# The Influence of Ground Water Pumping On Wetlands in Crane Flat, Yosemite National Park, California

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By:


**David J. Cooper, Ph.D. and Evan C. Wolf, M.S.**

**Department of Forest, Rangeland and Watershed Stewardship**

**Colorado State University, Fort Collins, CO  80523**


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# Introduction

Peatlands are important features of mountain landscapes providing critical support for many species, carbon storage, and ecosystem stability for millennia. Peatlands occur throughout the Sierra Nevada, but they exist primarily as small, widely scattered ecosystems, and cover less than 0.1% of the mountain landscape. However, in many parts of the Sierra Nevada these hydrologically stable ecosystems are the only perennially wet environments through the long dry Sierra summer, and support a large number of plants, amphibians and aquatic invertebrates that rely on their constant water availability. These characteristics make peatlands disproportionately important with respect to land area and they require special attention when managing mountain landscapes.

Peatlands form in ecosystems where the rate of organic matter net primary production exceed the rates of decomposition, allowing an accumulation of undecomposed plant matter. This process requires slow rates of organic matter decomposition and occurs primarily in soils lacking free oxygen, created by perennial saturation. Even short periods of drying will allow oxygen to enter soil and greatly increase decomposition rates (Chimner and Cooper 2003a). Areas of perennially saturated soil are uncommon in steep mountain landscapes, where runoff processes transport water quickly down slope. This is especially true in the Sierra Nevada, where nearly rain-free summers allow extensive drying of most mountain soils. Saturated soil conditions occur only in areas where subsurface aquifers recharged by snowmelt water create perennial ground water flow paths that discharge at the ground surface.

Groundwater-supported peatlands are fens. They are differentiated from peatlands termed bogs, which receive their water primarily from direct precipitation. Fens have perennially, or nearly perennially saturated soils, a plant cover dominated by species with high below ground biomass production, many long-lived and clonal species and often a carpet of mosses, and soils with at least 40 cm of organic layers within the top 80 cm of soil. The soils should meet the criteria for organic soil, classified as Histosols by the NRCS (ftp://ftp-fc.sc.egov.usda.gov/NSSC/Soil_Taxonomy/tax.pdf).

All peatlands in the Sierra Nevada are fens supported by groundwater flow (Benedict and Major 1982), including those in Yosemite National Park. Bedrock weathering patterns as well as soil properties and geomorphic landforms determine the rate of precipitation infiltration, and the movement and discharge of groundwater. Local and landscape scale geologic and geomorphic patterns also control the location where ground water discharges, thereby determining where fens develop and can be maintained (Benedict 1982). Many fen ground water flow systems have been stable for thousands of years, as evidenced by thick peat accumulations (Wood 1975). In addition, radiometric dating of peat samples from peat bodies demonstrates the steady accumulation of organic matter over many millennia (Bartolome et al. 1990). Although major changes in climate can alter groundwater recharge and discharge processes and cause changes in meadow and peatland soil forming processes and vegetation (Wood 1975) the geologic configuration of the landscape maintains the underlying control of groundwater recharge and discharge patterns and processes (Benedict 1982).

Ground water level and its variation relative to the soil surface, as well ground water chemistry, determines the composition and productivity of peat-forming vegetation (Allan-Diaz 1991, Cooper and Andrus 1994) and influences the rate of peat accumulation (Moore and Bellamy 1973). Even slight changes in fen hydrologic regimes can disrupt the formation and maintenance of peat bodies (Cooper et al. 1998), and results in vegetation changes. Ditching or diversion of water is a common hydrologic disturbance in peatlands (Wheeler 1995), and can lower fen water tables (Glaser 1983, Glaser et al. 1990, Fisher et al. 1996, Chimner and Cooper 2003). Any process that changes the water level in a fen has the potential to disrupt the fundamental processes that formed and maintained the fen. The restoration of hydrologically impacted fens must first focus on reestablishing appropriate water levels (Wheeler 1995, Cooper et al. 1998, Patterson 2005), and once the hydrologic regime is restored, efforts may then shift to revegetation (Cooper and MacDonald 2000) and maintenance of a positive carbon balance (Chimner and Cooper 2003).

More than 3 million people visit Yosemite National Park each year, with the greatest visitation during the dry summer months. Providing a reliable domestic water supply is a large and important issue. Because most small streams in the Sierra Nevada are intermittent, nearly all water used for domestic purposes within Yosemite National Park is groundwater pumped from relatively shallow aquifers. In Yosemite Valley, three

300+ m deep wells drilled into thick glacial deposits produce over 12,000 L/min. This is more than twice the amount of water needed in the Valley during the maximum demand day in 1997, when an average of approximately 5,000 L/min were consumed (Walker 1998). However, visitor uses in Yosemite National Park are not confined to Yosemite Valley, and also occur in highland areas to the north and south of the Valley, separated from the Valley by 700 m high vertical walls. Because it is unfeasible to pump water from the Valley to other areas of consumption, ground water pumping wells have been drilled to develop local water supplies for campgrounds, lodges, and other permanent facilities.

One area of domestic water need and use is around Crane Flat where a gas station, campground and the Yosemite Institute (YI) are located and share water pumped from one well located in Crane Flat Meadow. This groundwater pumping well, covered by a small, shingled shed, is known as the "Doghouse", and the meadow immediately adjacent to it has been dubbed Doghouse Meadow. The maximum production of this well is between 127 and 137 L/min, and the volume of water pumped from the well is a direct function of the duration of pumping. During the summer, when water demands are high, pumping occurs for 8 to 12 hours during the night, and produces an approximate daily volume of 60,000 L to 99,000 L, which is used to fill a storage tank (J. Roche personal communication). However, the volume pumped varies daily, with larger volumes needed on weekends, as well as by the season, with the largest volumes needed in July and August, and very small volumes in winter.

The Doghouse pumping well was installed in 1984 and has been the sole source of water for all users in the Crane Flat area since that time. It is 122 m deep, with the upper 15 m of the drill hole sealed with a solid steel casing packed with sand, while the bottom 107 m of drill hole was left open. The upper casing was installed to create a sanitary seal that would prevent surface and near surface groundwater from leaking into the well casing. The pump was installed into the well hole with its intake at 98 m depth (Crews and Abbott 2005b).

Increases in visitor use of the Crane Flat area over the past 20 years, and a proposed expansion of the Yosemite Institute Environmental Education Campus, have led to a proposal to increase the amount of water pumped from the Doghouse well.

Yosemite National Park staff was concerned that increased water withdrawals might impact the wetlands in Crane Flat, and commissioned this study to determine: (1) whether the meadow hydrologic regime, soils and/or vegetation are influenced by existing well operations, (2) whether additional pumping could influence the hydrologic regime, soils or vegetation of the meadow, and once it was learned that Doghouse Meadow contained a fen, (3) whether fens were common or rare in the area of the Tioga Pass Road, and what water levels, soils and vegetation occurs in fens in the region.

## Study area

Crane Flat is located in the west-central portion of Yosemite National Park, at 1890 m elevation. The uplands are covered with conifer forests dominated by white fir (*Abies concolor*), sugar pine (*Pinus lambertiana*), and lodgepole pine (*Pinus contorta*). The underlying bedrock in the watershed is primarily igneous intrusive rock Arch Rock Granodiorite and El Capitan Granite with a ridge of metamorphic rock, the Pilot Ridge Quartzite, to the northwest. The Tioga Pass Road (US Highway 120) bisects Crane Flat Meadow. The meadow area to the southwest of the road, which contains the pumping well, is Doghouse Meadow, while the meadow northeast of the road retains the name Crane Flat Meadow. A small meadow adjacent to the YI campus is referred to as the YI Meadow. The Doghouse Meadow is 6.53 ha in area, Crane Flat Meadow is 12.73 ha, and YI Meadow is 1.26 ha.

We chose two meadows, Drosera and Mono Meadows, located at similar elevations to Crane Flat as reference sites to analyze the hydrologic regime and vegetation of undisturbed fens. Drosera Meadow is 3.79 km northeast of Doghouse Meadow, just south of the Tioga Pass Road, at 2070 m elevation, and 7.03 ha in area. Mono Meadow is south of Yosemite Valley, 21.6 km southeast of Crane Flat, at 2080 m elevation, and 5.69 ha in area. Neither meadow has evidence of significant human impacts to their hydrologic regime, or vegetation.

To determine whether fens similar to Doghouse Meadow are common in the area, we analyzed the corridor within 1 km of a 38.61 km section of the Tioga Pass Road from Crane Flat to Porcupine Flat (at 2440 m elevation) to identify all meadows and determined whether or not they were fens. Meadows were first identified on natural color aerial photos and visited in the field during 2005.

# Methods

We analyzed the meadow hydrologic regime, soils and/or vegetation throughout Doghouse and Crane Flat Meadows. At nine sites within Doghouse Meadow, along three parallel transects, we installed nested instruments, with one ground water monitoring well, and two or three piezometers, during the period 30 May through 1 June 2004.

Monitoring wells were created from hand augered holes. When boring the monitoring well holes we made certain not to auger through confining or low permeability mineral soil layers, so that the well reflected the water table that was in equilibrium with atmospheric pressure. Once bored, the open hole was bailed for one or more hours to remove all fine suspended material, and until clean water came from the hole. We then installed 2" diameter fully slotted Schedule 40 PVC pipe, capped on the bottom, backfilled with native soils, and sealed the hole with fine-grained mineral sediment.

Piezometers were constructed by slipping a ½ inch diameter steel rod into ½ inch inside diameter unslotted PVC pipe. The rod extended past the PVC end by ~2 cm, and at the top end was held in place with vice grips. Holding the vice grips, the rod and PVC were pushed into the soil to the desired depth. The rod was then pulled out and the vice grips removed. To install piezometers into the gravel, we pushed the rod to the gravel horizon, and then pounded on the rod end with a heavy rock, until the rod end was 20-50 cm into the gravel. Some piezometers were constructed from ½ inch inside diameter metal conduit pipe, which is thinner than PVC pipe, and was used for piezometers installed to greater depths in the gravel. In addition, 6 steel drive-point piezometers were installed in the Doghouse Meadow with the bottom of the screened section 190 to 640 cm below the ground surface. The steel drive point was attached to a 38 cm long screened section of 1.25" diameter schedule 80 steel pipe. Sections of 1.25" schedule 80 steel pipe were coupled onto the drive point, a drive cap was placed on the opposite end to protect the pipe and threads, and the point and pipe were driven down into the ground by hand using a fence post pounder.

In sites with a surface peat layer thicker than 40 cm, the monitoring well was within the peat body. We also installed one piezometer near the base of the peat body, and another in the underlying coarse gravel. In sites with mineral soil, we placed a monitoring well in the meadow soil, above any possible confining layers, a piezometer whose bottom was near the bottom of the meadow soil, and another piezometer within the sand/gravel.

We logged the soil characteristics from the ground surface to at least 1.5 m depth, or the depth at which the coarse gravel layer was encountered. Seven of the nine sites near the Doghouse Well had a surface layer of peat that was 9 to 140 cm thick, underlain by mineral soils. The other two sites lacked peat. Mineral soils directly underlying the peat were fine grained, with sand to silt and some clay, and graded to coarse sand and gravel with increasing depth. Sites without thick peat deposits had loam to silt mineral soils, also grading to sand and gravel at depth.

At six other sites in Doghouse Meadow, we installed a nest of instruments consisting of one fully slotted groundwater monitoring well and one piezometer. Six of these seven sites had a surface layer of peat, which varied from 26 cm to 131 cm thick, underlain by mineral soils. The wells were installed as described above, and one piezometer was placed into the underlying sand/gravel. A total of 57 wells and piezometers were installed into Doghouse Meadow. Each well or piezometer was given a unique number, and each nest was assigned a letter. For nests within the three parallel transects a letter-number combination was assigned, with the letter corresponding to transect and the number to the nest within the transect (Appendix A, Figure 1, 2, and 3).

Two instrument nests were placed in the reference meadows, Drosera and Mono. Several wells were also placed in Crane Flat Meadow and the YI Meadow to monitor their water levels.

Five wells were installed on the edge of the Crane Flat Meadow by a drill rig fitted with a hollow-stem auger. These wells were used to monitor deeper water tables in the uplands adjacent to the study wetlands. Bore holes were drilled to a depth 3-4 m below the water table. This resulted in a range of depths for the five rig-augered wells of

5.6 to 13.6 m deep. Fully slotted 2" diameter schedule 40 PVC pipe was placed in each bore hole, and the holes were back-filled with the drill cuttings.

The water level in the wells and piezometers were measured by hand approximately weekly during the snow-free season. Additionally, several wells and deep piezometers were instrumented with logging pressure transducers (Global Water GL-15) that recorded the water level at fixed time intervals of 5, 30, or 60 minutes, depending on the season and application.

We analyzed the vegetation in a 1 m radius circular plot around each well nest in the Doghouse Meadow, Drosera Meadow, and Mono Meadow, using the monitoring well as the center point. In each plot a complete list of vascular plants and bryophytes was made, and the canopy coverage, by species, was estimated visually.

An infrared gas analyzer (IRGA) was used to determine the gross primary production (GPP) and respiration (R) rates of the Doghouse Meadow soils and plants for one date in July 2004. From these values we calculated a net ecosystem exchange (NEE) rate of carbon, which indicates whether the peatland was gaining or losing carbon on that day as an indicator of peatland functioning during the summer of 2005. These measurements were made by Dr. Rodney Chimner (Michigan Technology University, Houghton, MI).

We collected water samples for stable oxygen isotope analysis from the monitoring wells after first bailing each well until dry at least three times. Water was also collected from the Doghouse pumping well, and the natural springs at the top of the west arm of Doghouse Meadow. The samples were stored frozen in HDPE airtight bottles and analyzed immediately at a lab at Colorado State University. The ratio of $\delta^{18}O$ to $\delta^{16}O$ was determined by mass spectroscopy. We calculated the isotope ration relative to that of a standard, Standard Mean Ocean Water (SMOW), as:

$\delta^{18}O$ (‰) = [($^{18}O/^{16}O$) sample / ($^{18}O/^{16}O$) standard]-1 x 1000.

We also used the following regression equation to calculate corrected $\delta^{18}O$ values: 'corrected $\delta^{18}O$' = ('$^{18}O$ offset' * 0.9906) - 6.315

All instruments, including the Doghouse well, and the ground surface were surveyed for location and elevation using a TOPCON® total station. The detailed spatial data was used to assign 3-dimensional information to water-level data, make accurate site maps, develop water table elevations for cross-sections near the Doghouse, and will be used in larger scale groundwater models.

Precipitation and snow-water-equivalent data, recorded at the Gin Flat weather station ~ 4 km northeast of Doghouse Meadow at 2150 m elevation, was obtained from the California Department of Water Resources (http://cdec.water.ca.gov/cgi-progs/queryFx?GIN).

# Results

Soils

The fen area of Doghouse Meadow, where the peat body is at least 40 cm thick, is ~280 m long, 20 m wide and 0.488 ha in area (Figure 2). The maximum peat thickness at our monitoring well holes was 140 cm at nest A-2, well 1 (Appendix A). Crane Flat Meadow contains some peat layers up to 27 cm thick, but we did not find 40 cm of peat in any location. We also found no peat in the YI meadow. The peat body in Doghouse Meadow appears to be oxidizing and subsiding. This is noticeable on the fen margin near the pumping well where bare peat occurs, and the surface in much of the fen is uneven and hummocked. Pocket gophers and other small mammals use the meadow for at least part of the year when the water table is well below the soil surface, and have cut burrows, and destroyed the peat structure in the fen center, near well nest G.

The two reference meadows, Drosera and Mono, contain extensive and thick peat bodies that were greater than 96 and 70 cm thick, respectively. The auger holes were not deep enough to reach the bottom of the peat layer at Drosera, so only a minimum peat thickness is known.

Hydrology

The maximum snow water equivalent (SWE) at the Gin Flat weather station was very different in water year 2004 (Oct 2003 – Sept 2004) and 2005 (Oct 2004 – Sept 2005). On 8 March 2004 the snowpack reached an annual maximum SWE of 71.9 cm, which is 83% of the 1981-to-present April 1$^{st}$ average of 86.9 cm. In 2005, the snowpack reached its maximum SWE of 107.5 cm on April 12th, which was 124% of the long-term average. This difference in quantity of SWE and the later melt-out led to a large difference in ground water recharge and much greater rates of ground water flow to Doghouse Meadow through the entire summer of 2005. During the summer of 2004 the ground water table declined ~100 cm from mid-June to late-September, while in 2005 water levels declined less than 50 cm (Figure 4 and 5, Appendix B). Although the summer water table decline in Crane Flat was smaller in 2005 than in 2004, a decline occurred in all Doghouse Meadow wells. During 2005 ground water levels in Drosera and Mono Meadow remained within a few cm of the soils surface from June through late September (Figure 6).

The water sources for Doghouse Meadow likely include surface and ground water flow from Crane Flat Meadow, as well as surface and ground water flow from the western arm springs. The peat body occurs where these two flow paths intersect, which likely produces an upward flow of ground water. At most well/piezometer nests the head in piezometers is higher at most or all times than the water level in monitoring wells, indicating an upward flow from the gravel aquifer into the peat body (see well hydrographs in Appendix B and cross sections in Appendix C).

The water table in Doghouse Meadow responded rapidly to precipitation events. The clearest example was the ~1 m water table rise in one day during and following October 16th, 2004 when 10.8 cm of precipitation (rain and snow) fell at Gin Flat (Figure 5). The only significant rainfall to occur between early June and early October in either 2004 or 2005 was a 3.0 cm event on June 30th, 2004, which produced a 10 to 20 cm water table rise, and the elevated water table from this rain event lasted for more than 6 days.

Water levels in Doghouse Meadow changed on a daily basis, with a sharp decline each night beginning around midnight, and continuing for several hours, before rising just as sharply to near the previous day's height each morning. This pattern of decline and rise corresponded exactly with the timing of the daily start-up and shut-off of the Doghouse pumping well. Pumping occurs through the winter as well, but for short duration, and a water table decline occurred daily, but the drawdown was short lived.

On June 18th, 2004, the Crane Flat campground opened for the season, and the demand for water increased dramatically from winter use. The Doghouse pump began operating for more hours each night thereafter until the campground closed on October 11th, 2004. The initiation of this longer duration pumping schedule is evident in the well 49 hydrograph, which shows a much longer drawdown period, and the initiation of a rapid decline in the deepest daily water level, and a steady decline in the maximum (highest) daily water level, after June 18th, as compared to previous nights (red arrow, Figure 7). As the pump is turned on each evening, water levels in wells and piezometers dropped rapidly. When the pump was turned off, the water levels recovered just as rapidly, but not to their former height. In early summer, a second smaller water level drawdown of ~2 cm occurred each afternoon, which likely is due to evapotranspiration (blue arrow on Figure 7), or other processes, but it is minor compared to the pumping well effects.

