proximity to the groundwater-fed tributary. The overlying soil type is Newark.




NO3-NO2-N (mg/L)
DOC (mg/L)
186 Pre
186 Post


Pre-restoration: System appears C-rich; consistently low NO_3-NO_2-N:DOC
Post-restoration: NO_3-NO_2-N is especially high when C becomes limiting; downslope of 194 where nitrates are persistently high
$R^2 = 0.6492$
NO3-NO2-N (mg/L)
DOC (mg/L)
200 Pre
200 Post
Linear (200 Post)


Located near groundwater tributary
System appears C-rich and nitrates are consistently low
$R^2 = 0.2879$
NO3-NO2-N (mg/L)
DOC (mg/L)
196 Pre
196 Post
Linear (196 Post)


Located near surface water fed tributary
Pre-restoration: High NO3-NO2-N:DOC, perhaps C-limited?
Post-restoration: trend appears to reverse
$R^2 = 0.3752$
NO3-NO2-N (mg/L)
DOC (mg/L)
197 Pre
197 Post
Linear (197 Pre)
Linear (197 Post)

Introduction: Low-High Residence

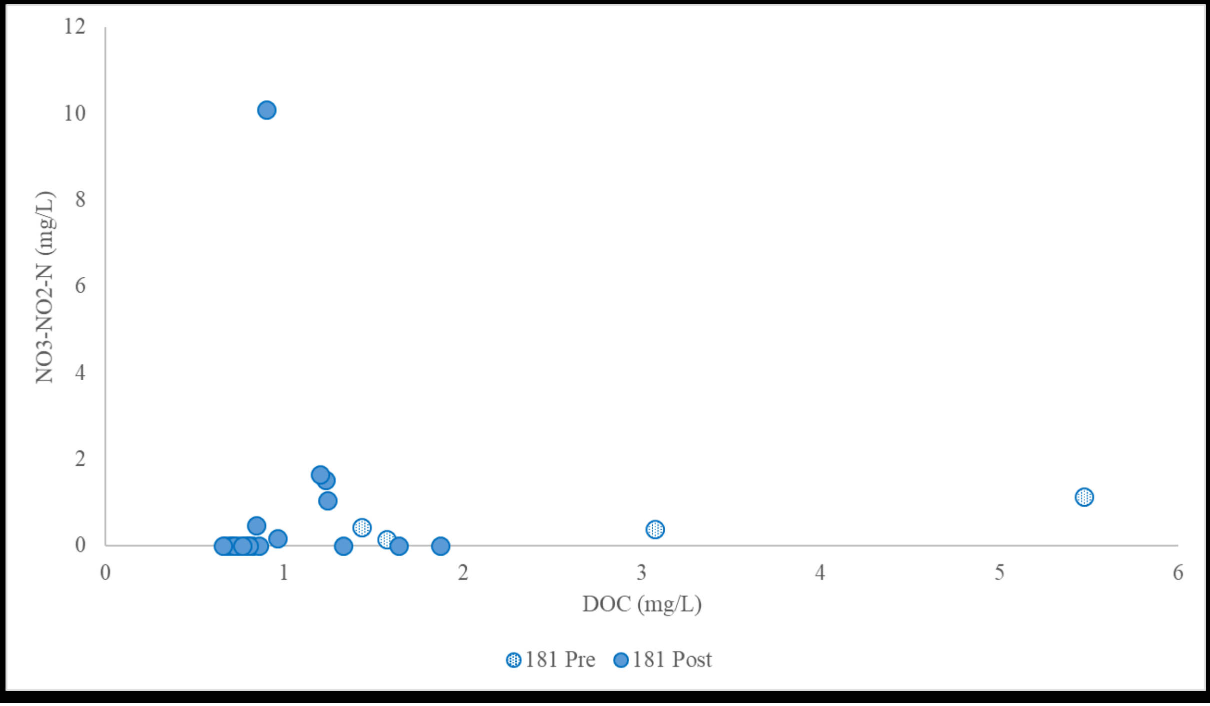
Groundwater residence time at these wells was faster than the catchment average pre-restoration, but slower than the catchment average after the restoration occurred. Thus, the **groundwater flow paths at these wells became *less active* post-restoration**.

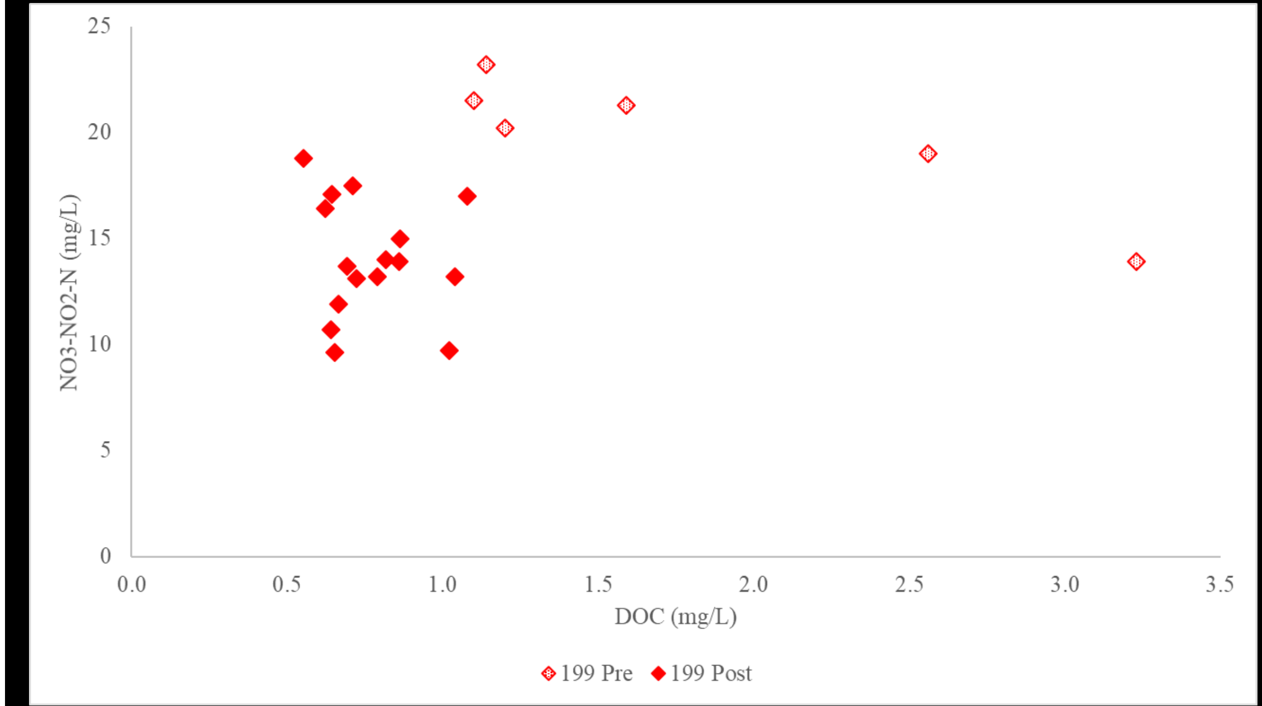
Well 199 is located upslope in the **unrestored area**, whereas **181** and **189** are inside the **restored area**.

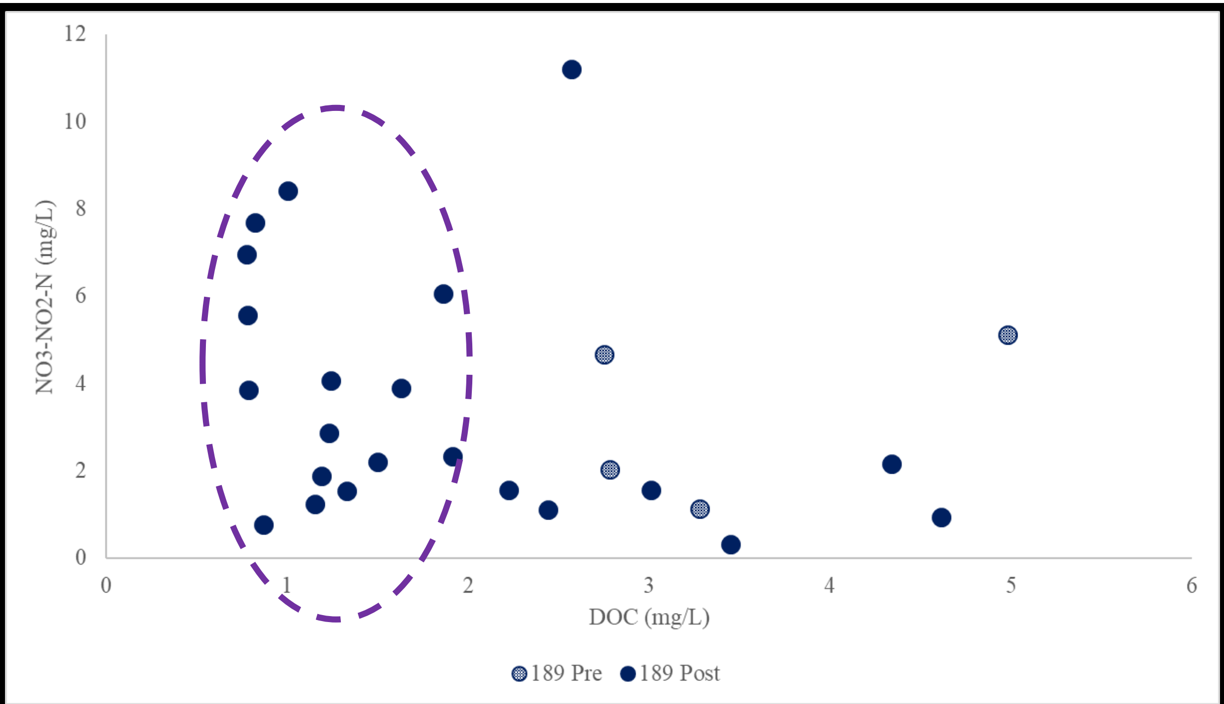
Well **181** had a depth of 4.9 ft, but was replaced post-restoration so the depth became 2.6. The screened interval (SI) begins at 1.6 ft (relict) - The soil type is Newark.

Well **189** had a pre-restoration depth of 7.8 ft, and was replaced post-restoration but the depth remained the same. The screened SI begins at 3 ft (C horizon/bedrock) - The soil type is Newark.

Well 199 had a depth of 12.5 ft pre-restoration. This depth became 11.5 ft when the well was replaced post-restoration but the SI begins at 6.5 ft (bedrock). The overlying soil type is Conestoga.







Pre-restoration: There appears to be higher DOC, even where NO_3-NO_2-N is low. In the unrestored area, oxic conditions at **199** may inhibit denitrification.

Post-restoration: the NO_3-NO_2-N:DOC seems to stabilize at **199** and **181**, however the ratio of nitrates to DOC at **199** are still high. **189** is located directly downslope of **194** which may explain some of the trends we see along the left side of the graph.

Introduction: High-Low Residence

Groundwater residence time at these wells was longer than the catchment average pre-restoration occurred, but turnover seemed to *increase* post-restoration resulting in a lower than average residence time. Thus, the **groundwater flow paths at these wells became *more active* post-restoration.**

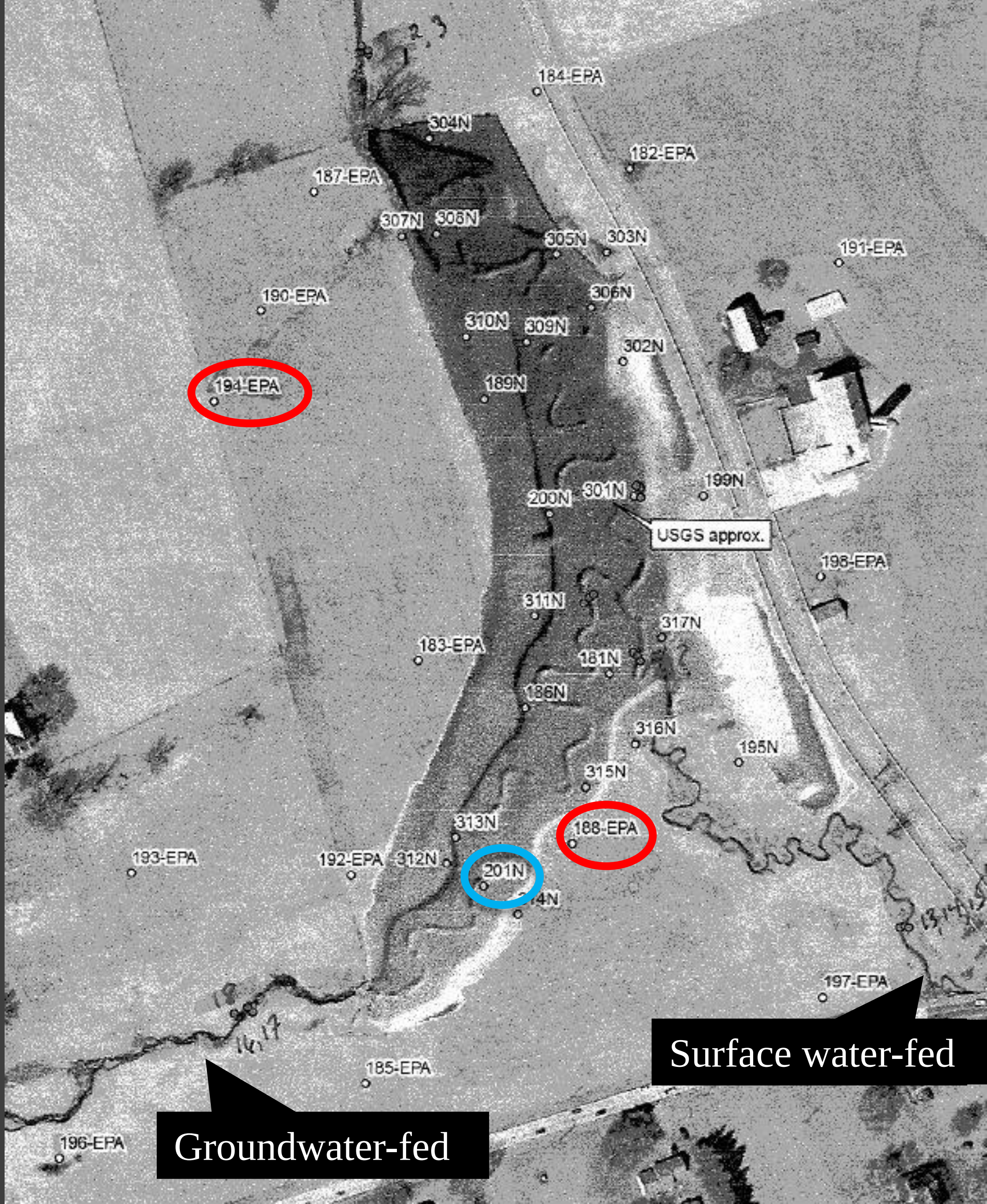
Wells 188 and 194 are located in the unrestored area, whereas 201 is inside the restored area.

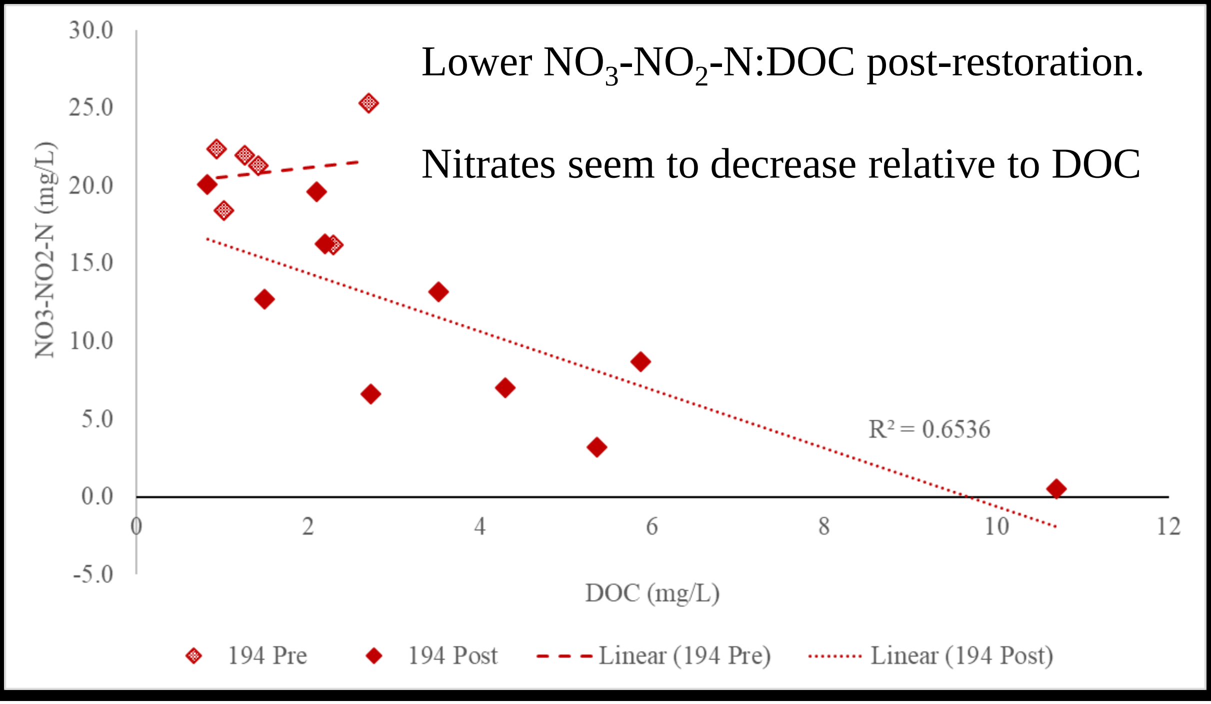
Well 194 is located further uphill of the restoration area than 188. This spatial difference may be important as we consider the restoration zone of influence.