The pumping schedule from the Doghouse well reveals that nights with longer duration pumping produce deeper and more sustained water level declines than nights with shorter duration pumping. For example, long duration pumping on August 29-30, and Sept 11 produced deep draw-downs. Nights with short duration or no pumping resulted in a water level recovery, for example August 16-17 and September 14-15 (Figure 8). These effects are apparent in wells close to the Doghouse pumping well but are less detectable in wells more than 90 m away from the pumping well.

A logarithmic curve fit to the water table depth on the morning of July 8th, 2004, as a function of distance from the Doghouse explained 44.7% of the variability in the data (Figure 9). Wells close to the Doghouse experience greater daily fluctuations than did wells farther away. Exponential curves fit to the daily fluctuation in water level vs. distance from the Doghouse well, explained over 96% of the variability in the data (Figure 10).

The pumping-induced water table drawdown in Doghouse Meadow caused the entire peat body to dry out in 2004, producing aerobic soil conditions. Nearly the entire peat body crossed by transect A was above the water table on August 9th 2004 and the water level dropped below the peat body in most sites, while in 2005 water levels remained within the peat body (Appendix B). During all but the wettest periods, at least some of the upper soil layers and westernmost portions of the peat body on transect A are above the water table (Appendix C).

Carbon Gas Flux

The carbon flux analysis indicated that the Doghouse Meadow fen has a net loss of carbon due to high decomposition rates. The gross primary production (GPP) at Doghouse Meadow is lower than at Drosera Meadow and other Sierra fens we analyzed, while the respiration (R) rate is higher. Low GPP and high R result in a negative net ecosystem exchange (NEE) rate. This means that more carbon is being released from the fen than is being stored, thus Doghouse Meadow peat body is decomposing faster than it is being formed (Figure 11). An annual carbon budget would provide more detailed information on how much C is being lost from the Doghouse fen. It is likely that much higher rates of respiration occur in the early summer as water tables are just starting to be drawn down, and yet the soils are still moist. Once the water table is drawn down, and the soils dry, respiration rates likely decline.

Meadow Vegetation

The water table change in Doghouse Meadow is triggering a shift in the composition of meadow vegetation. Fen and perennially wet meadow specialists such as *Oxypolis occidentalis, Drosera rotundifolia, Vaccinium uliginosum, Eleocharis pauciflora, Sphagnum subsecundum,* and *Carex scopulorum* are common in the reference meadows, but uncommon or absent in Doghouse Meadow and elsewhere in Crane Flat, where meadow generalists or dry meadow species such as *Potentilla gracilis, Veratrum californicum, Poa pratensis, Solidago canadensis,* and *Lupinus sp.* are common.

Analysis of the vegetation data and two hydrologic parameters, highest and lowest growing season water levels, using the direct gradient ordination technique canonical correspondence analysis (CCA), indicated that the reference meadow sites (wdr4 and w70) plot on the far left side of the ordination space, where plots with small summer water table declines occur. Several Doghouse Meadow plots in the area of deepest peat (w1, w10 and w14) are on the far right side of the ordination space, indicating that their lowest summer water table is very deep. The centroids of indicator plant species plotted on the figure indicates that fen specialist listed above are located on the left side of the ordination space, where water tables are high and stable, while dry meadow and generalist species are on the right, and occur in plots with deeper summer water tables (Figure 12).

The area of Doghouse Meadow with >40 cm of peat soil must have had suitable hydrologic conditions, similar to those occurring in the reference meadows, for thousands of years to accumulate up to 140 cm of peat. Their position in the ordination space far away from the reference fens indicates that the hydrologic regime and vegetation at these sites has shifted significantly from its historical natural range of variation.

Stable O isotope analysis of water sources

Our stable oxygen isotope data (Figure 13) indicates that piezometer water is slightly more depleted in $\delta^{18}O$ (more negative values) than water from monitoring wells within the peat body. This difference may be due to evaporative enrichment of water in the peat body. However the differences in isotopic signature between piezometer water, and monitoring water are very small and do not indicate multiple water sources. The groundwater emerging from the west arm spring complex have the most negative $\delta^{18}O$ values, indicating that it has not undergone evaporative fractionation (resulting in more enriched or more positive values), nor mixed with other waters. The isotopic signature of the pumping well water is intermediate between that of the west arm springs and the meadow groundwater, suggesting that the Doghouse well water is a mixture of the two sources.

Pump Tests of the Doghouse Meadow Aquifer

On September 19$^{th}$ and 20$^{th}$, 2005, contract drillers performed pump tests on the Doghouse Meadow well and the new YI production well. The YI production well is 122.5 m deep into fractured granite bedrock and was capable of producing a maximum yield of 35.0 L/min (Crews and Abbott 2005a). However, the contractor recommends not drawing the water level in the well down further than 30.5 m from the ground surface, which lowered the potential maximum yield to 22.7 L/min. They calculated a specific capacity (SC) for the fractured granite aquifer between 0.42 and 0.83 L/min per m of drawdown. These values are consistent with other fractured granite aquifers (Crews and Abbott 2005a).

The pump test performed at the Doghouse well included the use of a packer that isolated sections of the well to determine where major inflows of water occurred. The packer was placed at 27.7 m depth, separating the well into two disconnected sections, the upper part including the solid steel casing and the unconsolidated alluvium and till beneath the Doghouse Meadow, and the deeper fractured bedrock. The pump test was performed on the section below 27.7 m. Initial pump discharge from the lower section was 71.9 L/min, but dropped below 18.9 L/min after 5 minutes of pumping and was less than 11.4 L/min after 10 minutes. This rate of water yield did not change with continued pumping. During the pump tests of the section below 27.7 m, no water level response occurred in the hand-read ground water monitoring wells, 10, 51, and 56 (Crews and Abbott 2005b), or in the logger-instrumented wells, 49, 58, and 60 (Figure 14). The estimated specific capacity for the section of the Doghouse well below 27.7 m is 0.42 L/min per m of drawdown, consistent with the lower-end calculation made from the YI production well pump test.

The packer was then removed to perform a pump test on the fully open Doghouse well hole. Upon removal of the packer, water was heard cascading down the well hole. The open well hole is the condition under which normal daily pumping occurs. Pump discharge from the open well hole was a constant 100.0 L/min during 80 minutes of pumping. The water level in the Doghouse well dropped 7.3 m during the open-well pump test and recovered to within 3 cm of the initial level within 15 minutes. The water level in piezometer 51 dropped about 0.5 cm during the pump test, but the other hand-read wells, 10 and 56, did not respond (Crews and Abbott 2005b). The data logger in piezometer 49 recorded a ~8 cm drop in water level 4-5 minutes following each of the two packer deflations (Figure 14). Following the packer-deflation drop, the water level in piezometer 49 recovered slightly before dropping 10-20 cm in response to pumping from the open Doghouse well. Water levels rose once the pumping ceased. Two other wells with data loggers were much farther from the Doghouse than piezometer 49, and showed no response to the pump test (Figure 14).

Specific capacity for the entire depth of the open Doghouse well hole is calculated as 15.24 L/min per meter of drawdown. This value is approximately 20 times greater than the specific capacity calculated for the YI production well, and very much higher than expected for a fractured granite aquifer. During normal daily pumping, the vast majority of water pumped from the Doghouse well appears to be drawn from the upper portion of the well, above approximately 27.7 m in depth, which is above the fractured bedrock system in mostly decomposed granite (Crews and Abbott 2005b).

A second, impromptu, pump test occurred from 8 am October 17th, 2005 to 8 am October 20th. During this 72-hour time period the Doghouse pump was running at a constant rate of approximately 93.1 L/min, and a total of 402,102 L of water were pumped. The pump was then inactive for the next 98.5 hours, until October 24th at 10:30 am. Six data loggers were recording water levels in Doghouse Meadow, and one in Crane Flat Meadow, during this pump test and recovery. Only the four instruments closest to the Doghouse detected water level responses to the pump test, and the magnitude of the response was inversely related to the distance of the instrument from the Doghouse (Figure 15).

It should be remembered that this pump test was conducted during the summer of 2005 following a winter with a large snowpack. Water levels in Doghouse Meadow had remained relatively stable through the summer, and therefore it would not be expected that this pump test would produce large water level draw-downs in the meadow. Had this test been conducted in 2004, very different results would have been obtained.

Fens along the Tioga Pass Road Corridor

Ten of 31 meadows that occur within 1 km of the Tioga Pass Road between Crane Flat and Porcupine Flat were fens, including the reference site, Drosera Meadow and the study site, Doghouse Meadow. There are an additional four fens, or former fens, in the White Wolf vicinity that have been heavily impacted by ground water pumping. Six other meadows that were identified on aerial photographs but not visited were classified as likely fens due to their landscape position and appearance on the photos. The remaining 11 were classified as either wet or dry meadows, or judged to be no-fens from their appearance on the air photos (Figure 16).

# Discussion

Fens are uncommon in Yosemite National Park. Only 10 of 31 meadows visited along the Tioga Pass road had suitable hydrologic regimes to have resulted in the formation of a peat soil, and development of a fen ecosystem. These meadows are small, and constitute a tiny fraction of the Yosemite landscape, yet as the only perennially wet meadow environments they provide critical habitat for many species of plants, amphibians, small mammals, and birds, including the Great Gray Owl which were observed twice in fens (Mono and Drosera Meadows). Fen formation and persistence relies on the perennial flow of ground water into meadows, the maintenance of saturated soils through the summer, and the support of clonal plants that produce an abundance of below ground biomass. Our carbon flux analyses, conducted during a short period in August 2004, indicate that Doghouse Meadow is losing more carbon than any other site investigated, including a very heavily grazed meadow in the Sierra National Forest, Glen Fen. The rate of carbon loss from Doghouse Meadow is approximately equal to the rate of carbon gain at Drosera Meadow. How these numbers would vary over an entire year and through wet and dry years is unknown.

In addition to the increased organic matter decomposition rates, the dryer conditions have allowed Doghouse Meadow to become suitable habitat for small mammals, including pocket gophers and voles that burrow through soils, eat below ground plant structures, and have caused extensive damage to parts of the meadow. Their digging and disturbance exposes peat to more rapid rates of oxidation than were measured by our carbon flux studies. The small mammals have also exposed peat allowing it to dry out, and created habitat for plants exotic to the meadow, such as Kentucky bluegrass (*Poa pratensis*).

Ground water pumping at Doghouse Meadow is directly linked to daily and seasonal ground water level declines in Doghouse Meadow. Daily water level changes, particularly in 2004, exactly match the timing of pumping cycles. The rapid daily drawdown of the water table was nearly equally matched by water table rise when the pumps were shut off, indicating that sufficient ground water inflow to the meadow was occurring to maintain the water table near the soil surface, even during 2004. The stable oxygen isotope signature of pumped water indicates that it is a blend of water flowing from Crane Flat Meadow and water from the west arm springs, which discharge from the igneous-metamorphic rock contact. Sites with ground water flow path convergence often produce zones of ground water upwelling, and are the location of fen formation. Hence, the location of this pumping well intercepts both flow paths, and interrupts the hydrologic processes that allowed the fen to form. Because this location has a regional concentration of ground water flow, and pumping rates are low in the spring, Doghouse Meadow is at least seasonally saturated, which up to the present has precluded the invasion of this meadow by lodgepole pine trees. However, the meadow vegetation is different from other fens in the region, and some of these differences may be due to the pumping. For example, it is unknown whether *Sphagnum* or *Drosera rotundifolia* once occurred in Doghouse Meadow. However, it is likely that *Veratrum californicum*, and *Poa pratensis* did not occur historically, and *Deschampsia cespitosa* has greatly increased in the meadow as well.

## **Management Implications**

The pumping has shifted the Doghouse Meadow fen from a peat accumulating to a peat losing ecosystem. In the long-term all peat could be lost, and the system would become a wet meadow in the center, although dry meadow conditions could develop on the meadow margins, allowing the invasion of lodgepole pine. An even greater danger than short term changes are the effect of wildfire on the peat body. In a dry year, when the peat body dried out, a wildfire, or any type of burn could lead to the oxidation of much of the peat body. Once the peat is gone, the water holding capacity of the site would be greatly reduced.

There appear to be four options for water management that would influence wetland maintenance or restoration in Doghouse Meadow: (1) retain the current level of pumping, (2) terminate all pumping during the summer, (3) experiment with the duration of periods of pumping and no pumping, and (4) allow pumping only in summers following winters with a large snowpack. To maintain current human use and restore the meadow to a functioning condition, larger storage capacity tanks could be installed to store winter snowmelt water for summer use. If water use efficiency was improved in the campground, gas station, and YI, then the reduced water needs may be met with stored water.  However, tanks are expensive, and may not hold sufficient water to meet the demands of human users.  The installation of additional pumping wells near the YI may not have produced sufficient water to supply the existing or future needs of the YI.

Option 3 above may provide a management alternative where a modified pumping schedule, combined with larger storage capacity could provide for human and meadow water needs.  As shown in Figure 17, if water could be pumped for a longer period of time, such as several days in a row, the water table could be drawn down.  When water storage tanks are filled, the pumps could be turned off for a period that would allow the water table to recover to the soil surface, and re-saturate soils.  If the soils had sufficient water retention time, the saturation may retard organic matter decomposition processes.  A pumping scenario, shown in Figure 17, could be used between mid-June and mid-September on most years.  There would have to be considerable experimentation with this pumping scenario, and the duration of drawdown would vary by water year, with more pumping being possible in summers following larger snow years.  This approach would need a strong monitoring component.  If the soils alternatively wetted and dried, soil respiration rates might be higher than they would be if the soils were dried once.  Also, the wetting and drying could lead to higher nitrogen mineralization rates, producing a fertilizer effect, and further increasing decomposition rates.  These effects could be measured with a careful monitoring program that measured water levels, carbon gas flux, and nutrient availability.  Because of the ongoing need to provide water for domestic use, we recommend option 3, with experimentation on pumping rates and duration, and rest duration that will allow the water level to recover.  In addition, monitoring is essential to understand whether this produces a fertilizer effect, and produced the desired hydrologic effect of maintaining saturated soils in the upper soil horizons, and eliminates habitat for pocket gophers and voles.

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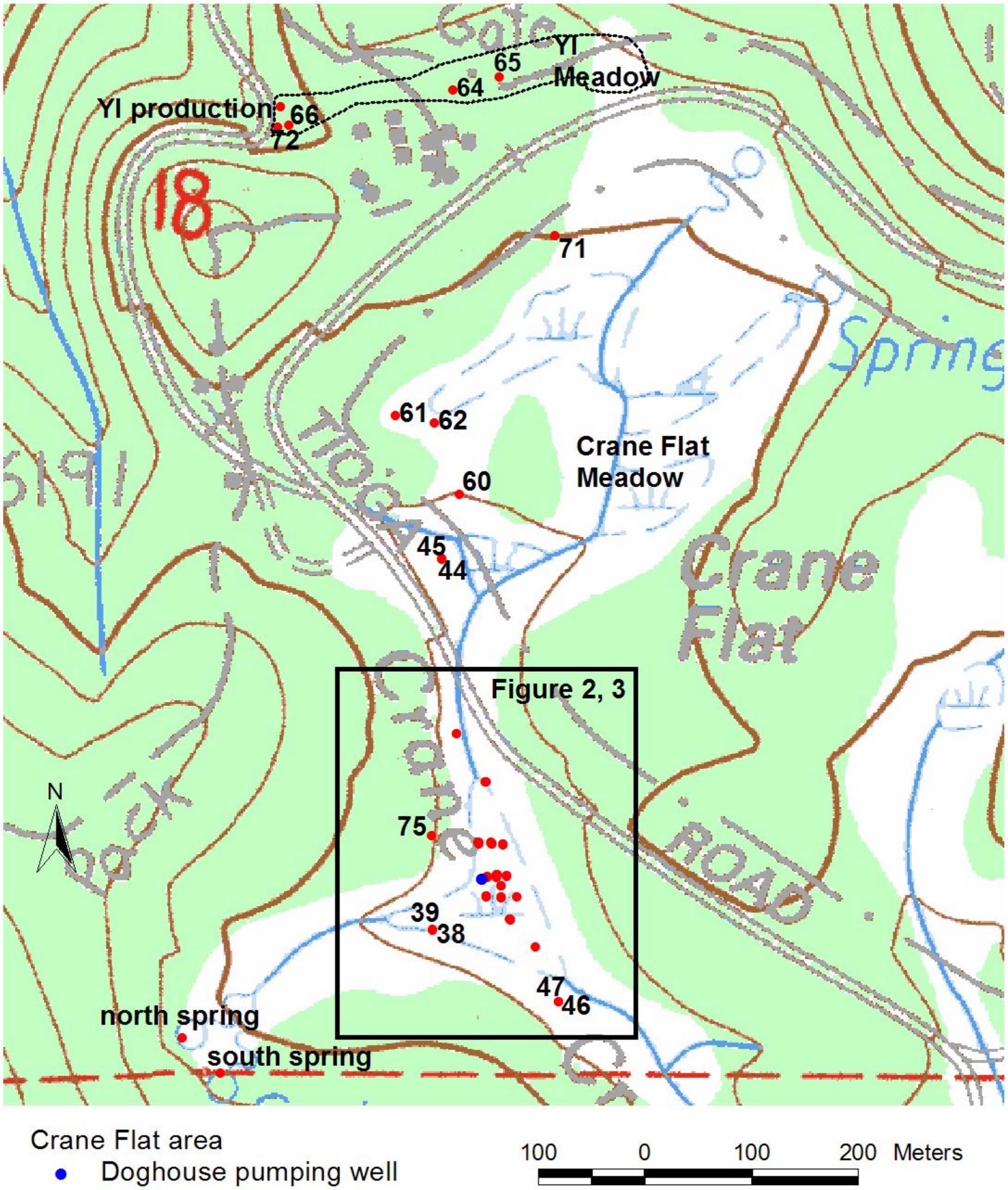



**Figure 1.** Overview of the Crane Flat area with the wells and springs outside the central Doghouse Meadow labeled. Base map is a USGS 7.5' series topographic quad with 40-foot (12.2 m) contours. The thick contour line that runs through the meadow areas is the 6200-foot (1889.8 m) line.