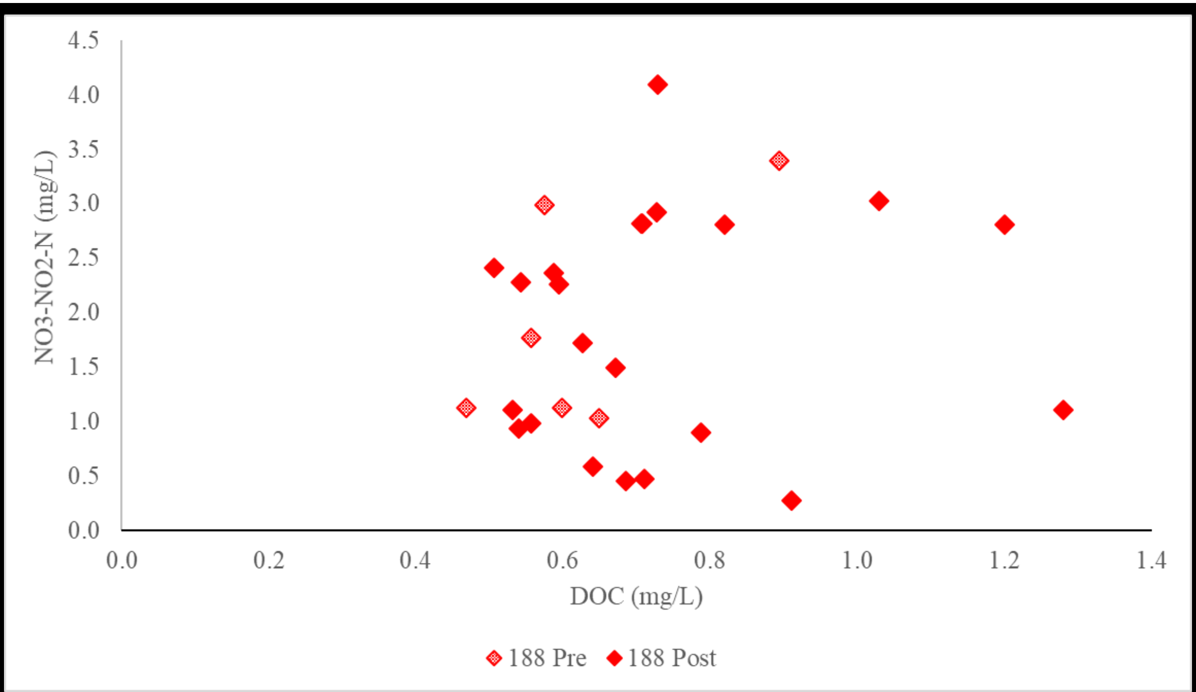
Well 188 has a depth of 11.7 ft, but screened interval (SI) begins at 6.7 ft (C horizon) - The soil type is Newark.

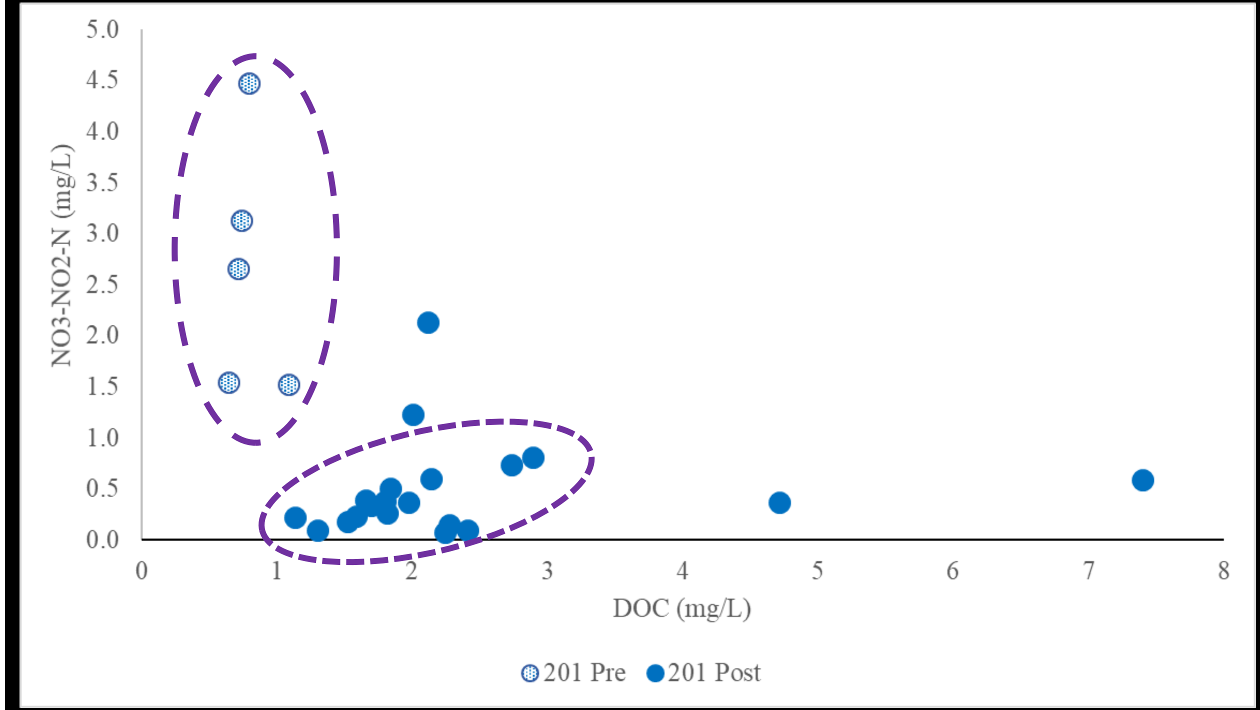
Well 194 has a depth of 14.0 ft, but the SI begins at 9 ft (bedrock). The overlying soil type is Pequea.

Well 201 depth was 11.8 ft pre-restoration and was re-drilled to 3.5 ft (SI begins at 2.5 ft) post-restoration. The soil type is Newark.









Co-located wells 188 and 201 demonstrate consistent low NO_3-NO_2-N and stable DOC relative to 194, which is located further from the restored area