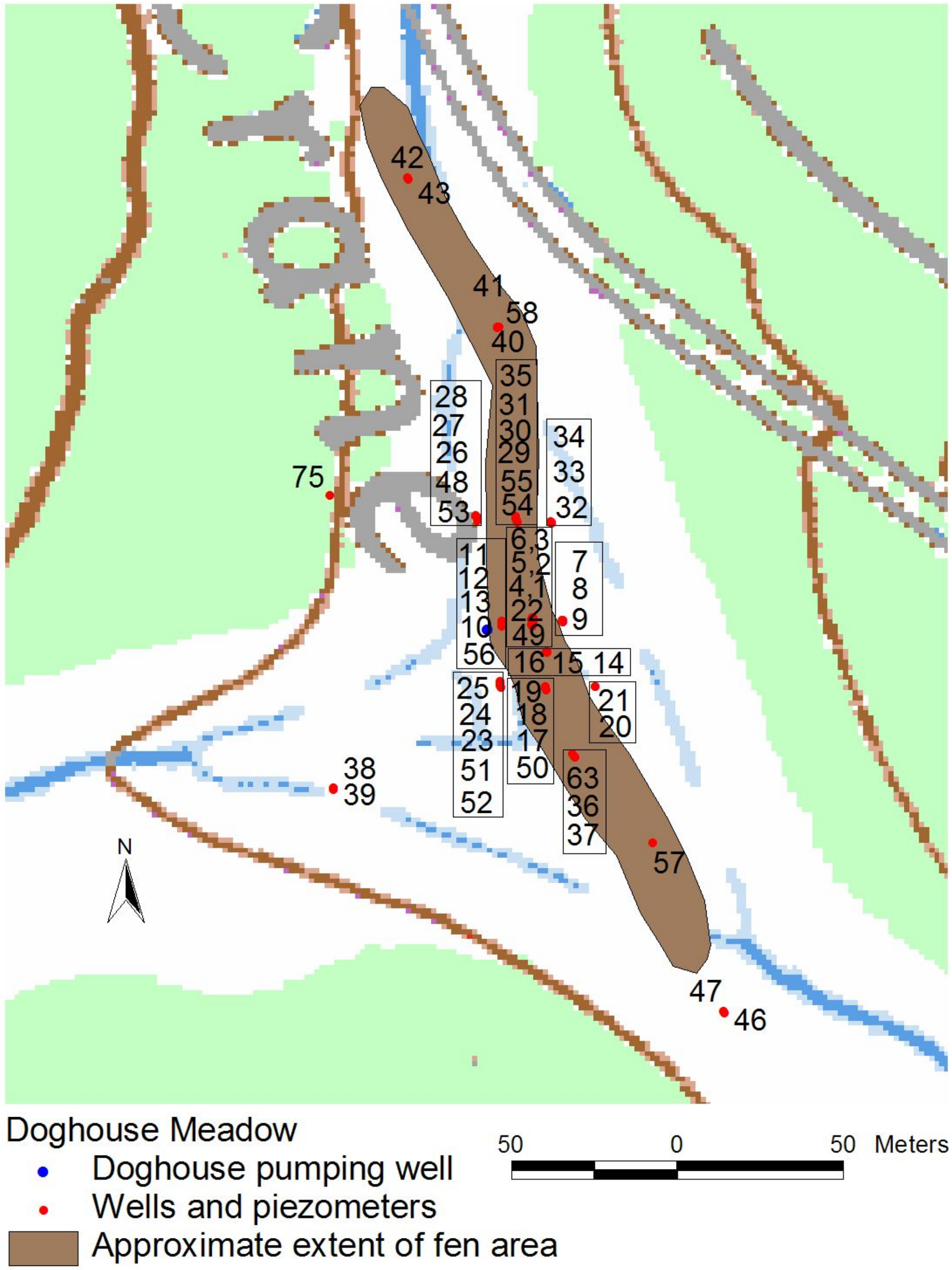



**Figure 2.** Close-up of the monitoring well and piezometer nests installed in Doghouse Meadow. Each box represents one nest, located at the red dot, and the well and piezometer numbers.

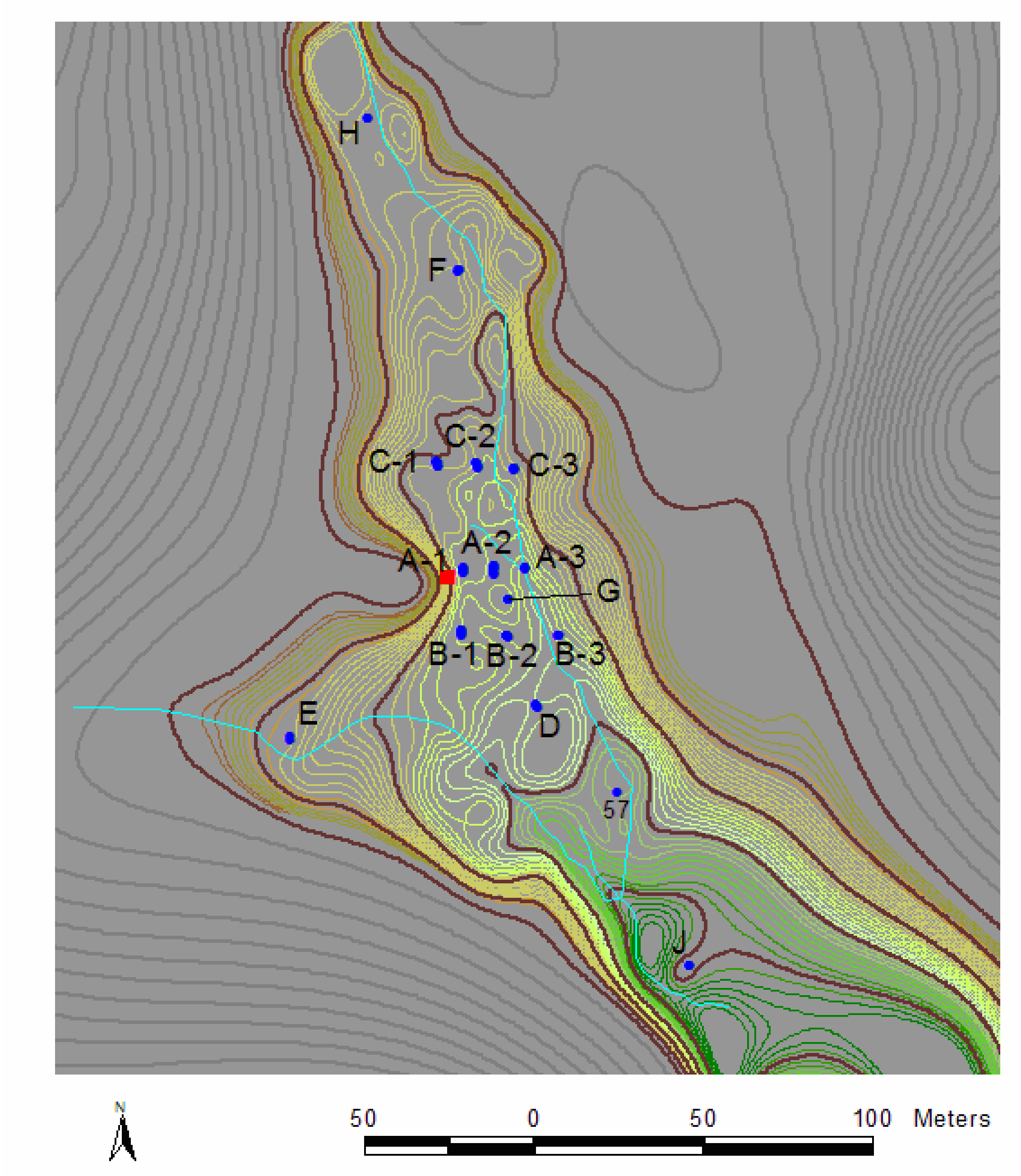



**Figure 3.** Topographic map of the Doghouse Meadow area created from a ground surface survey. Thick brown contour lines are at 1m intervals. Thin, color contours are at 10 cm intervals, grading from brown (higher) to green (lower). Blue dots are well and piezometer locations labeled by nest code. The red square is the Doghouse pumping well. The light blue lines are the major surface flow paths. Flow direction is from northwest to southeast.

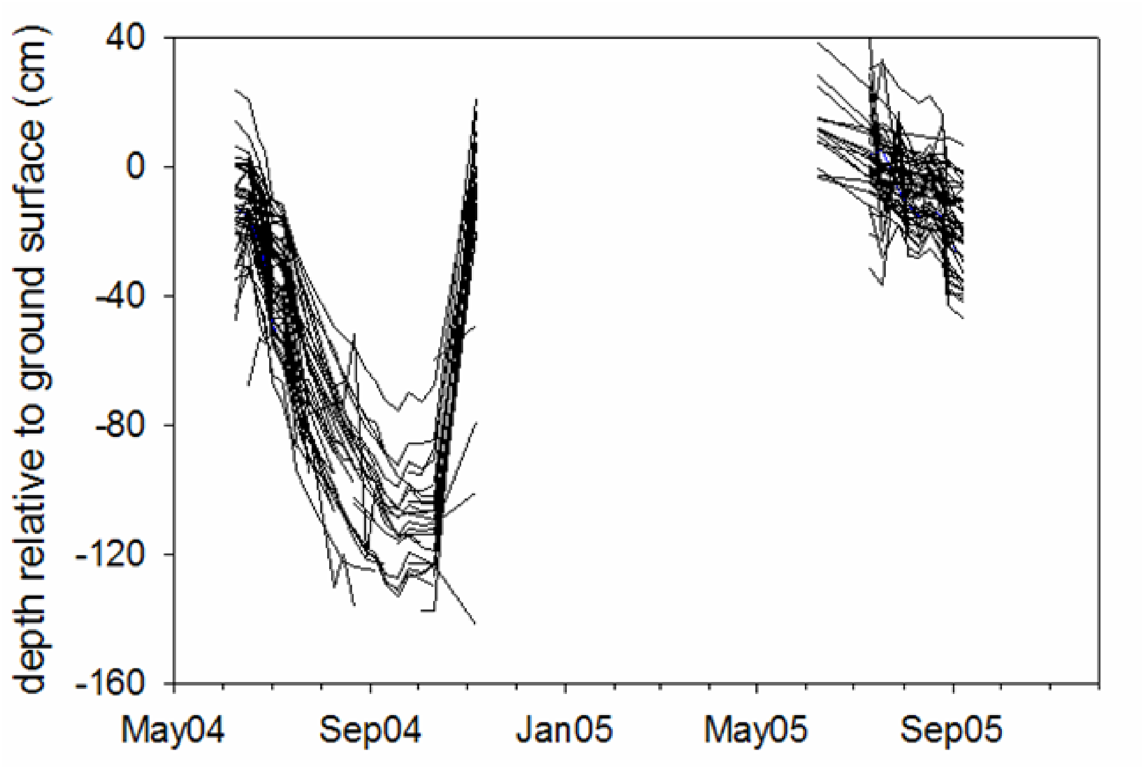



**Figure 4.** All hand-read water levels for instruments 1 through 55, measured during the snow-free seasons of 2004 and 2005.

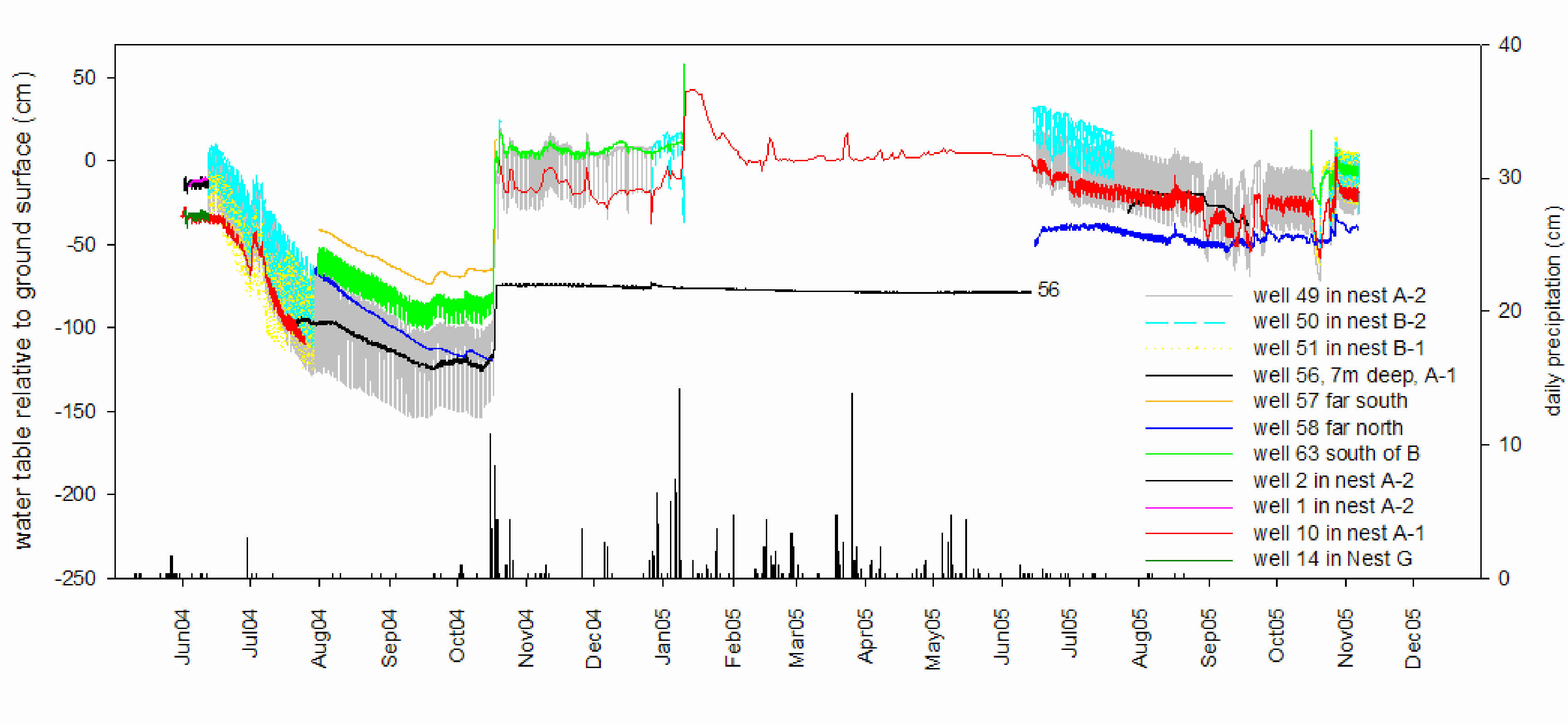



**Figure 5.** All water-level logger data (colored lines, left y-axis) and precipitation data (vertical bars, right y-axis) for Doghouse Meadow during 2004 and 2005. Gaps in water level data are due to movement of loggers to new wells, or removal for the winter.

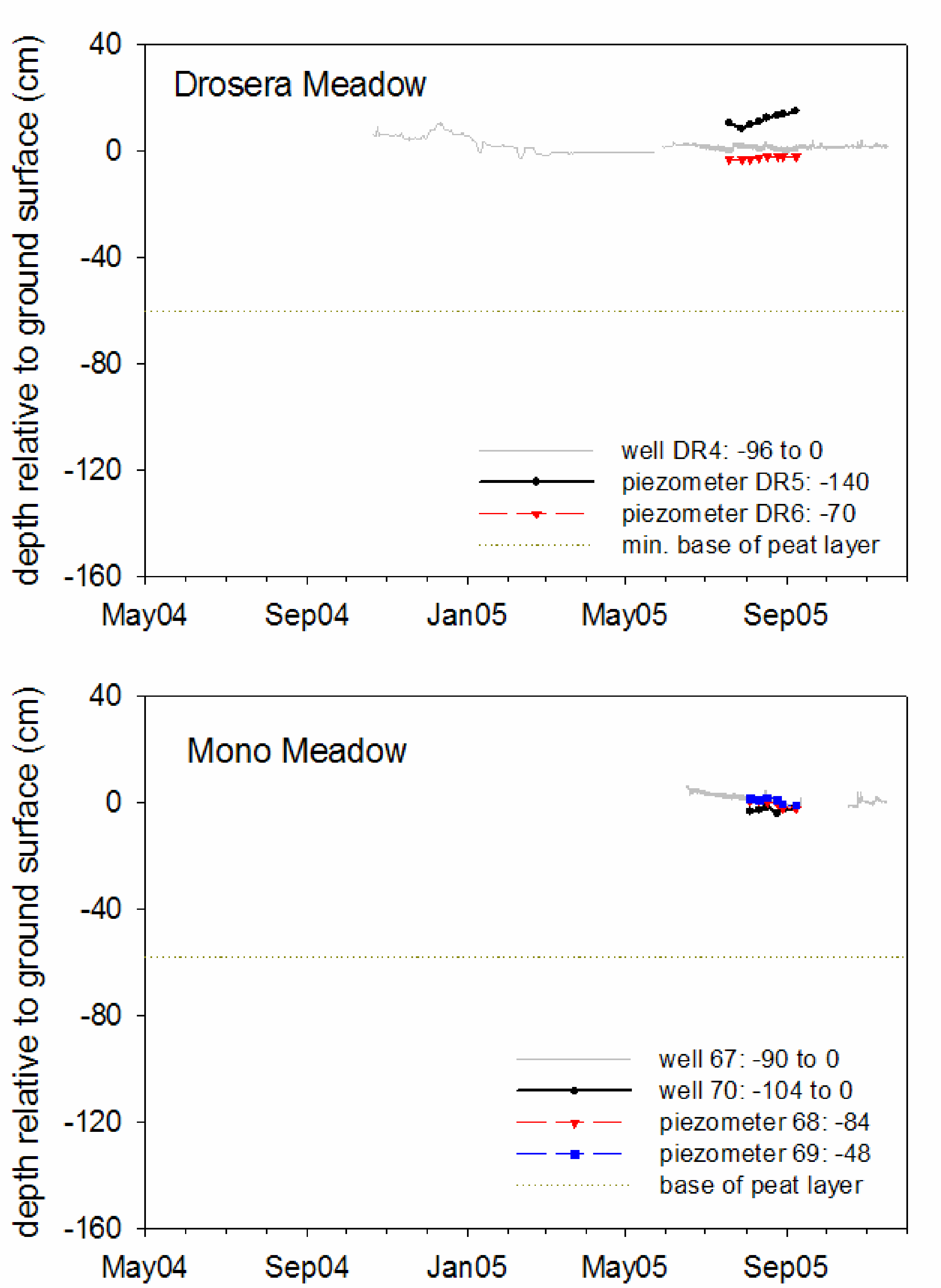



**Figure 6.** Hydrographs of the water table elevation relative the ground surface in the two reference meadows, Drosera and Mono.