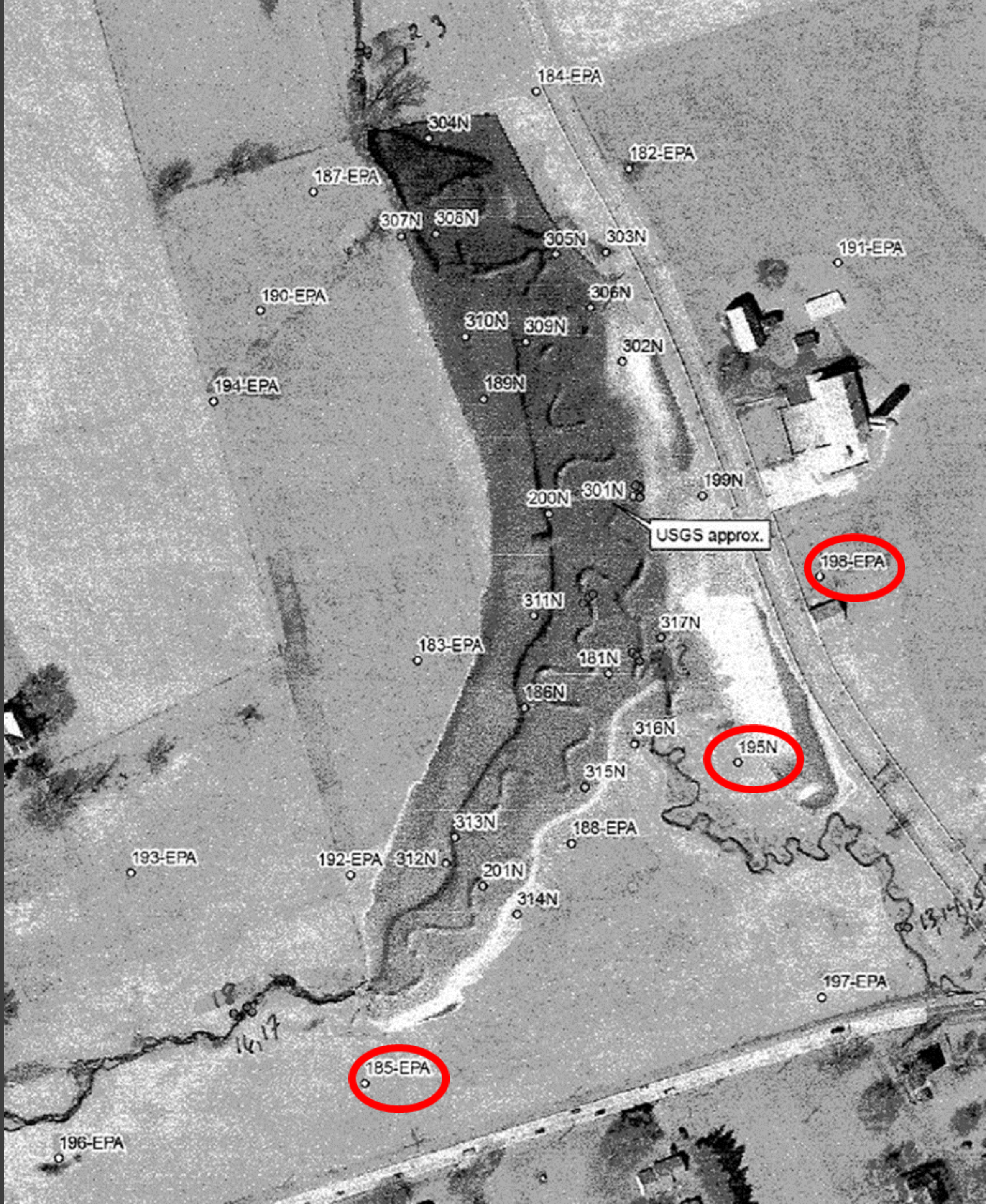
Introduction: High-High Residence

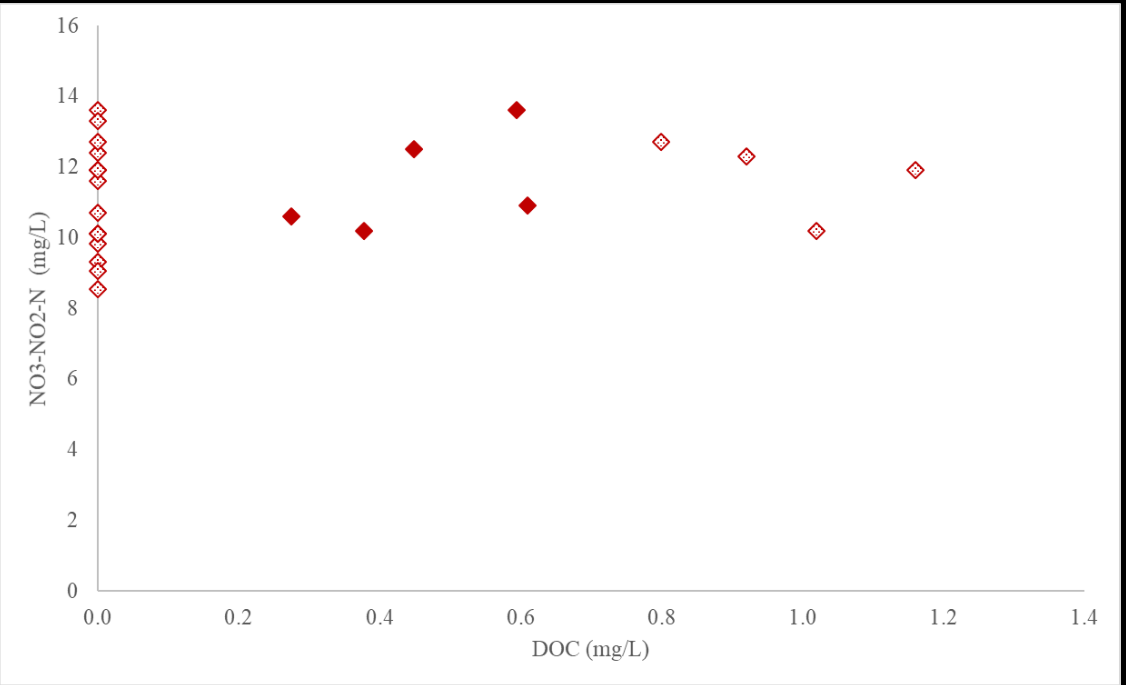
Groundwater residence time at these wells was longer than the catchment average both before and after the restoration occurred. **Groundwater at these locations assumes relatively *inactive flow paths*.**

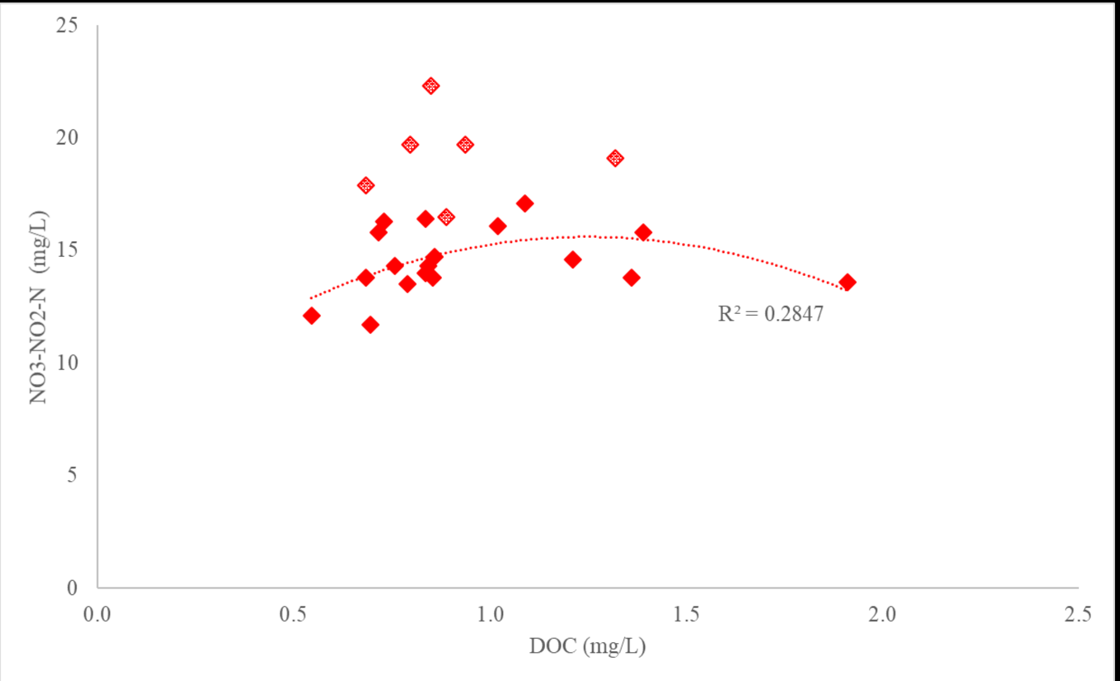
All wells are located outside of the restored area.

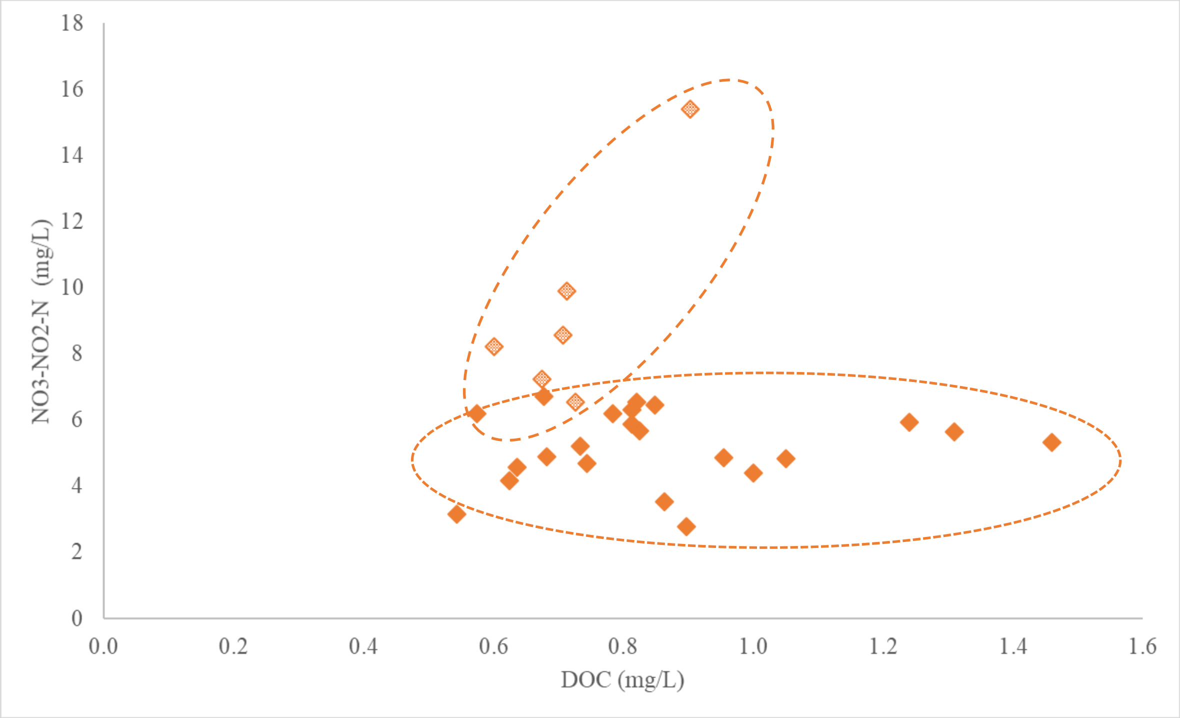
Well 195 (pre depth: 10 ft, post: 8.0 ft) and well 198 (depth: 9.1 ft) are located nearest to the surface water-fed tributary (eastern branch). SI begins at 3 and 5 ft, respectively.

Well 185 (depth: 6.4ft, SI at 5 ft) is located nearest to the groundwater-fed tributary (western branch). This well was decommissioned in 2015.