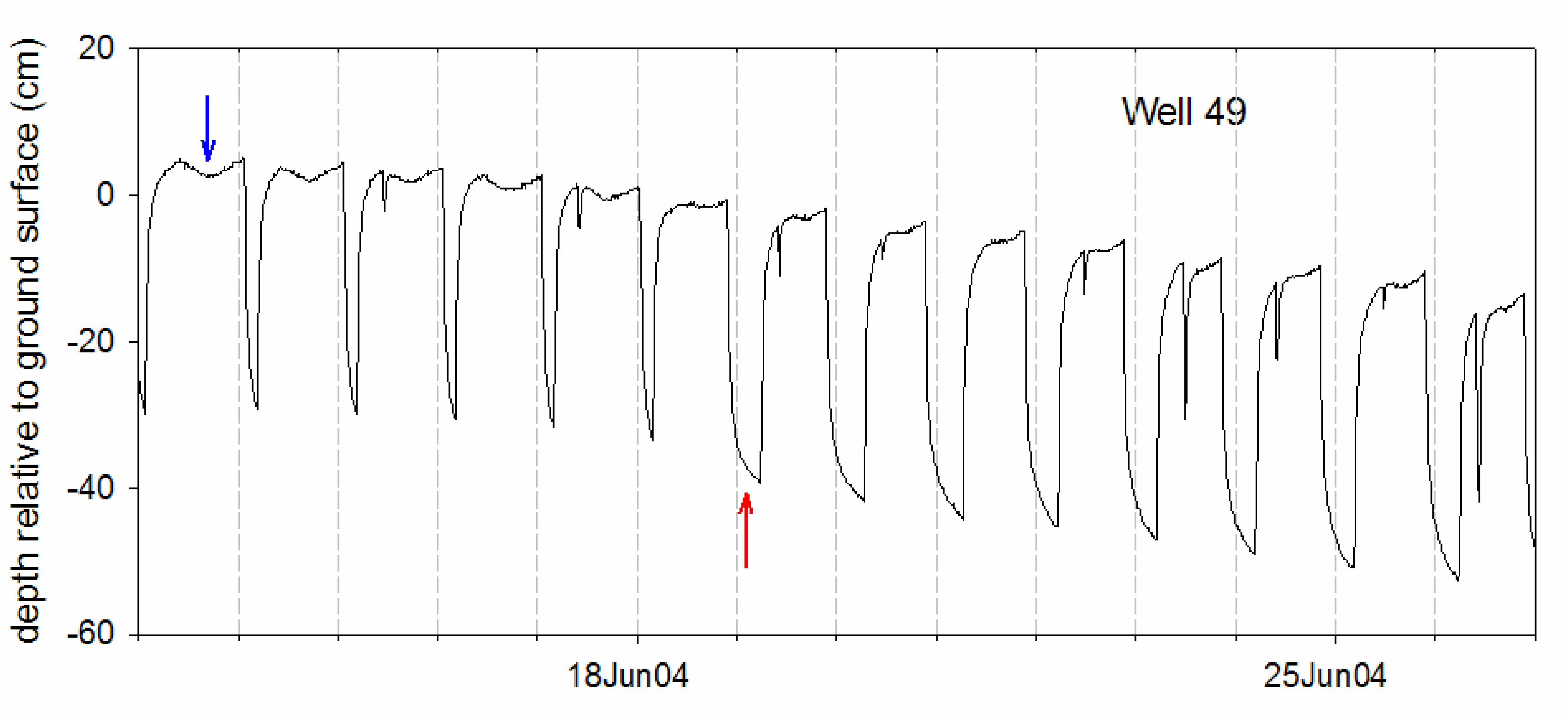



**Figure 7.** A portion of the bi-modal hydrograph from well 49 in Doghouse Meadow. The dashed grey lines are at midnight of each day shown. The blue arrow highlights a minor daytime drop in water level and the red arrow indicates the initiation of a longer duration in the major nighttime drop in water level following the opening of Crane Flat campground on June 18th.

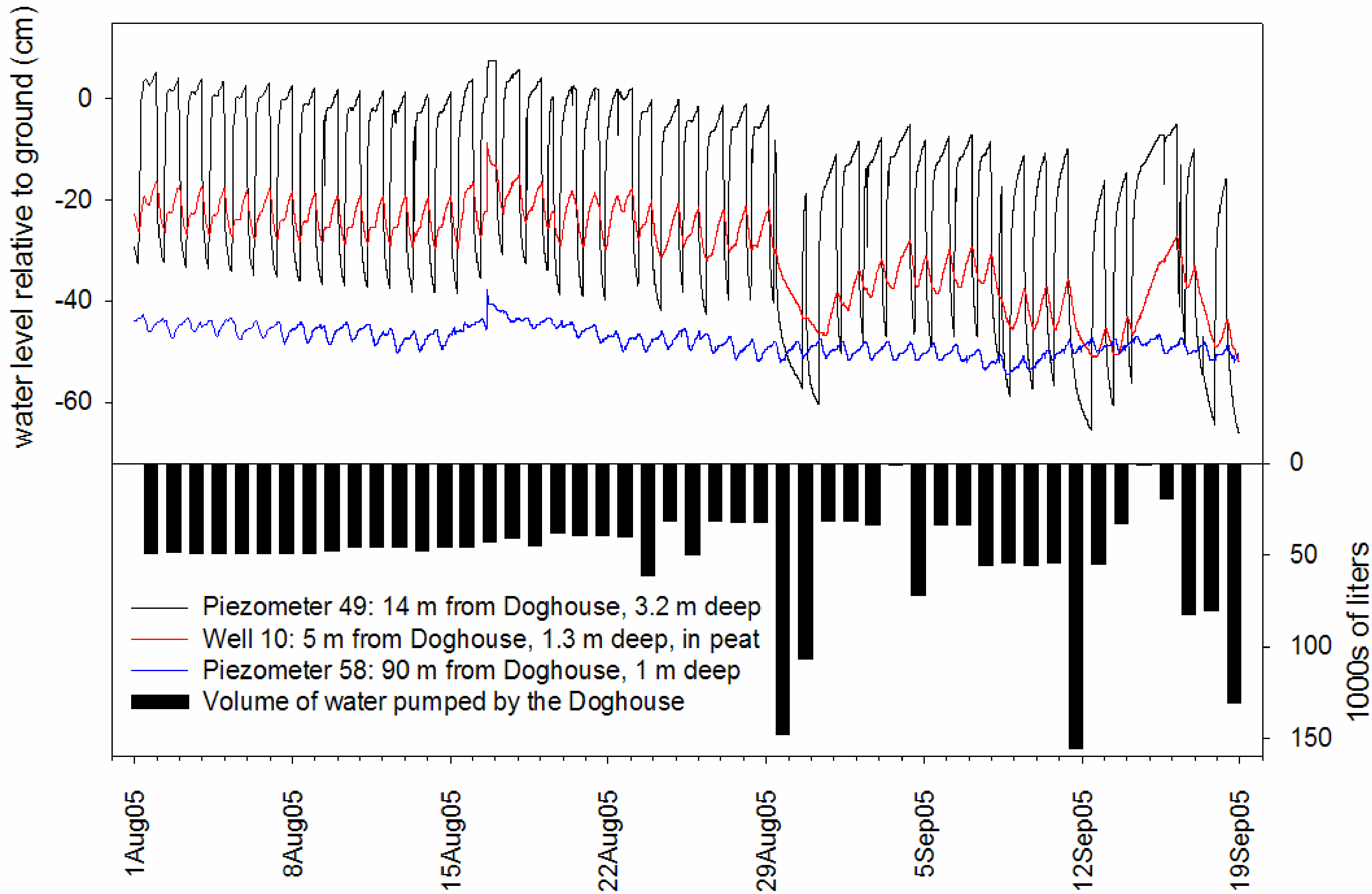



**Figure 8.** The pumping schedule for the Doghouse well (black bars) and the response of three wells (lines at top) located at different distances from the Doghouse and at various depths (see legend).

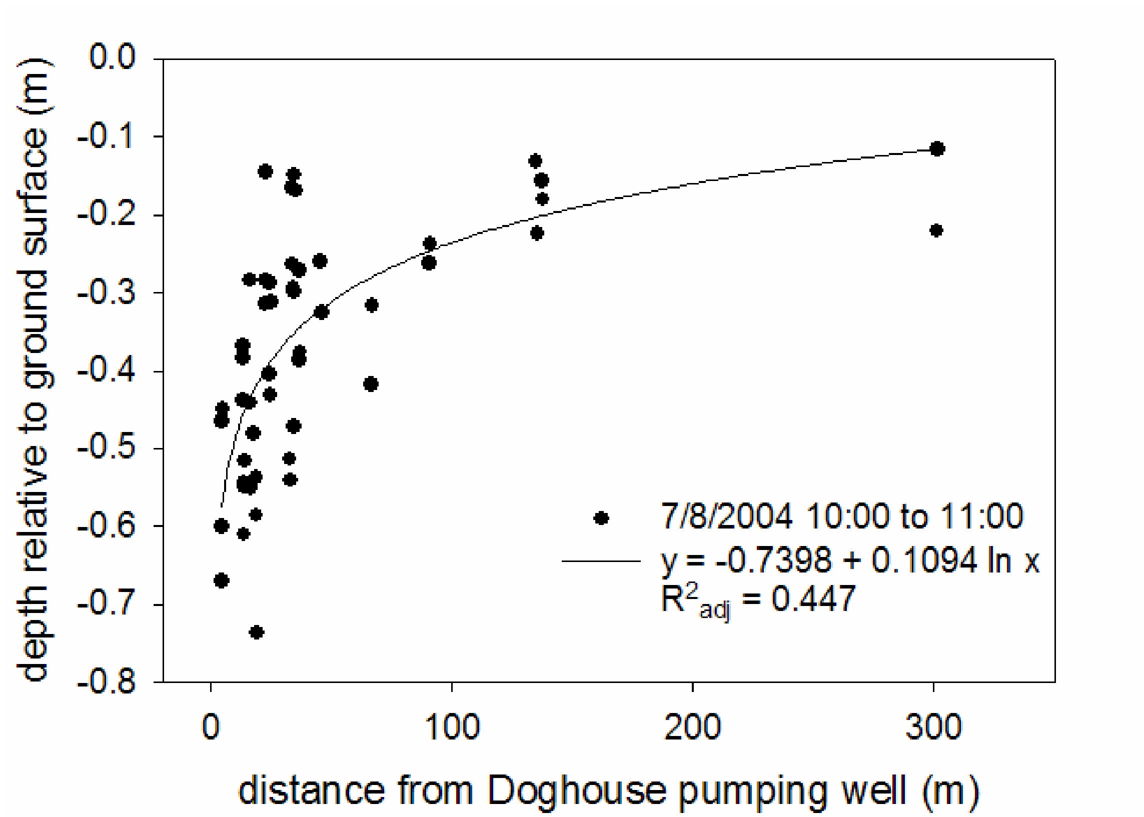



**Figure 9.** The water level of 49 hand-read wells on the morning of July 8th, 2004 as a function of distance from the Doghouse pumping well. A logarithmic function was fit to the data and the equation and correlation coefficient are shown in the legend.

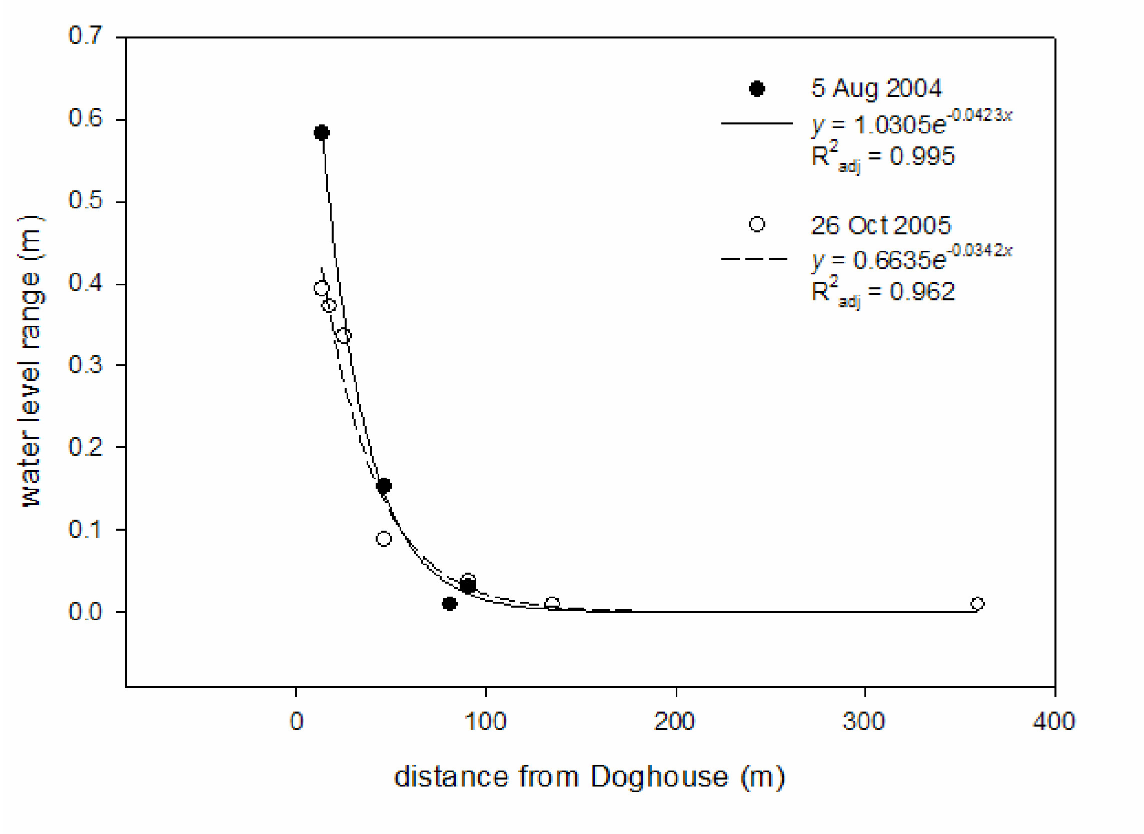



**Figure 10.** The range of daily water level in data-logged wells as a function of the distance from the Doghouse well. Each dot represents the difference between the minimum and maximum water levels in one well on the indicated day versus the distance of the well from the Doghouse. There were four wells with data loggers on 5 Aug 2004, and seven on 26 Oct 2005.

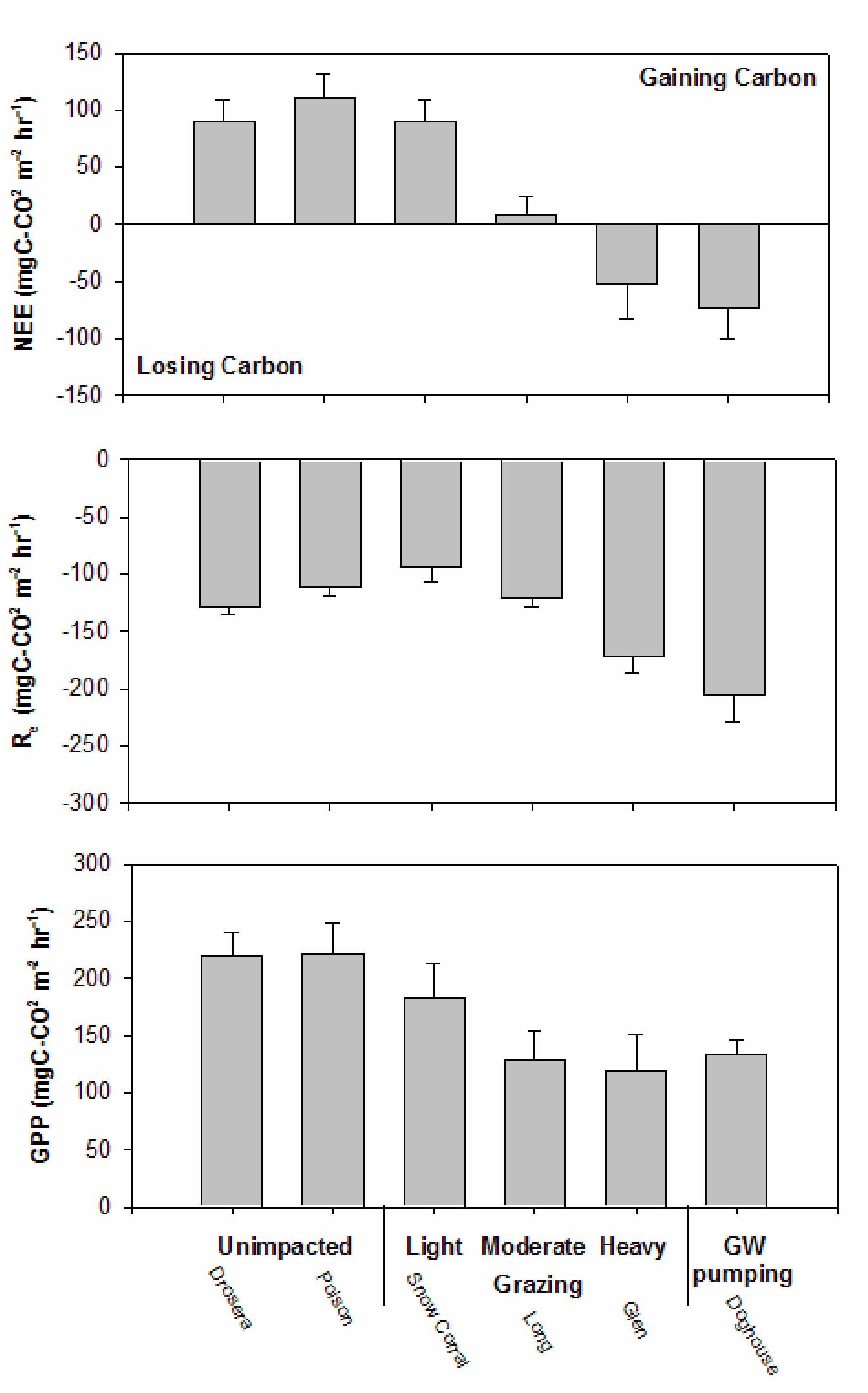



**Figure 11.** The net ecosystem exchange (NEE, top panel), which is calculated from the respiration (R, middle panel) and gross primary production (GPP, lower panel) rates measured on site, for Doghouse Meadow (far right), Drosera Meadow (far left) and several other Sierra fens in August 2004.