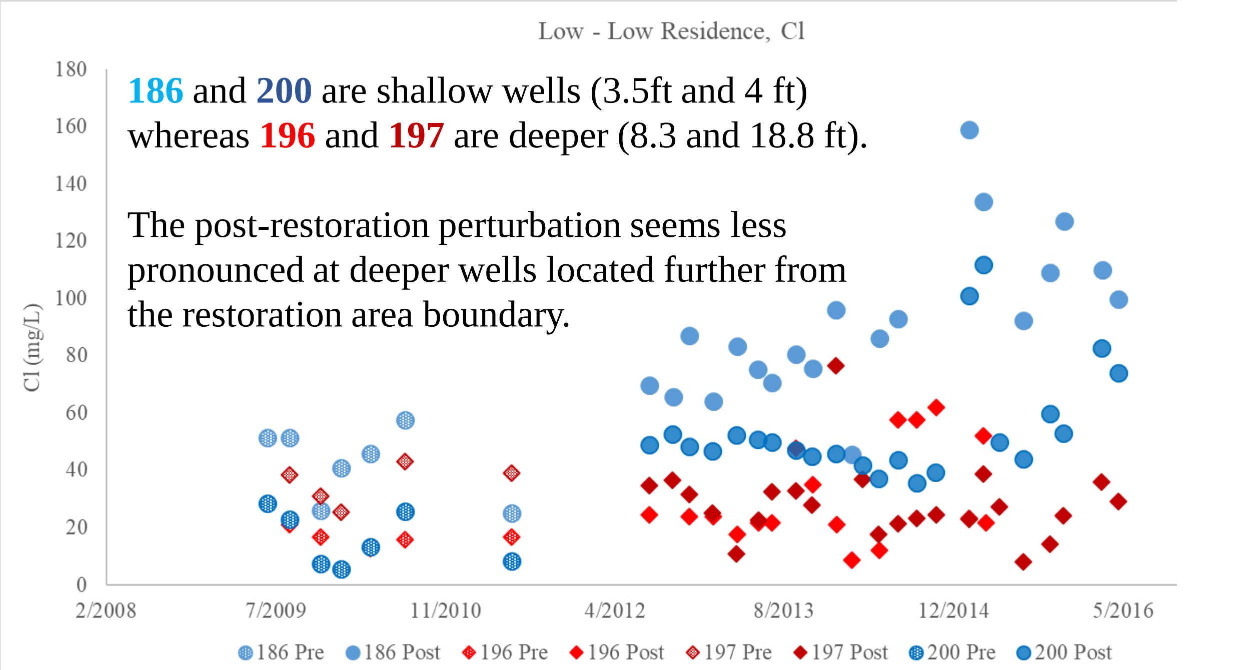


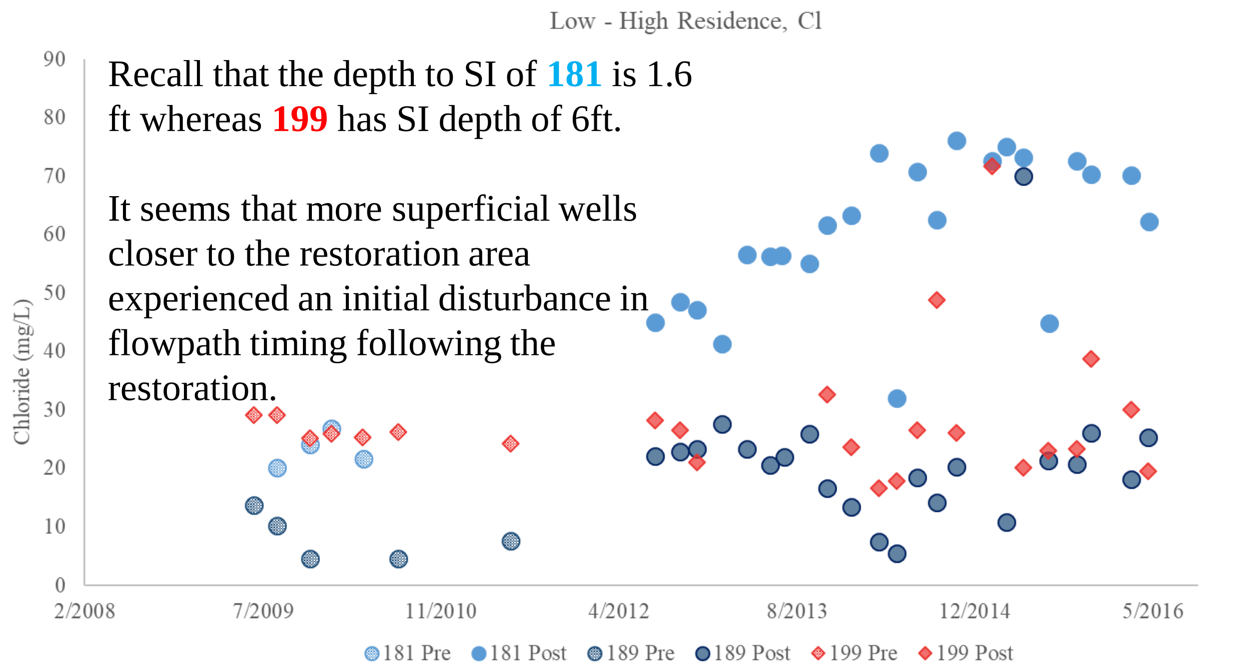




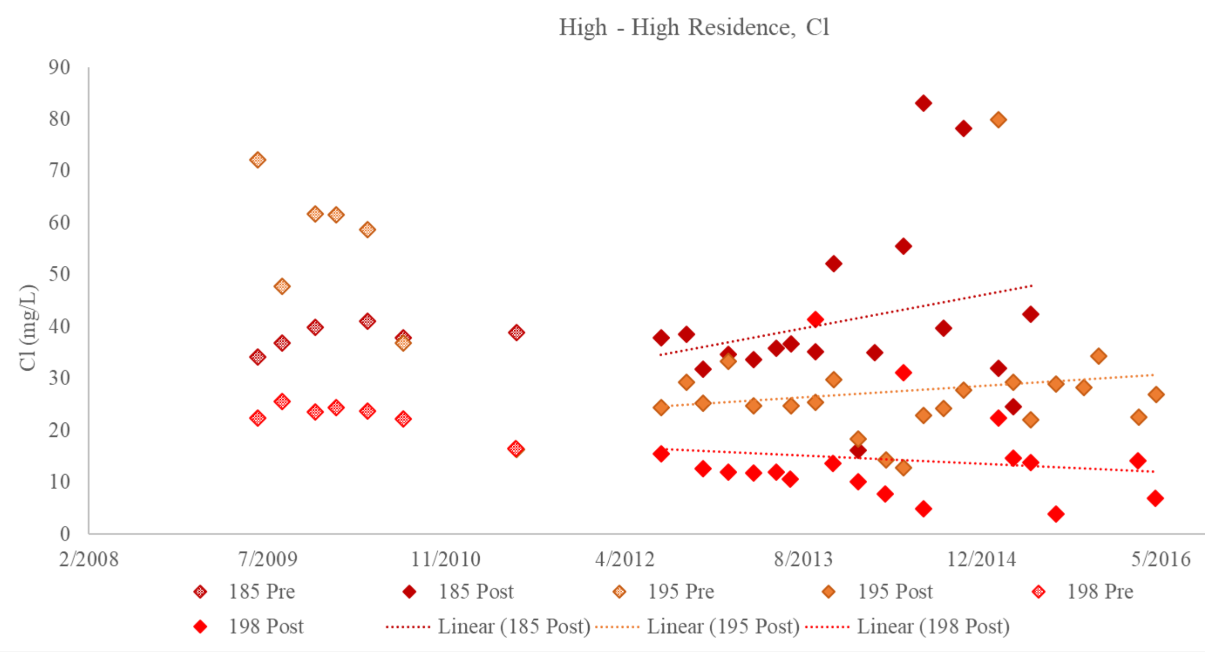


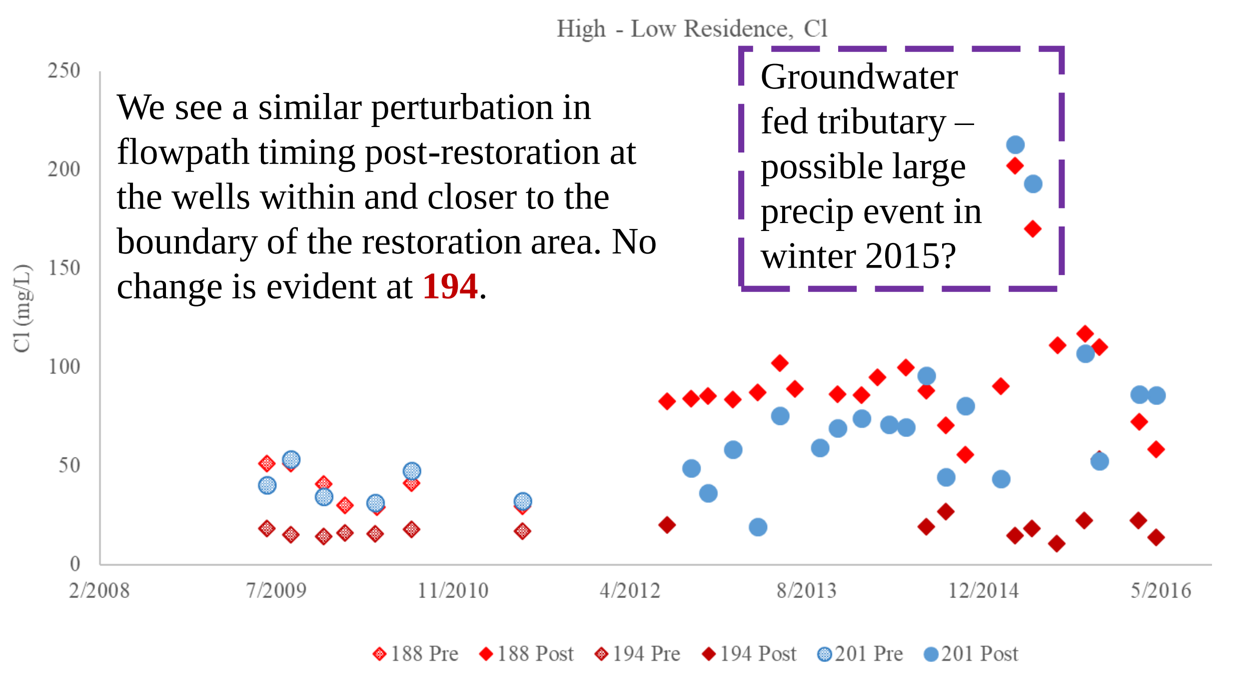
DOC is consistently low (< 2mg/L) relative to NO_3-NO_2-N at these wells located outside of the restored area with long residence times

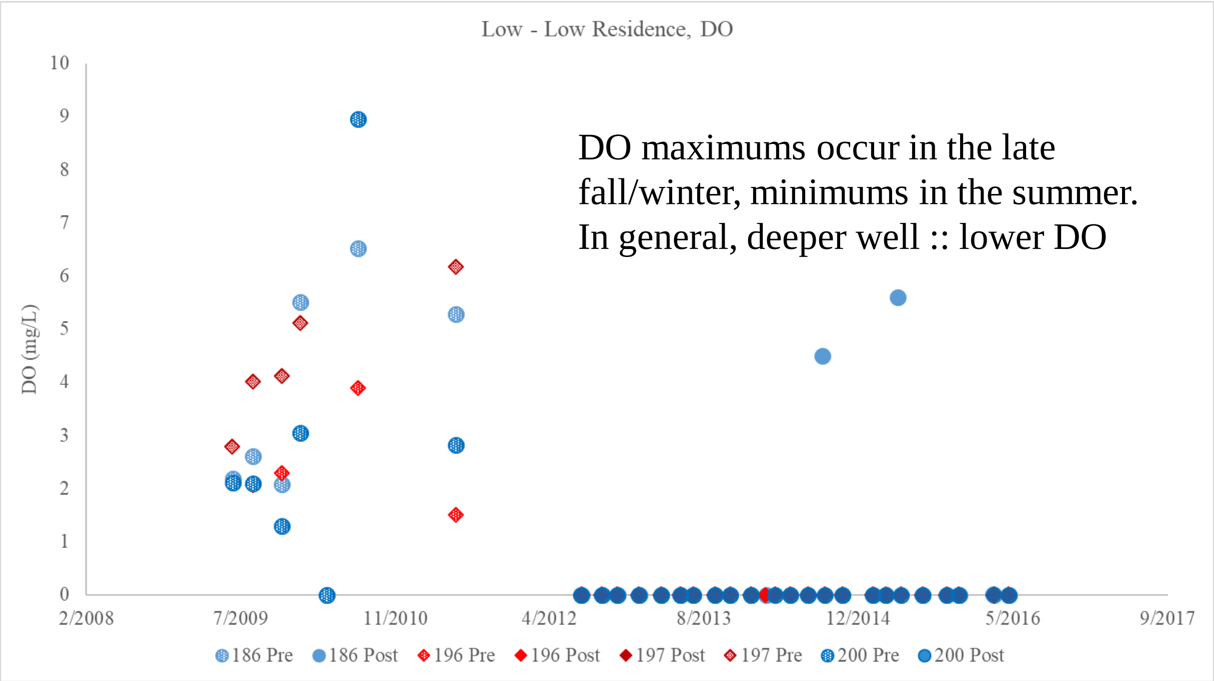




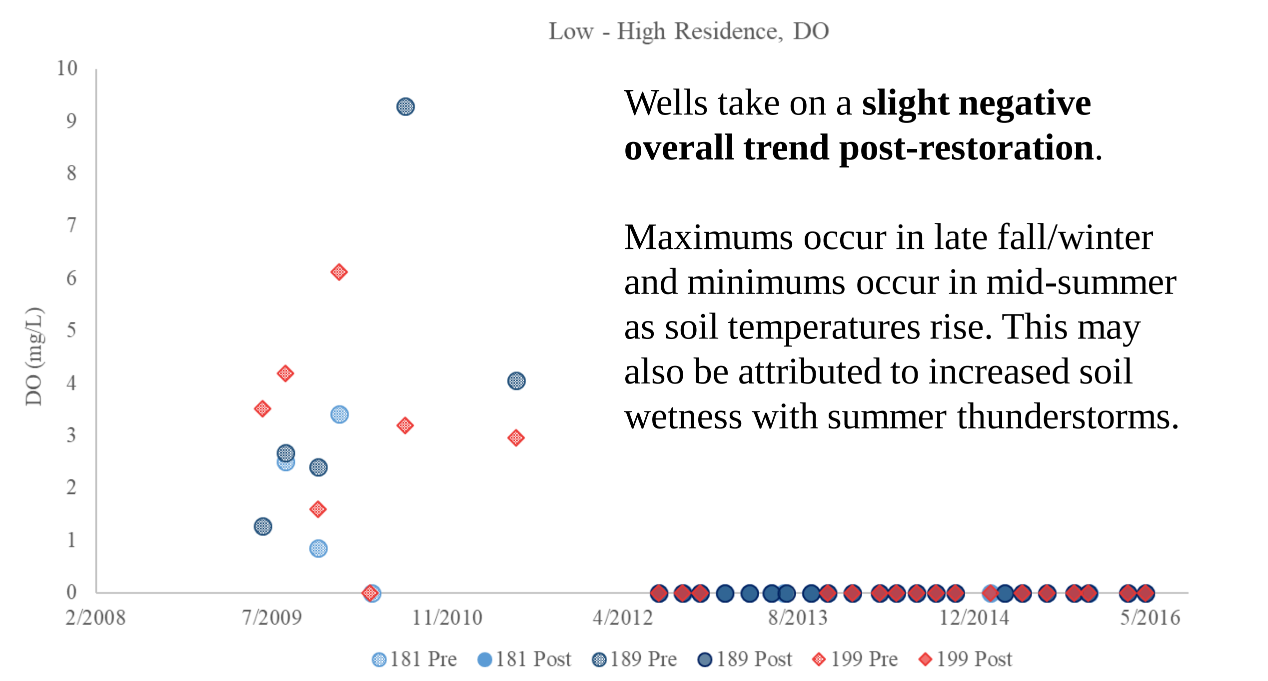
Chloride is a useful and complementary tracer to stable isotopes because it remains relatively inert in systems during recharge events.







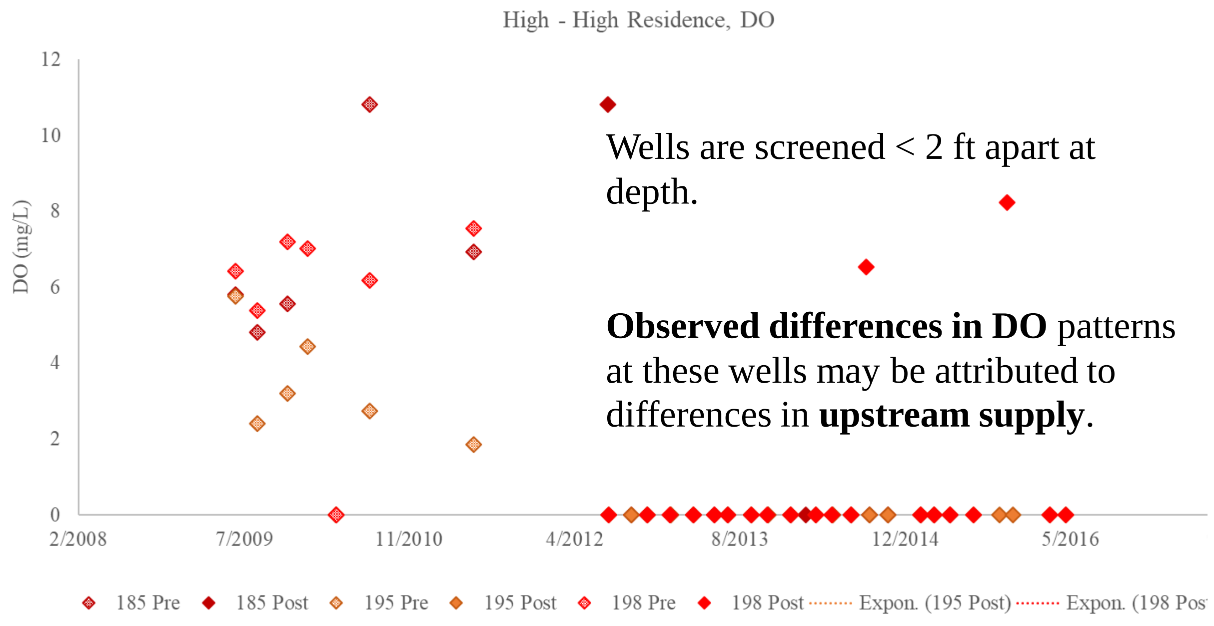
DO maximums occur in the late fall/winter, minimums in the summer. In general, deeper well :: lower DO



Wells take on a **slight negative overall trend post-restoration**.