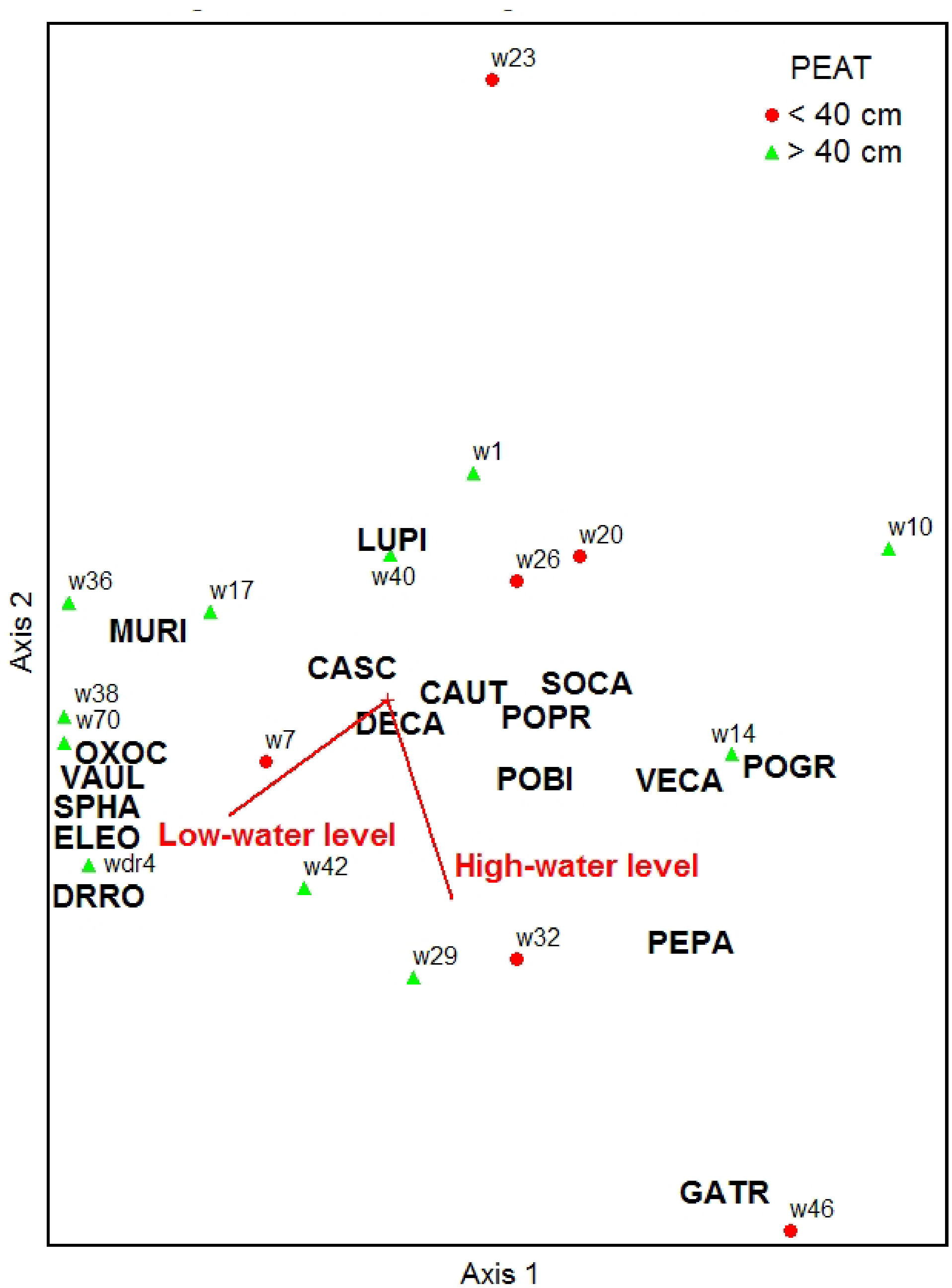



**Figure 12.** Canonical correspondence analysis of vegetation data for wells (symbols with labels starting with "w") and centroids of key species. Red points are wells with <40 cm of peat, while green point have >40 cm of peat. DRRO = *Drosera rotundifolia*, VAUL = *Vaccinim uliginosum*, OXOC = *Oxypolis occidentalis*, CASC = *Carex scopulorum*, LUPI = *Lupinus*, DECA = *Deschampsia caespitosa*, MURI = *Muhlenbergia rigens*, SPHA = *Sphagnum*, ELEO = *Eleocharis*, CAUT = *Carex utriculata*, SOCA = *Solidago canadensis*, POPR = *Poa pratensis*, POBI = *Polygonum bistortoides*, VECA = V*eratrum californicum*, POGR = *Potentilla gracilis*, PEPA = *Perideridia parishii,* GATR = *Galium trifolium*. Hydrologic gradients are shown by the vectors, with higher water elevations in the direction of the line moving away from the intersection, and lower water elevations in the opposite direction.

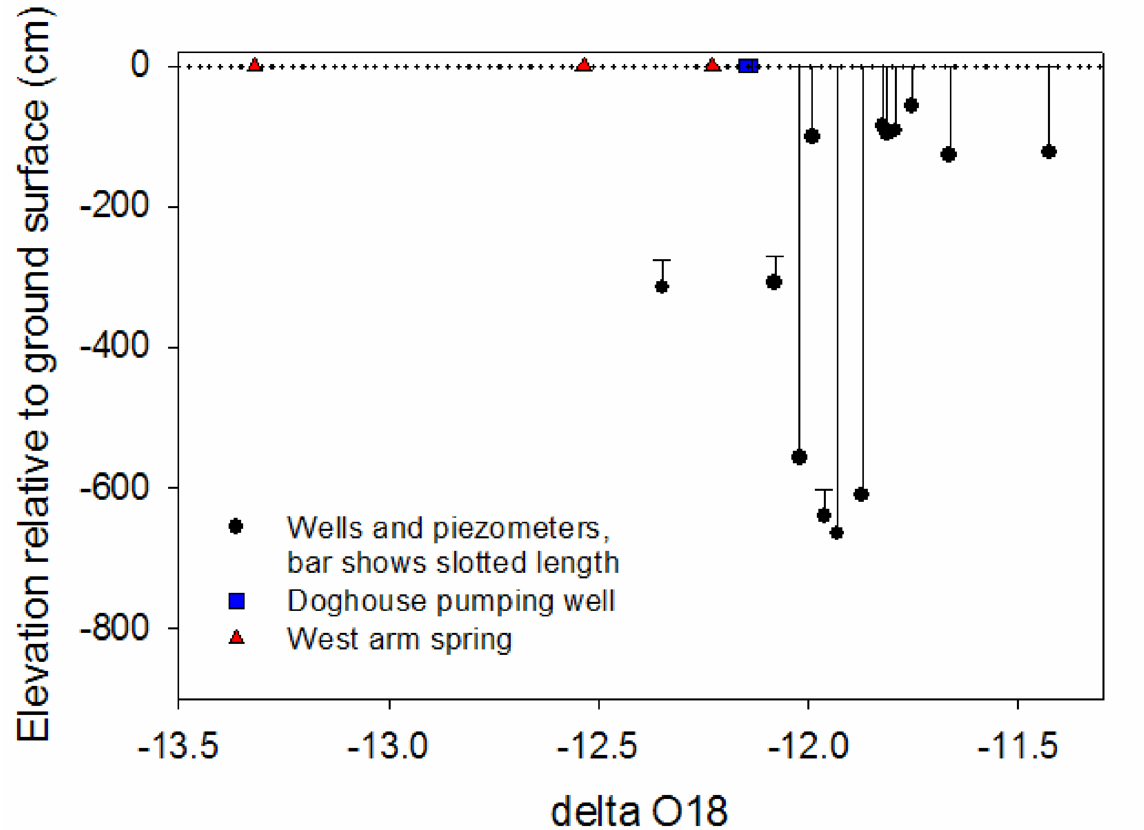



**Figure 13.** The ratio of O18 to O16 (delta O18) from different water sources at different depths for 2004. The less negative delta O18 values (to the right) are enriched in the heavier isotope, probably via evaporation of the lighter isotope.

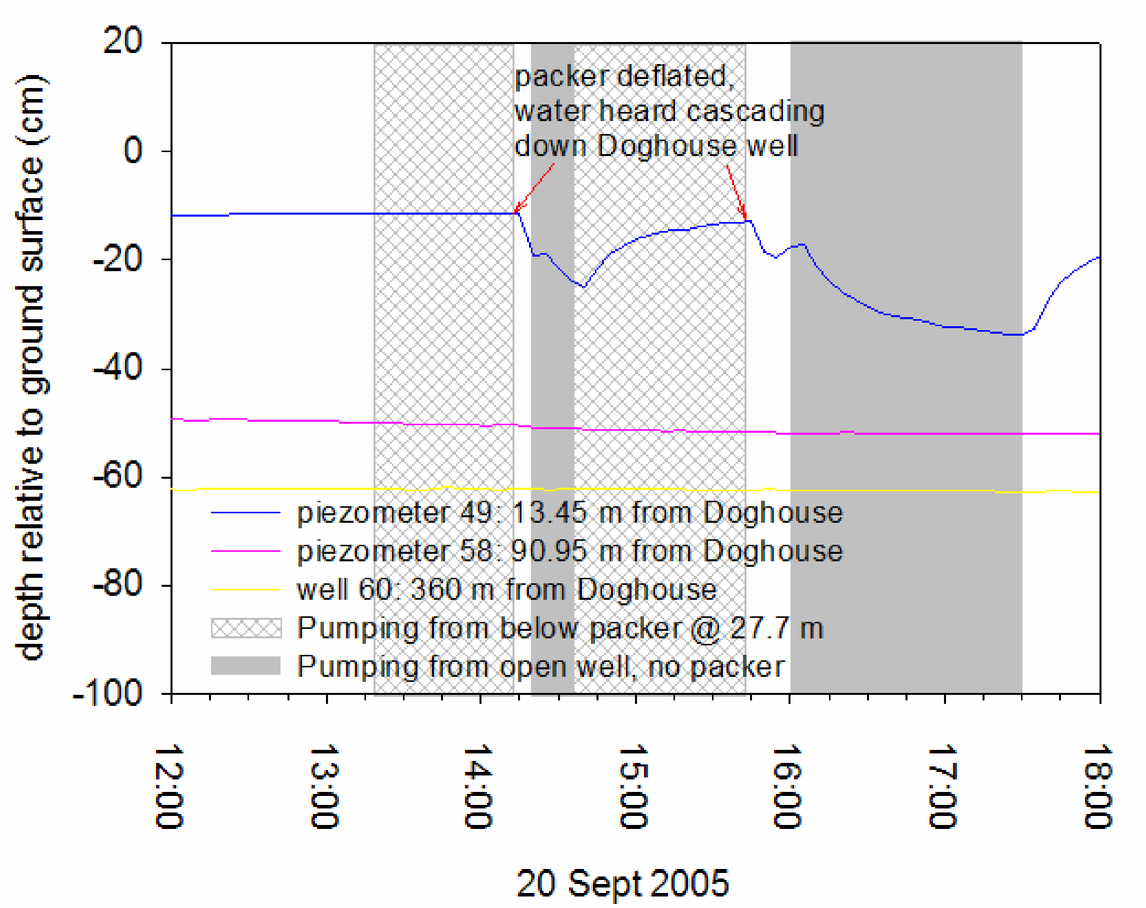



**Figure 14.** Results from a short-duration pump test in the Doghouse well. A packer was used to seal off the upper 27.7 m of the well, with pumping occurring below the packer, during the time periods shown in grey cross-hatching. The packer was deflated at the times indicated by the red arrows. Standard pumping, in the open well, occurred during the time periods shown in solid grey. No pumping occurred during time periods shown in white. The water level response in three instruments with data loggers is shown as colored lines.

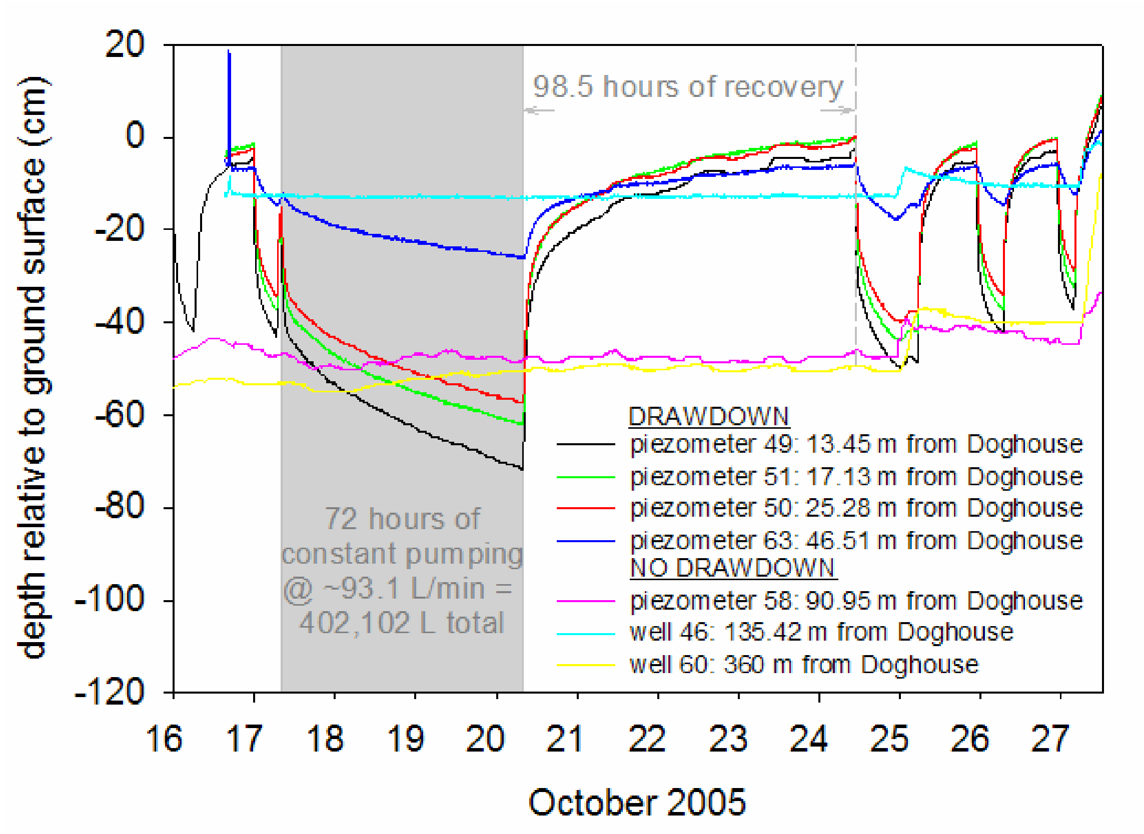



**Figure 15.** Continuous pumping during the 72 hour (three-day) period 17 Oct 2005 to 20 Oct 2005, followed by 98.5 hours of recovery. Water level drawdown and recovery are shown for seven wells and piezometers at different distances from the Doghouse pumping well. No drawdown was detected in the 3 wells furthest from the Doghouse, and drawdown magnitude was inversely related to distance from Doghouse in the 4 wells that did show a response to pumping.

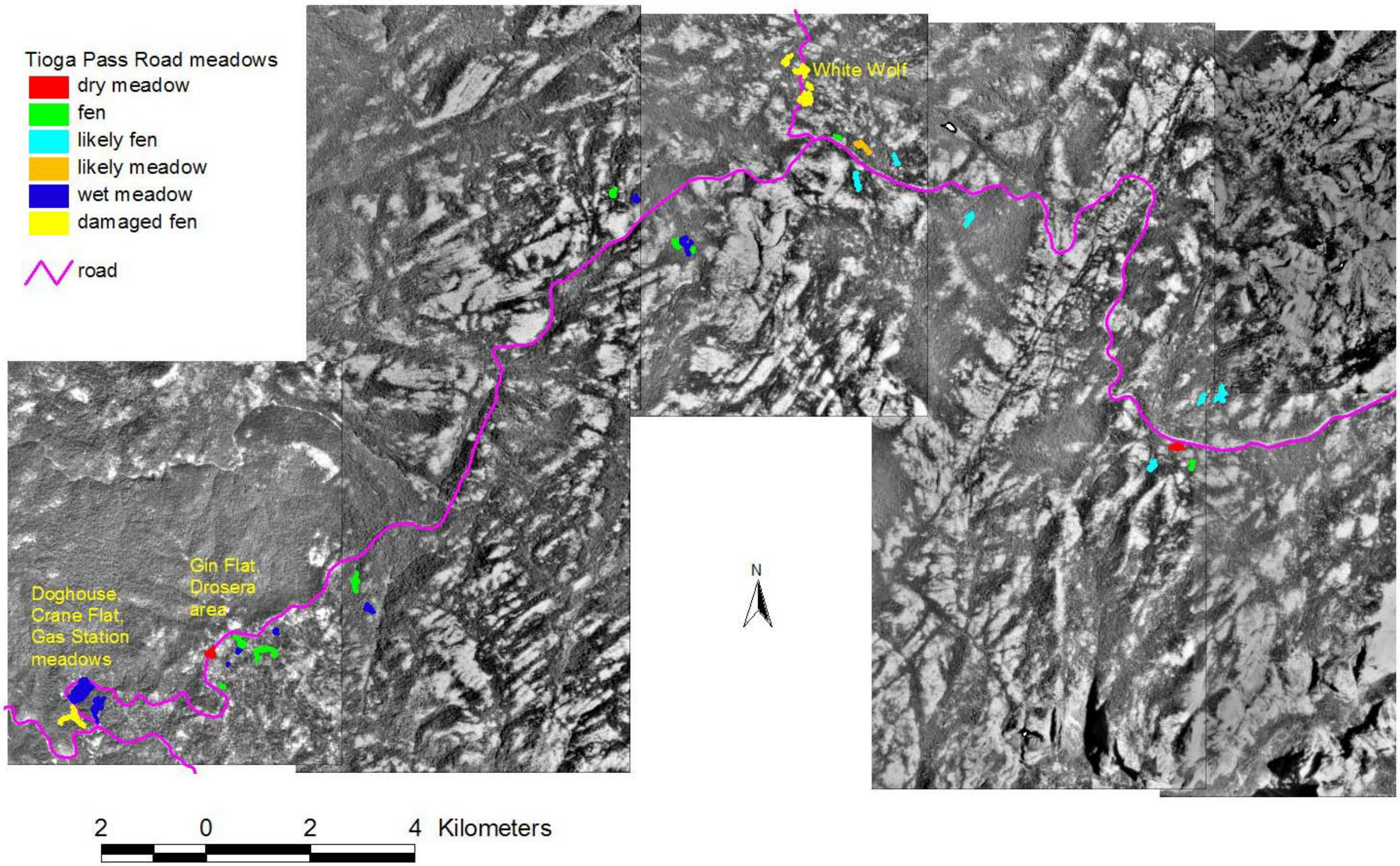



**Figure 16.** Aerial photography used to identify meadows in the vicinity of Tioga Pass Road, which were then visited for classification.