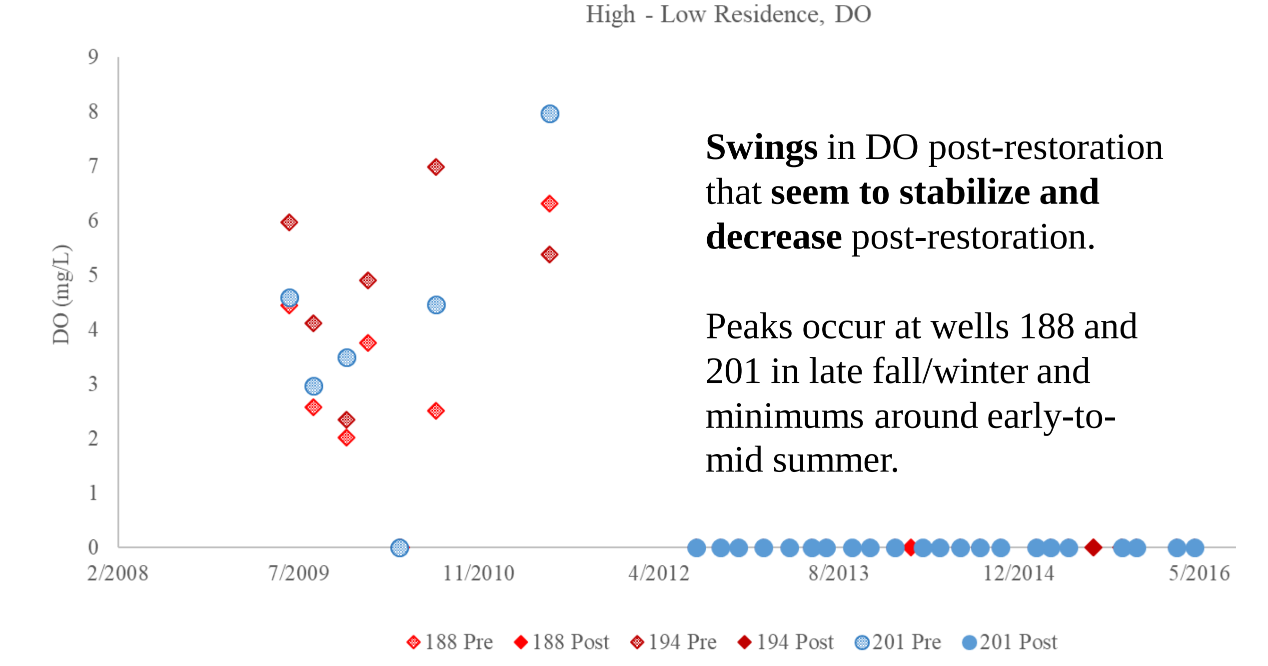
Maximums occur in late fall/winter and minimums occur in mid-summer as soil temperatures rise. This may also be attributed to increased soil wetness with summer thunderstorms.

Dissolved oxygen appears to have decreased and stabilized across all groundwater wells post-restoration.



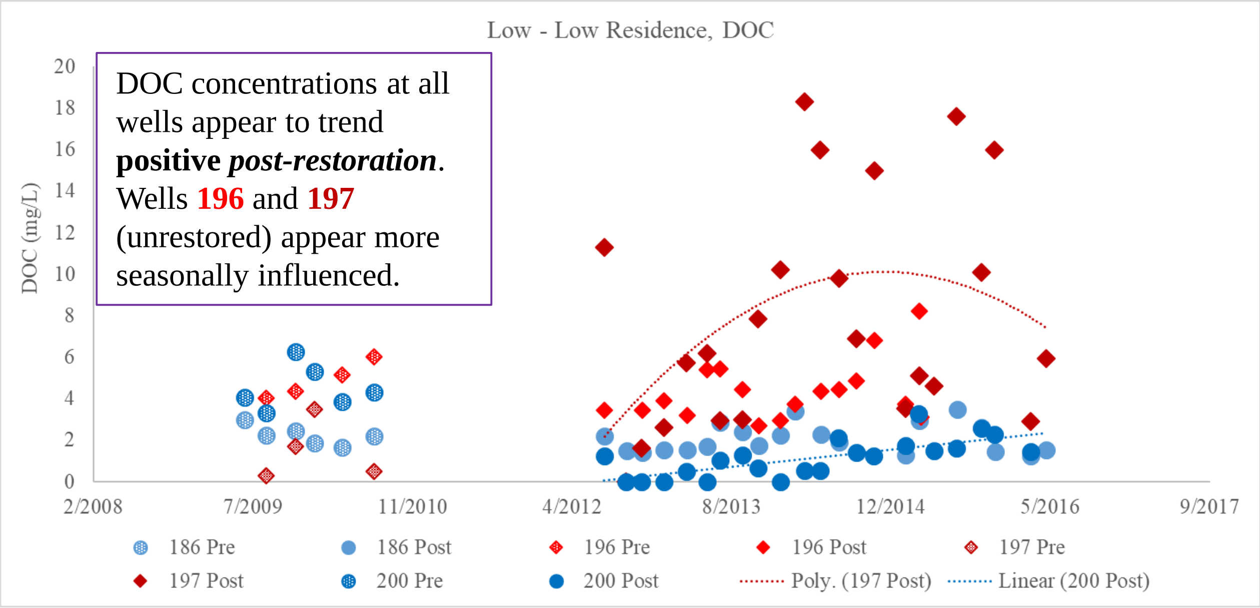
Wells are screened < 2 ft apart at depth.

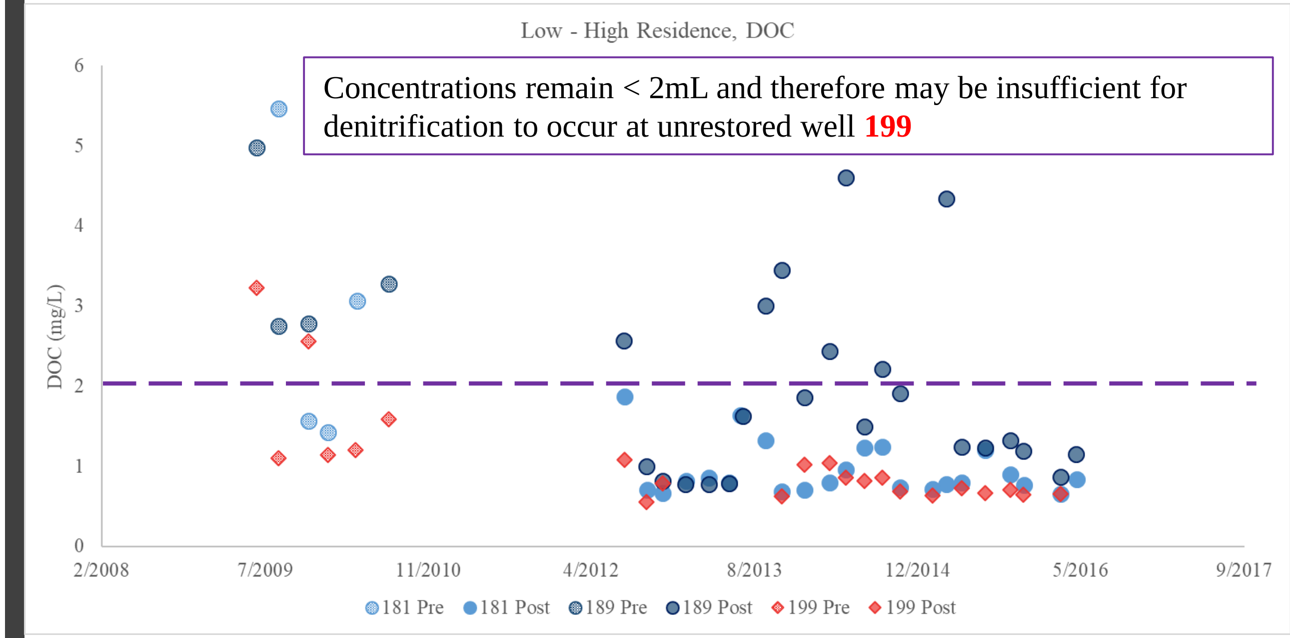
Observed differences in DO patterns at these wells may be attributed to differences in **upstream supply**.



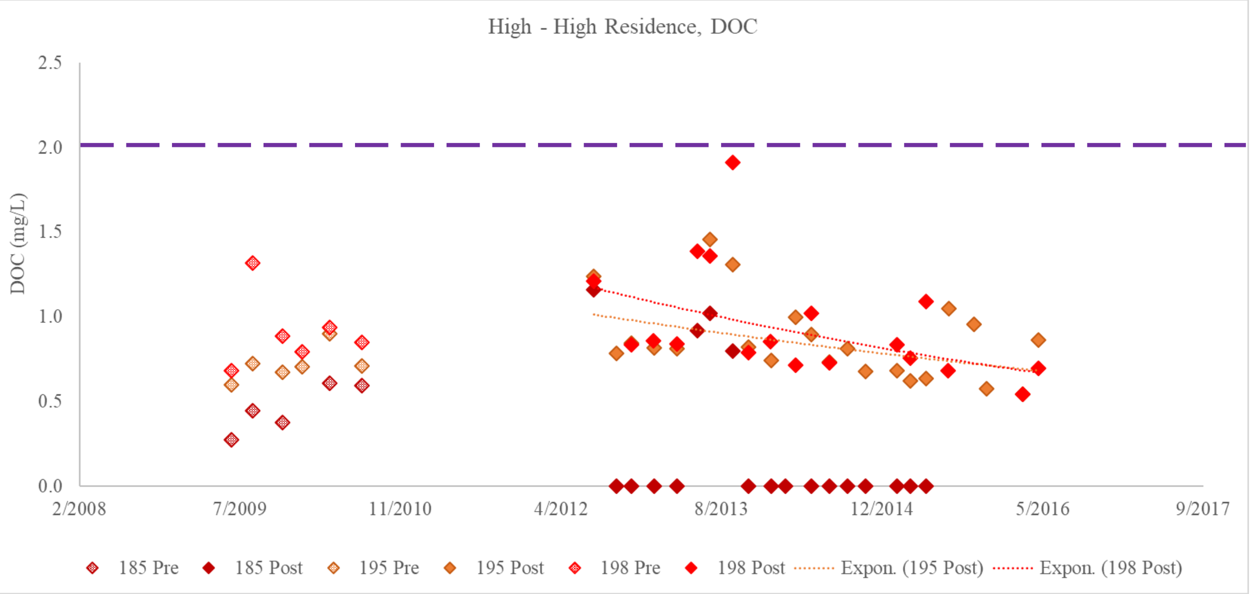
Swings in DO post-restoration that **seem to stabilize and decrease** post-restoration.