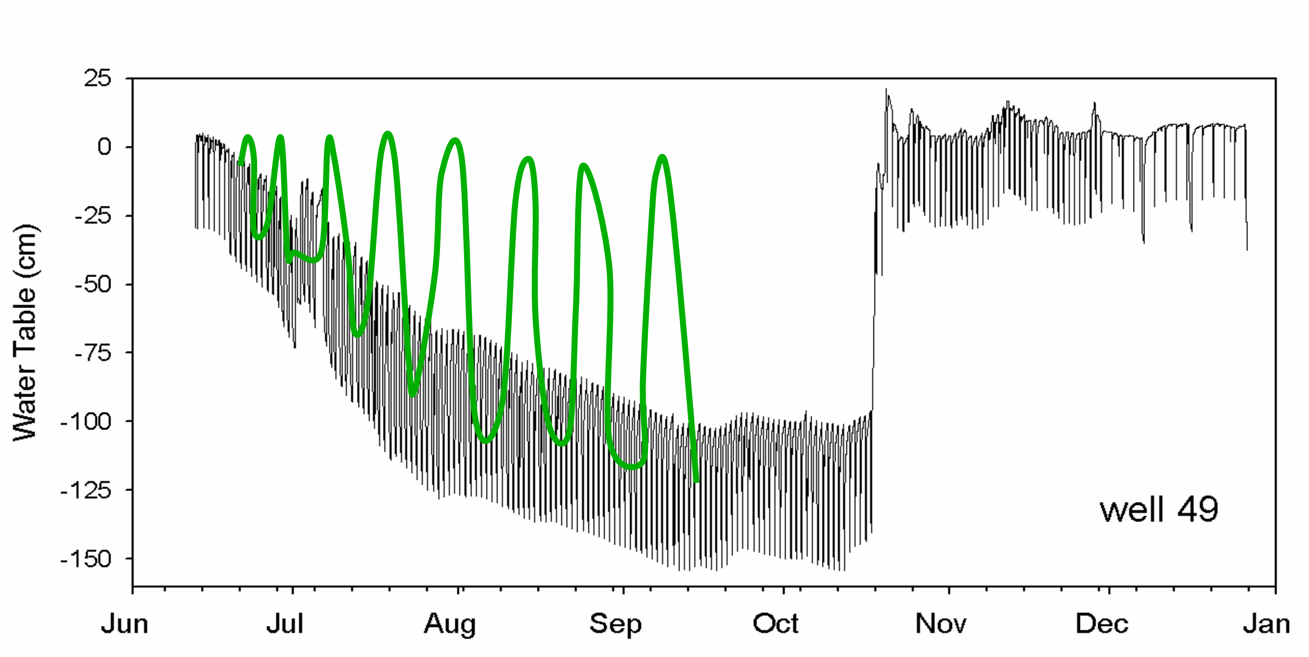



**Figure 17.** Suggested pumping scenario for a dry summer is shown in green line, while the pumping scenario from 2004 is shown in black.

## Appendix A

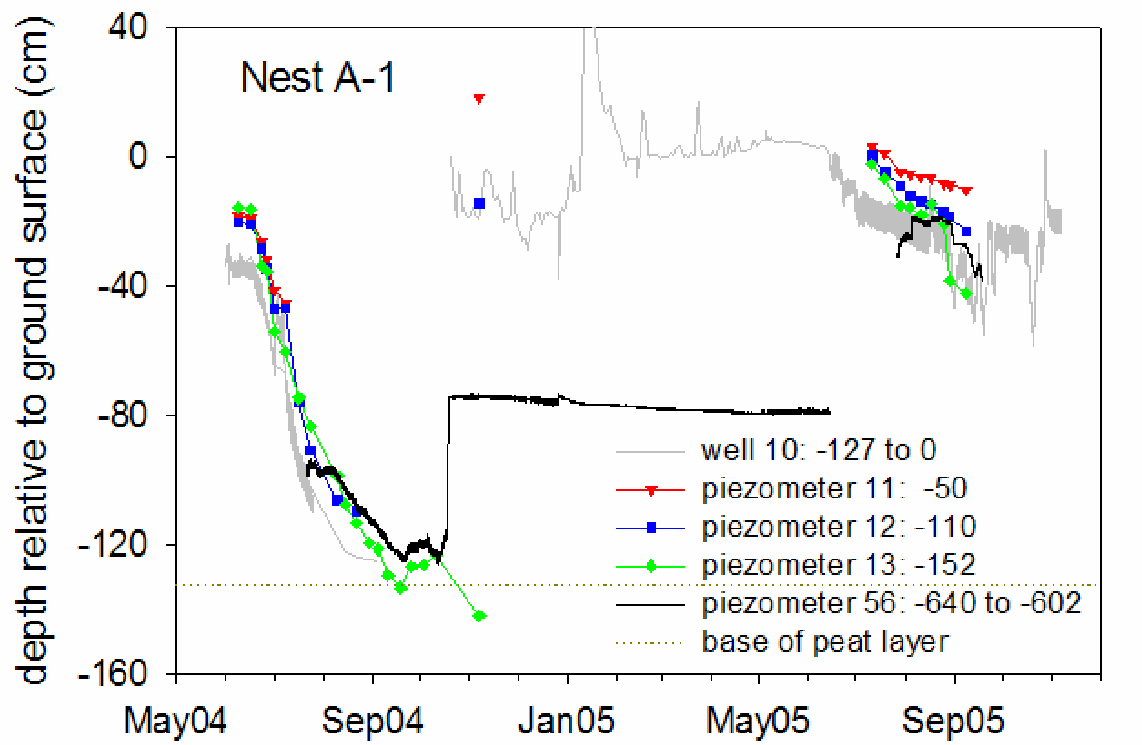
Description of wells and piezometers in Doghouse, Crane Flat, Drosera and Mono Meadows.

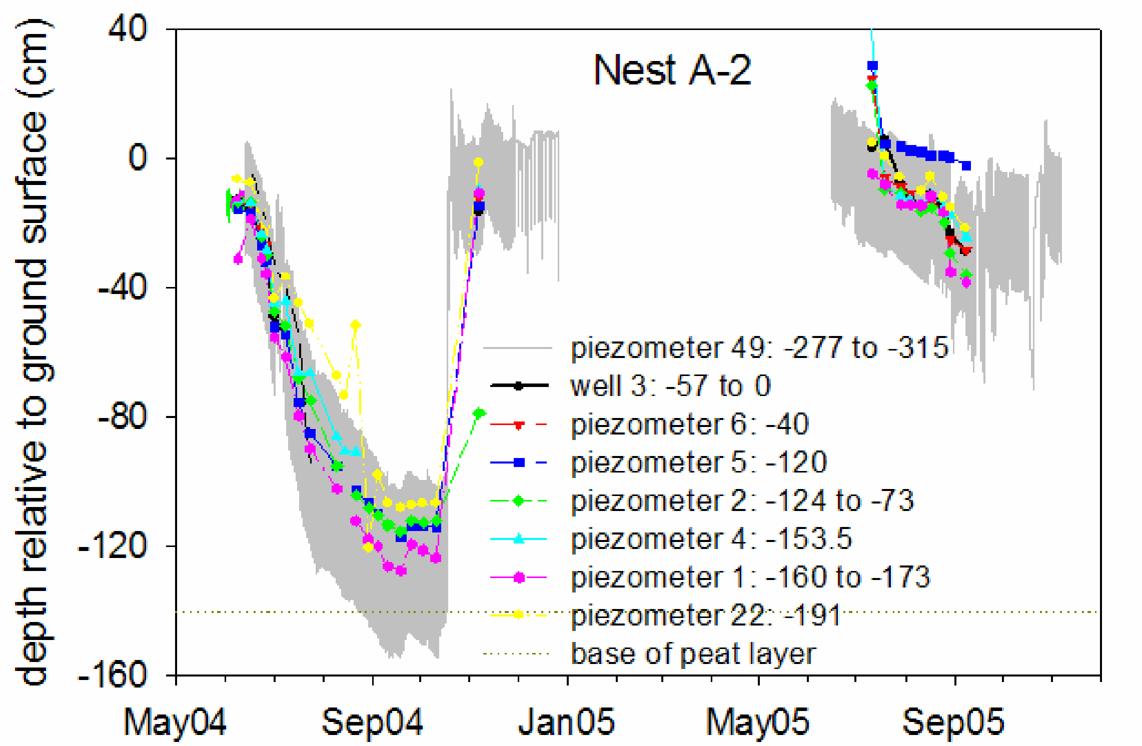
| Well # | Nest code | Pipe diameter (in) | Instrument Type | Depth of lowest opening (cm) | Depth of highest opening (cm) | Peat depth (cm) | Depth to coarse sand/ gravel (cm) | Distance to Doghouse pump (m) | Elevation (m) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | A-2 | 2 | piezometer | -173.0 | -160.0 | -140.0 | -155.0 | 13.76 | 1874.550 |
| 2 | A-2 | 2 | piezometer | -124.0 | -73.0 | -140.0 | -155.0 | 13.93 | 1874.518 |
| 3 | A-2 | 2 | well | -57.0 | 0.0 | -140.0 | -155.0 | 14.15 | 1874.561 |
| 4 | A-2 | 0.5 | piezometer | -153.5 | -153.5 | -140.0 | -155.0 | 13.50 | 1874.548 |
| 5 | A-2 | 0.5 | piezometer | -120.0 | -120.0 | -140.0 | -155.0 | 13.61 | 1874.558 |
| 6 | A-2 | 0.5 | piezometer | -40.0 | -40.0 | -140.0 | -155.0 | 13.77 | 1874.553 |
| 7 | A-3 | 2 | well | -36.0 | 0.0 | 0.0 | -102.0 | 22.59 | 1874.374 |
| 8 | A-3 | 0.5 | piezometer | -31.0 | -31.0 | 0.0 | -102.0 | 22.76 | 1874.383 |
| 9 | A-3 | 0.5 | piezometer | -105.5 | -105.5 | 0.0 | -102.0 | 22.71 | 1874.337 |
| 10 | A-1 | 2 | well | -127.0 | 0.0 | -132.0 | -132.0 | 4.53 | 1874.660 |
| 11 | A-1 | 0.5 | piezometer | -50.0 | -50.0 | -132.0 | -132.0 | 4.88 | 1874.665 |
| 12 | A-1 | 0.5 | piezometer | -110.0 | -110.0 | -132.0 | -132.0 | 4.75 | 1874.673 |
| 13 | A-1 | 0.5 | piezometer | -152.0 | -152.0 | -132.0 | -132.0 | 4.62 | 1874.665 |
| 14 | G | 2 | well | -89.0 | 0.0 | -90.0 | -90.0 | 19.05 | 1874.639 |
| 15 | G | 0.5 | piezometer | -63.0 | -63.0 | -90.0 | -90.0 | 18.95 | 1874.654 |
| 16 | G | 0.5 | piezometer | -186.0 | -186.0 | -90.0 | -90.0 | 18.80 | 1874.652 |
| 17 | B-2 | 2 | well | -90.0 | 0.0 | -96.0 | -96.0 | 24.65 | 1874.373 |
| 18 | B-2 | 0.5 | piezometer | -80.0 | -80.0 | -96.0 | -96.0 | 24.41 | 1874.426 |
| 19 | B-2 | 0.5 | piezometer | -170.0 | -170.0 | -96.0 | -96.0 | 24.26 | 1874.417 |
| 20 | B-3 | 2 | well | -46.0 | 0.0 | -23.0 | -30.0 | 36.66 | 1874.377 |
| 21 | B-3 | 0.5 | piezometer | -60.0 | -60.0 | -23.0 | -30.0 | 36.48 | 1874.395 |
| 22 | A-2 | 0.5 | piezometer | -191.0 | -191.0 | -140.0 | -155.0 | 13.32 | 1874.529 |
| 23 | B-1 | 2 | well | -58.0 | 0.0 | 0.0 | -90.0 | 16.76 | 1874.516 |
| 24 | B-1 | 0.5 | piezometer | -60.0 | -60.0 | 0.0 | -90.0 | 16.36 | 1874.501 |
| 25 | B-1 | 0.5 | piezometer | -131.0 | -131.0 | 0.0 | -90.0 | 16.06 | 1874.518 |
| 26 | C-1 | 2 | well | -57.5 | 0.0 | -25.0 | -100.0 | 33.82 | 1874.941 |
| 27 | C-1 | 0.5 | piezometer | -60.0 | -60.0 | -25.0 | -100.0 | 34.12 | 1874.957 |
| 28 | C-1 | 0.5 | piezometer | -121.0 | -121.0 | -25.0 | -100.0 | 34.53 | 1874.983 |
| 29 | C-2 | 2 | well | -57.0 | 0.0 | -50.0 | -95.0 | 34.07 | 1874.729 |
| 30 | C-2 | 0.5 | piezometer | -60.0 | -60.0 | -50.0 | -95.0 | 34.44 | 1874.730 |
| 31 | C-2 | 0.5 | piezometer | -130.0 | -130.0 | -50.0 | -95.0 | 34.69 | 1874.755 |
| 32 | C-3 | 2 | well | -109.0 | 0.0 | -9.0 | -28.0 | 37.14 | 1874.841 |
| 33 | C-3 | 0.5 | piezometer | -25.0 | -25.0 | -9.0 | -28.0 | 37.34 | 1874.865 |
| 34 | C-3 | 0.5 | piezometer | -109.0 | -109.0 | -9.0 | -28.0 | 37.57 | 1874.890 |
| 35 | C-2 | 0.5 | piezometer | -160.0 | -160.0 | -50.0 | -95.0 | 34.98 | 1874.757 |
| 36 | D | 2 | well | -92.0 | 0.0 | -131.0 | -131.0 | 46.05 | 1874.202 |
| 37 | D | 0.5 | piezometer | -163.0 | -163.0 | -131.0 | -131.0 | 45.29 | 1874.211 |
| 38 | E | 2 | well | -86.0 | 0.0 | 0.0 | -118.0 | 66.88 | 1875.835 |
| 39 | E | 0.5 | piezometer | -136.0 | -136.0 | 0.0 | -118.0 | 66.59 | 1875.830 |

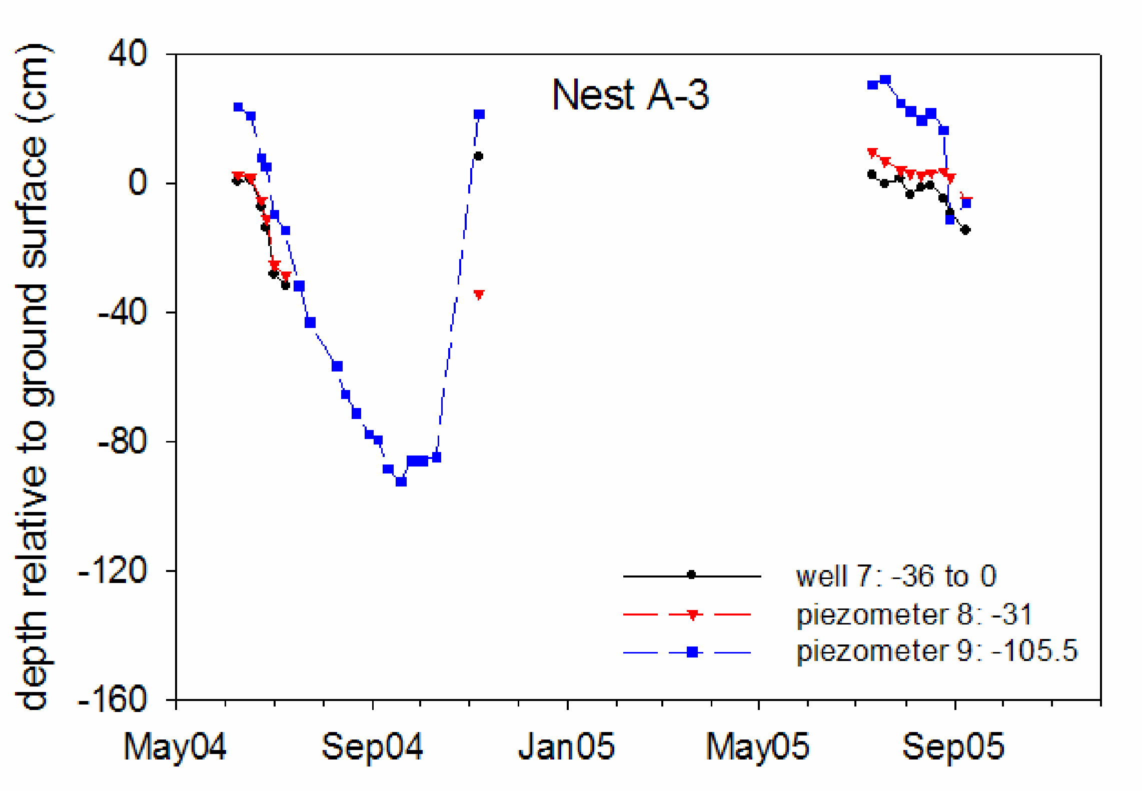
| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 40 | F | 2 | well | -96.0 | 0.0 | -109.0 | -109.0 | 90.64 | 1875.459 |
| 41 | F | 0.5 | piezometer | -150.0 | -150.0 | -109.0 | -109.0 | 90.96 | 1875.463 |
| 42 | H | 2 | well | -101.0 | 0.0 | -126.0 | -126.0 | 137.69 | 1875.739 |
| 43 | H | 0.5 | piezometer | -140.0 | -140.0 | -126.0 | -126.0 | 137.30 | 1875.730 |
| 44 | I | 2 | well | -60.0 | 0.0 | -27.0 | -86.0 | 301.01 | 1876.450 |
| 45 | I | 0.5 | piezometer | -116.5 | -116.5 | -27.0 | -86.0 | 301.49 | 1876.499 |
| 46 | J | 2 | well | -95.5 | 0.0 | -26.0 | -124.0 | 135.42 | 1873.033 |
| 47 | J | 0.5 | piezometer | -162.0 | -162.0 | -26.0 | -124.0 | 134.86 | 1873.042 |
| 48 | C-1 | 1.25 | piezometer | -190.0 | -152.0 | -25.0 | -100.0 | 33.28 | 1874.937 |
| 49 | A-2 | 1.25 | piezometer | -315.0 | -277.0 | -140.0 | -155.0 | 13.45 | 1874.542 |
| 50 | B-2 | 1.25 | piezometer | -308.0 | -270.0 | -96.0 | -96.0 | 25.28 | 1874.403 |
| 51 | B-1 | 1.25 | piezometer | -230.0 | -192.0 | 0.0 | -90.0 | 17.13 | 1874.474 |
| 52 | B-1 | 0.5 | piezometer | -75.0 | -75.0 | 0.0 | -90.0 | 17.70 | 1874.489 |
| 53 | C-1 | 0.5 | piezometer | -88.0 | -88.0 | -25.0 | -100.0 | 32.72 | 1874.909 |
| 54 | C-2 | 0.5 | piezometer | -85.0 | -85.0 | -25.0 | -95.0 | 33.31 | 1874.704 |
| 55 | C-2 | 1.25 | piezometer | -226.0 | -176.0 | -50.0 | -95.0 | 33.70 | 1874.707 |
| 56 | A-1 | 1.25 | piezometer | -640.0 | -602.0 | -132.0 | -132.0 | 4.29 | 1874.676 |
| 57 | V | 2 | well | -212.6 | -182.6 | -90.0 | -162.0 | 81 | 1873.696 |
| 58 | F | 2 | well | -129.0 | -99.0 | -103.0 | -103.0 | 91 | 1875.423 |
| 59 | W | 2 | well | -65.7 | 0.0 | 0.0 | 0.0 | | |
| 60 | X | 2 | well | -122.3 | 0.0 | 0.0 | -123.0 | 360 | 1877.568 |
| 61 | Y | 2 | well | -91.1 | 0.0 | 10.0 | -100.0 | 441 | 1880.616 |
| 62 | Z | 2 | well | -110.7 | 0.0 | 0.0 | 0.0 | 428 | 1879.092 |
| 63 | D | 2 | well | -209.0 | -179.0 | -100.0 | -155.0 | 46.5 | 1874.225 |
| 64 | YI | 2 | well | -95.6 | 0.0 | 0.0 | -82.0 | 738 | |
| 65 | YI | 2 | well | -70.4 | 0.0 | 0.0 | -60.0 | 749 | |
| 66 | YI | 2 | well | -155.3 | 0.0 | 0.0 | -105.0 | 728 | |
| 67 | MONO-A | 2 | well | -90.2 | 0.0 | -70.0 | N/a | > 2 km | |
| 68 | MONO-A | 0.5 | piezometer | -83.5 | -83.5 | -70.0 | N/a | > 2 km | |
| 69 | MONO-A | 0.5 | piezometer | -47.8 | -47.8 | -70.0 | N/a | > 2 km | |
| 70 | MONO-B | 2 | well | -104.0 | 0.0 | -58.0 | N/a | > 2 km | |
| 71 | rig augered | 2 | well | -595.0 | 0.0 | 0.0 | -200.0 | 604 | 1889.760 |
| 72 | rig augered | 2 | well | -556.0 | 0.0 | 0.0 | | 730 | |
| 73 | rig augered | 2 | well | -1362.0 | 0.0 | 0.0 | | > 2 km | |
| 74 | rig augered | 2 | well | -697.0 | 0.0 | 0.0 | | > 2 km | |
| 75 | rig augered | 2 | well | -556.0 | 0.0 | 0.0 | | 61 | |
| DR1 | DROSERA-A | 2 | well | -79.5 | 0.0 | -60.0 | N/a | > 2 km | |
| DR2 | DROSERA-A | 0.5 | piezometer | -159.3 | 0.0 | -60.0 | N/a | > 2 km | |
| DR3 | DROSERA-A | 0.5 | piezometer | -107.0 | 0.0 | -60.0 | N/a | > 2 km | |
| DR4 | DROSERA-B | 2 | well | -96.0 | 0.0 | -96.0 | N/a | > 2 km | |
| DR5 | DROSERA-B | 0.5 | piezometer | -139.5 | -139.5 | -96.0 | N/a | > 2 km | |
| DR6 | DROSERA-B | 0.5 | piezometer | -70.0 | -70.0 | -96.0 | N/a | > 2 km | |
| N spring | N/a | N/a | N/a | N/a | N/a | N/a | N/a | 318 | 1898.904 |
| S spring | N/a | N/a | N/a | N/a | N/a | N/a | N/a | 305 | 1898.904 |
| YI production well | N/a | 10 | pumping well | -122.5 m | 0.0 | 0.0 | | 746 | |
| Doghouse well | N/a | 8 | pumping well | -121.9 m | 0.0 | N/a | N/a | 0.0 | 1874.714 |

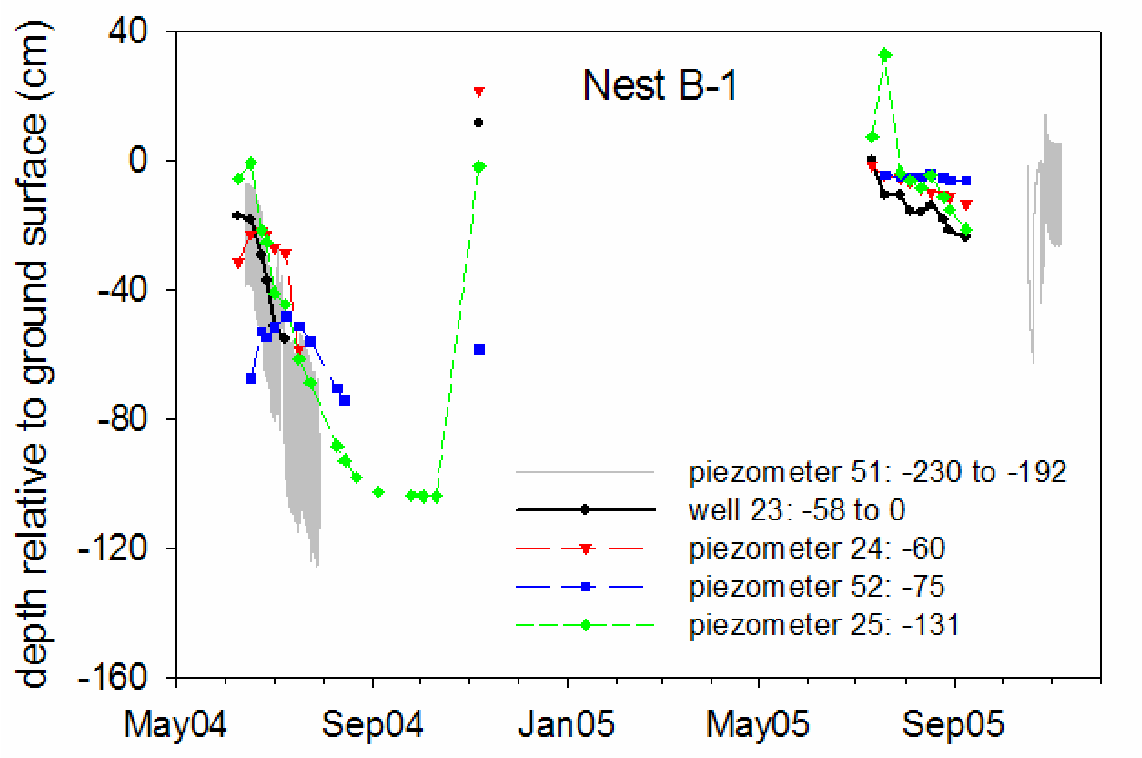
## Appendix B

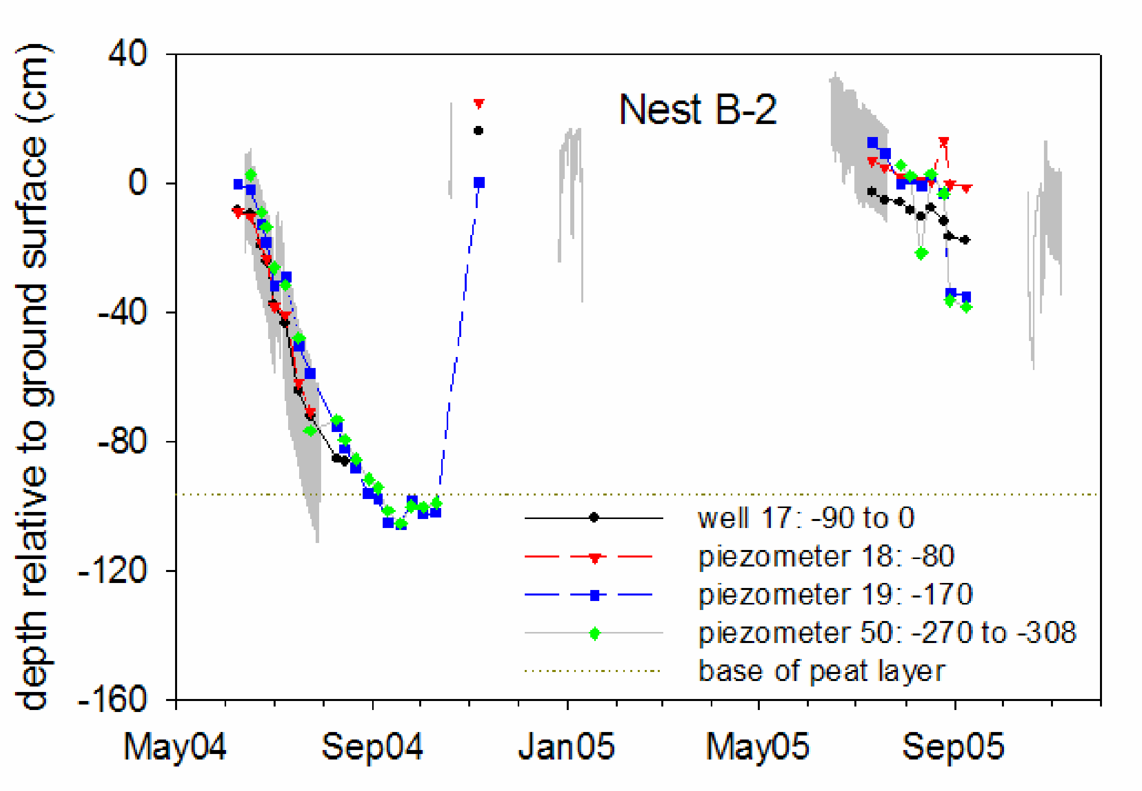
Well and piezometer data. Depth of instrument opening/slotting given in legend.

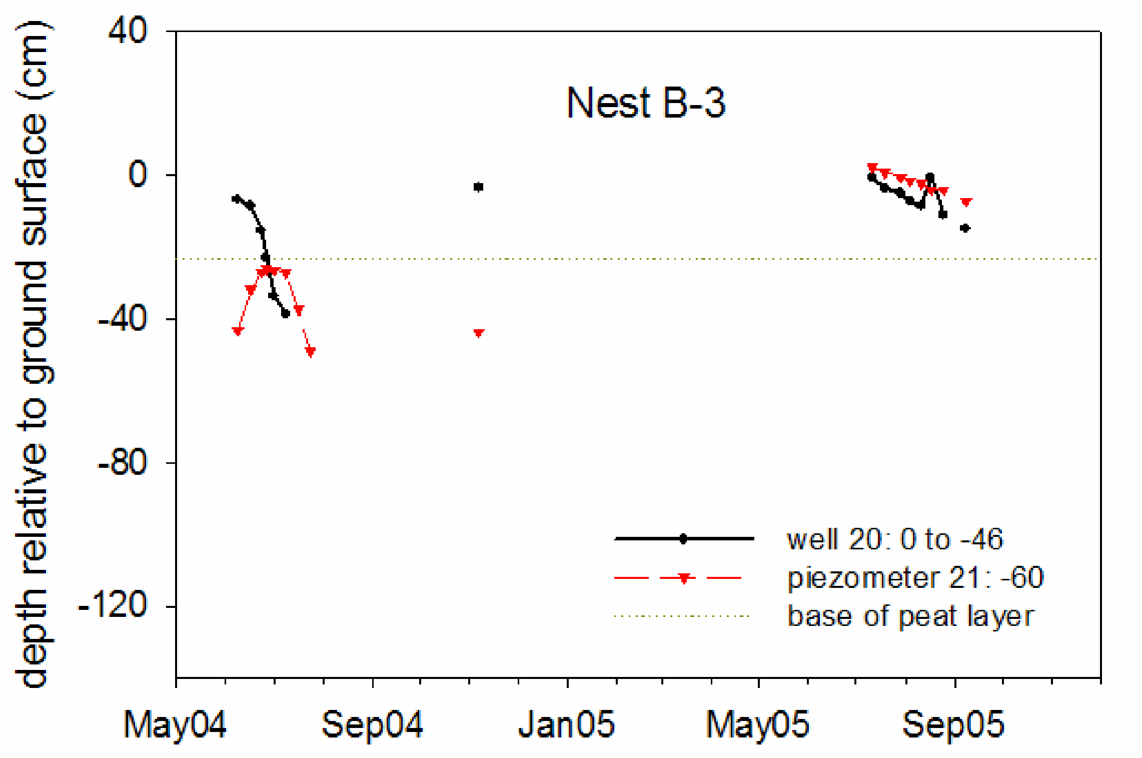


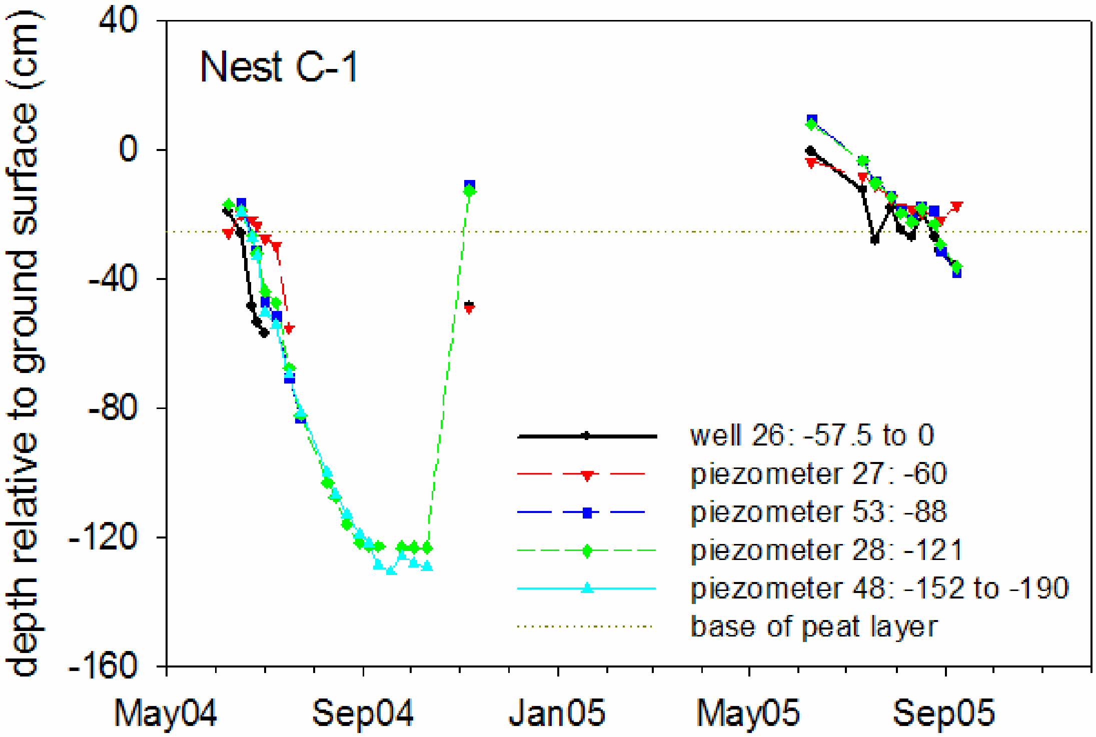



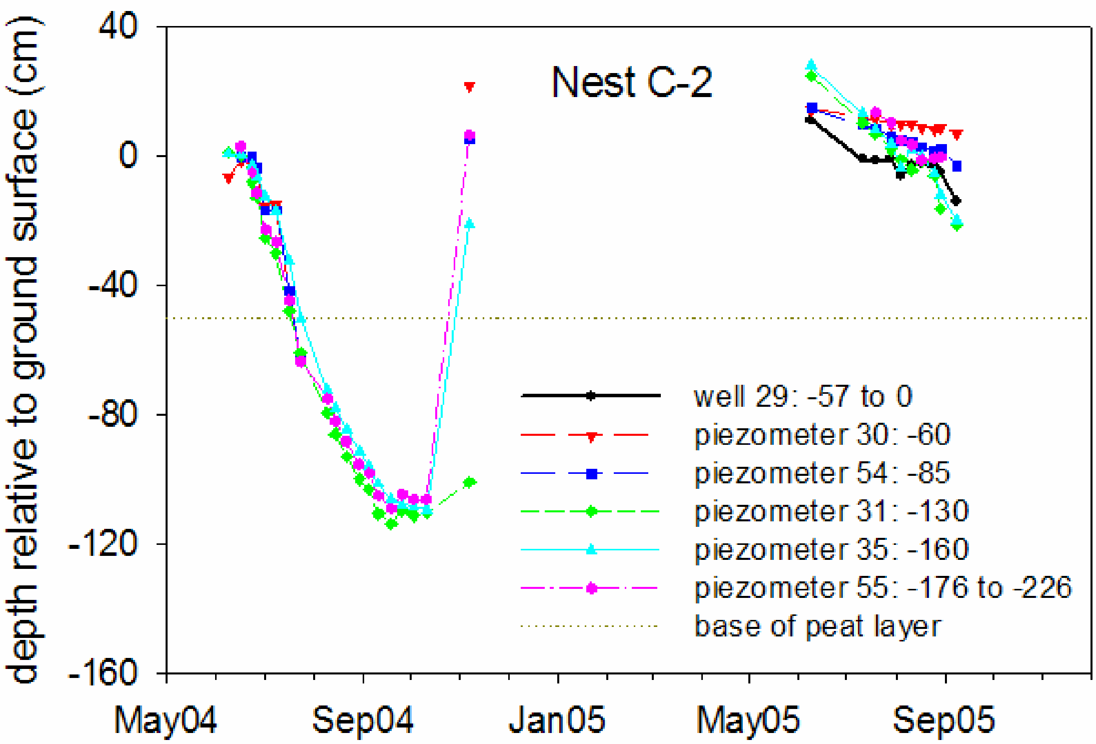

Nest A-3
depth relative to ground surface (cm)
40
0
-40
-80
-120
-160
May04
Sep04
Jan05
May05
Sep05
well 7: -36 to 0
piezometer 8: -31
piezometer 9: -105.5