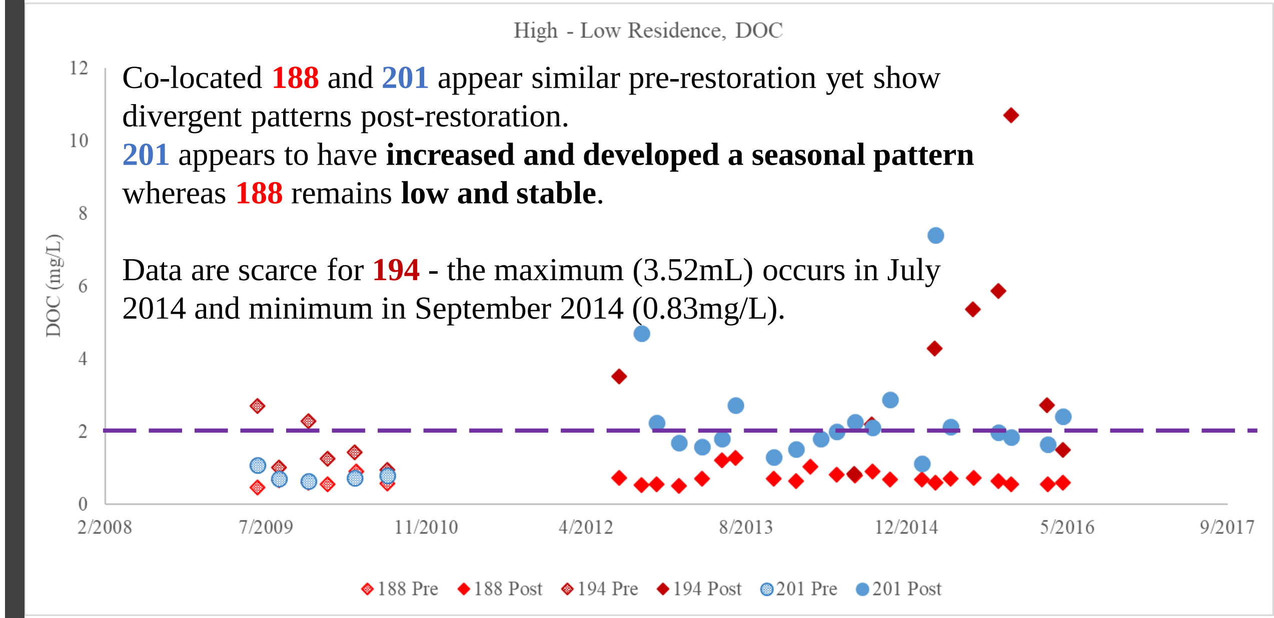
Peaks occur at wells 188 and 201 in late fall/winter and minimums around early-to-mid summer.

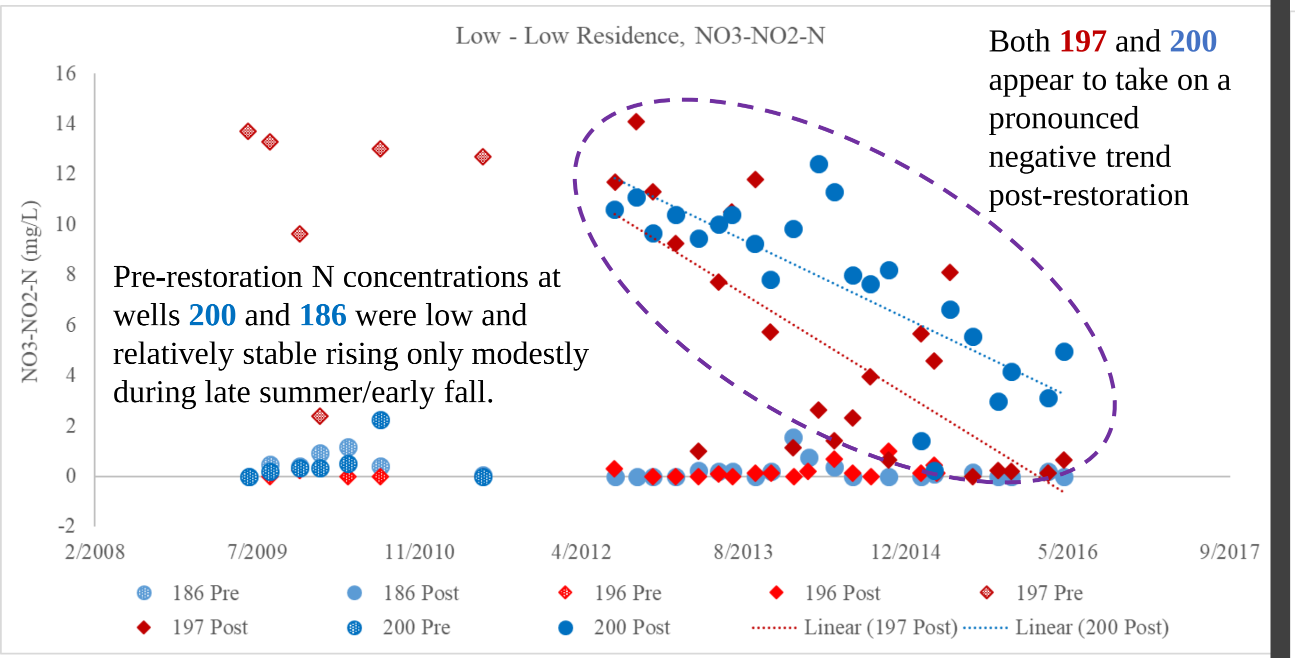


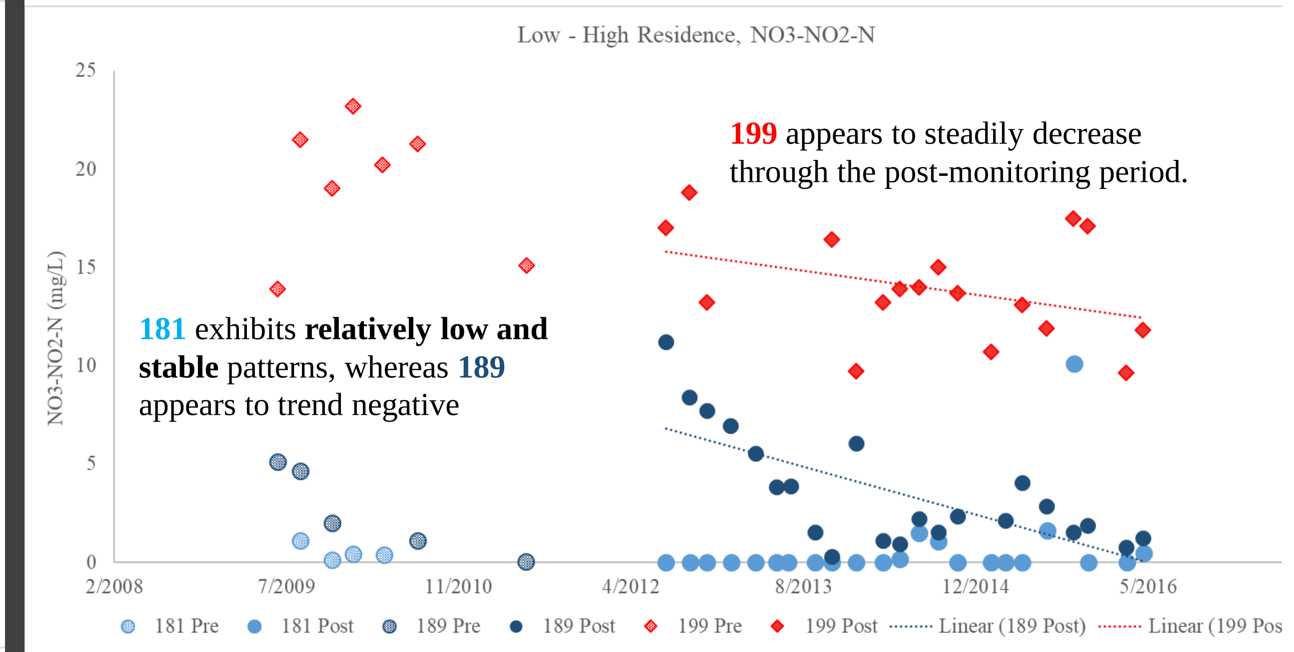


Wells appear to be carbon-limited. If groundwater remains in residence for longer periods of time, dilution of carbon inputs may play a factor in denitrification.









Seasonal patterns in N are evident at some wells. Peaks occurred in late spring-to-summer and lows in winter possibly related to DO +/- DOC.