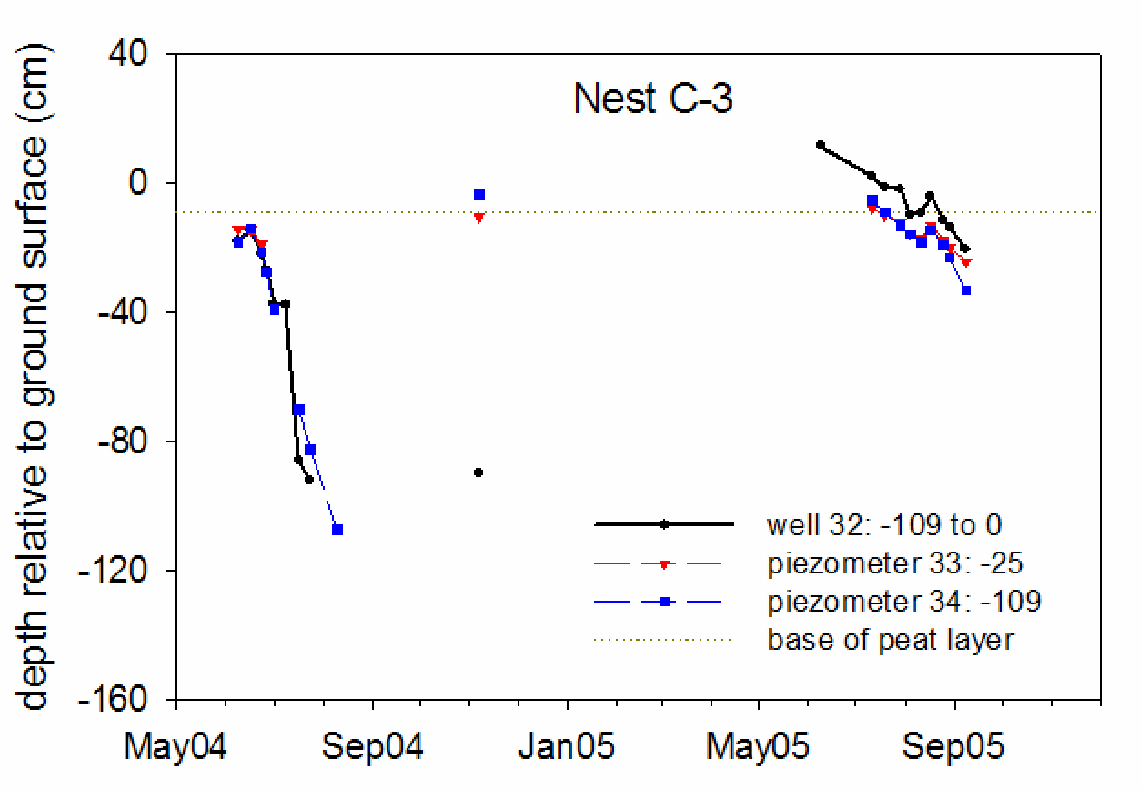

Nest B-1
depth relative to ground surface (cm)
40
0
-40
-80
-120
-160
May04
Sep04
Jan05
May05
Sep05
piezometer 51: -230 to -192
well 23: -58 to 0
piezometer 24: -60
piezometer 52: -75
piezometer 25: -131

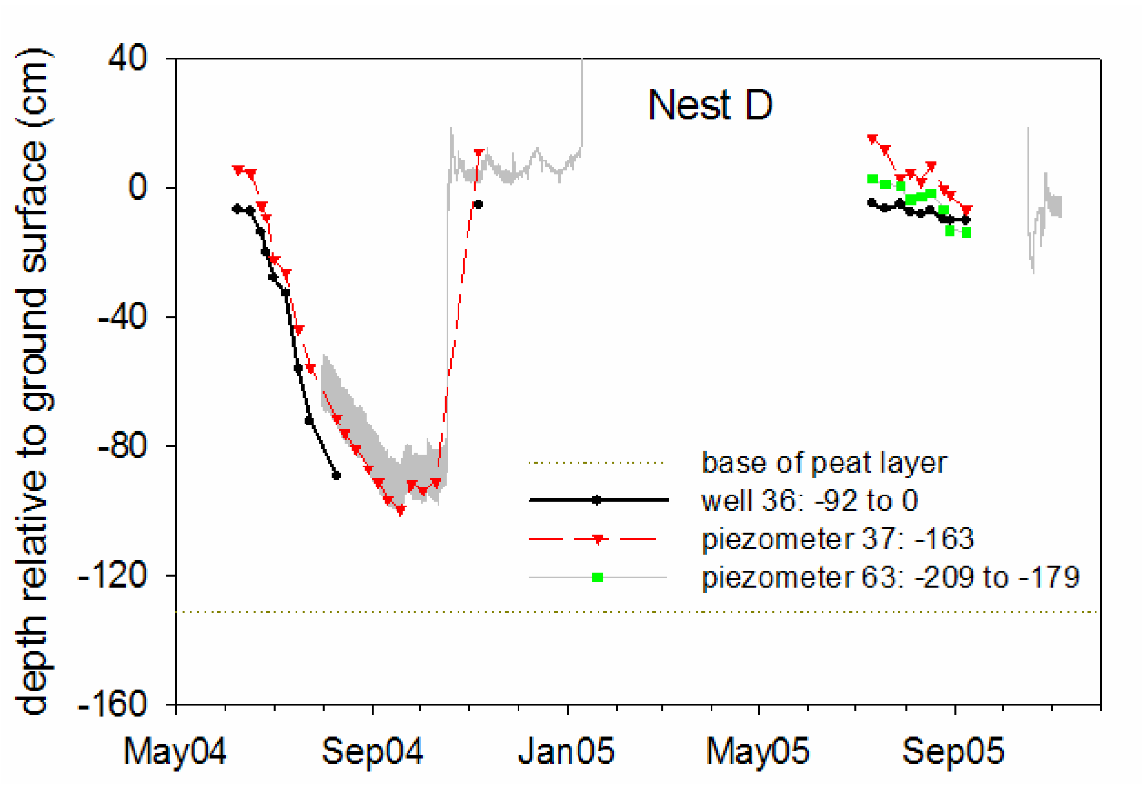

Nest B-2
depth relative to ground surface (cm)
40
0
-40
-80
-120
-160
May04
Sep04
Jan05
May05
Sep05
well 17: -90 to 0
piezometer 18: -80
piezometer 19: -170
piezometer 50: -270 to -308
base of peat layer

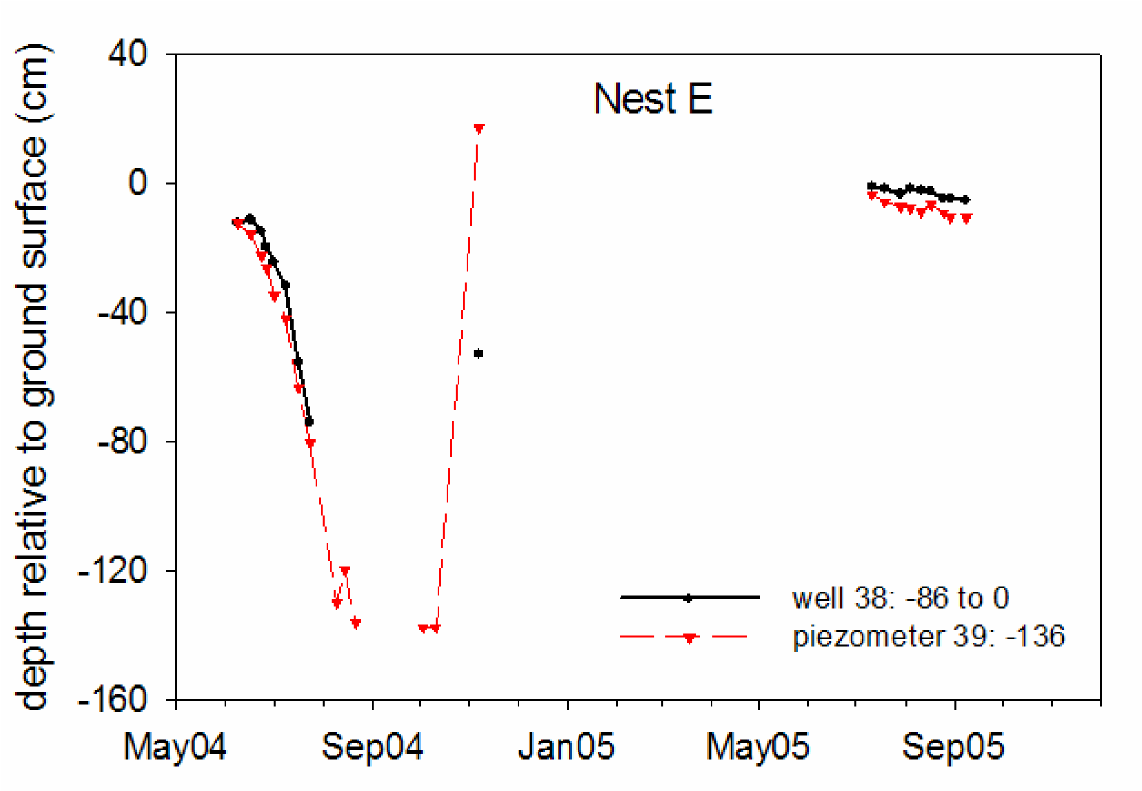

Nest B-3
depth relative to ground surface (cm)
40
0
-40
-80
-120
May04
Sep04
Jan05
May05
Sep05
well 20: 0 to -46
piezometer 21: -60
base of peat layer

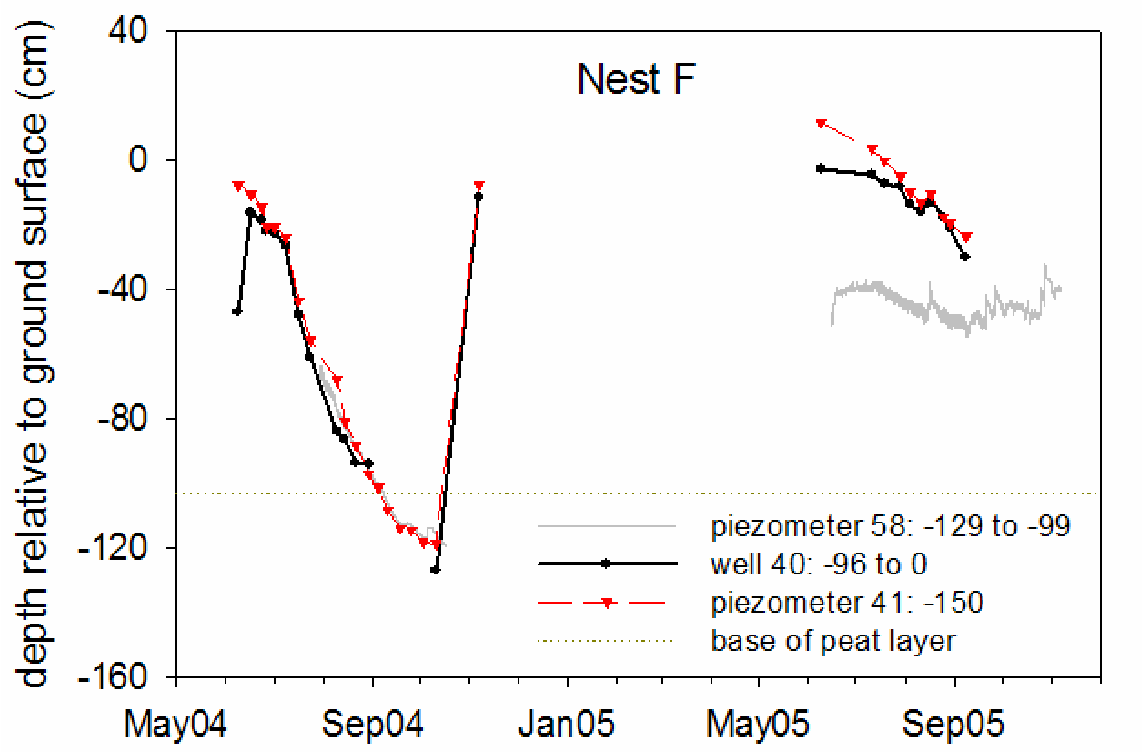

Nest C-1
depth relative to ground surface (cm)
40
0
-40
-80
-120
-160
May04
Sep04
Jan05
May05
Sep05
well 26: -57.5 to 0
piezometer 27: -60
piezometer 53: -88
piezometer 28: -121
piezometer 48: -152 to -190
base of peat layer

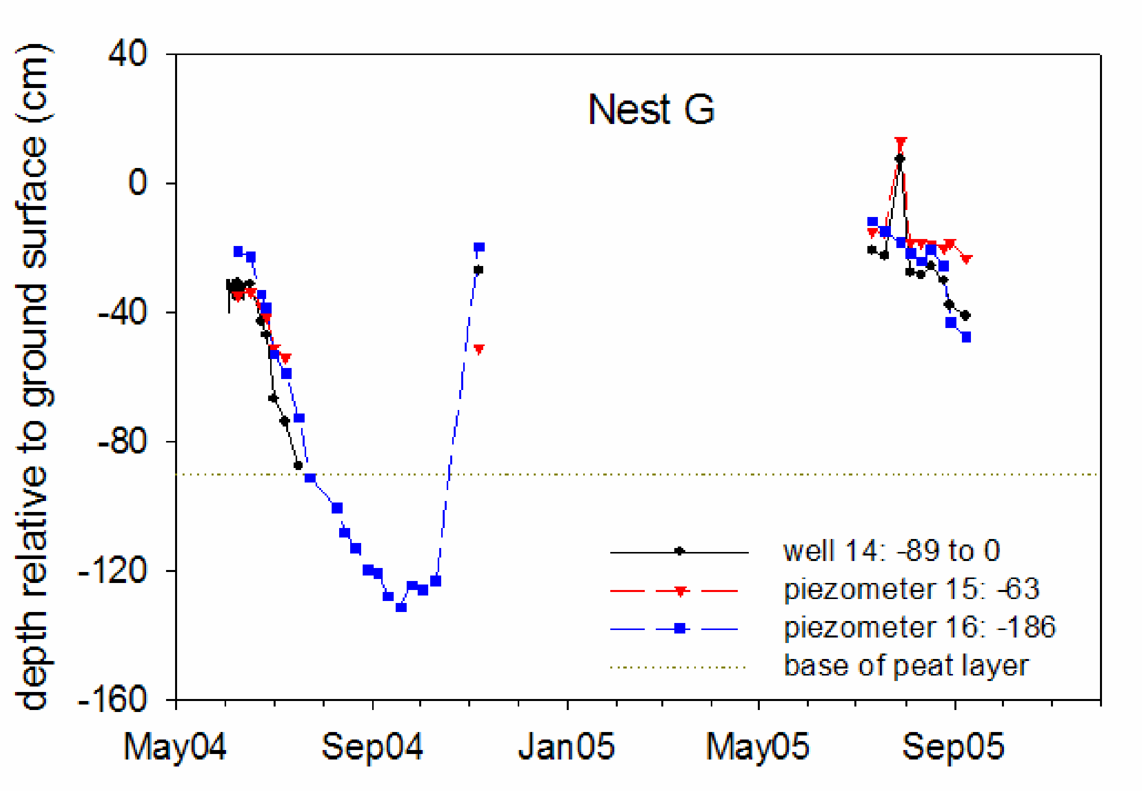

Nest C-2
depth relative to ground surface (cm)
40
0
-40
-80
-120
-160
May04
Sep04
Jan05
May05
Sep05
well 29: -57 to 0
piezometer 30: -60
piezometer 54: -85
piezometer 31: -130
piezometer 35: -160
piezometer 55: -176 to -226
base of peat layer

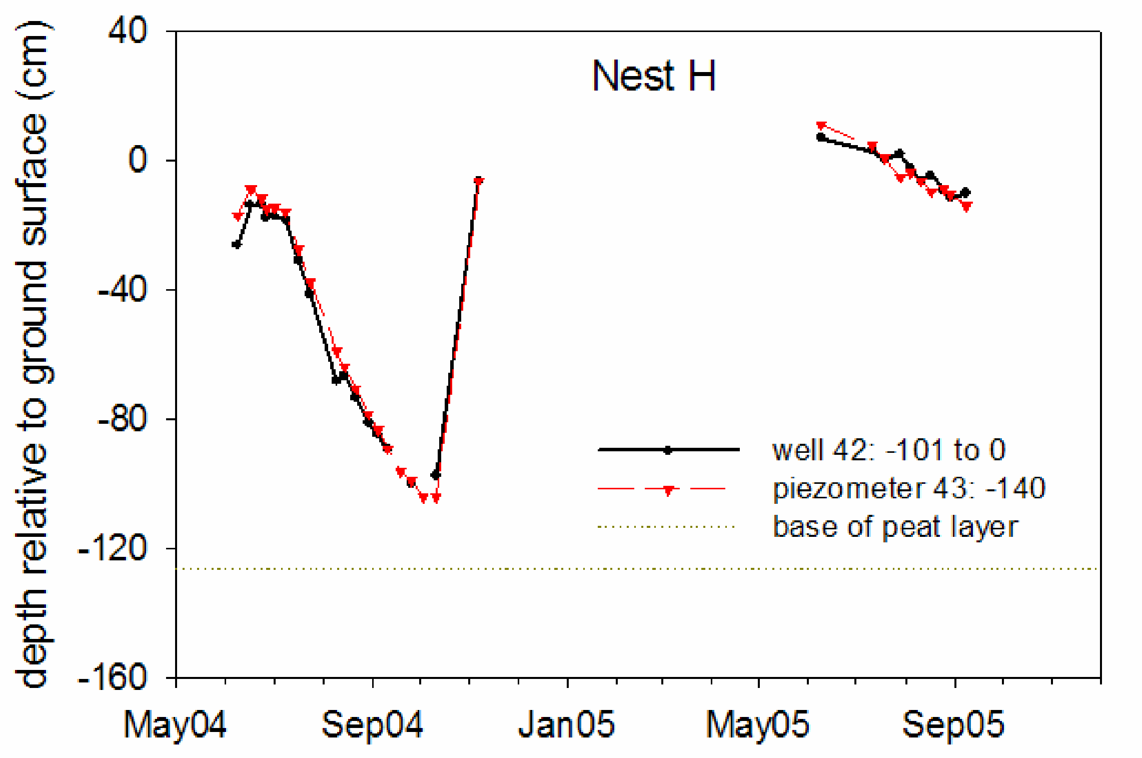

Nest C-3
depth relative to ground surface (cm)
40
0
-40
-80
-120
-160
May04
Sep04
Jan05
May05
Sep05
well 32: -109 to 0
piezometer 33: -25
piezometer 34: -109
base of peat layer

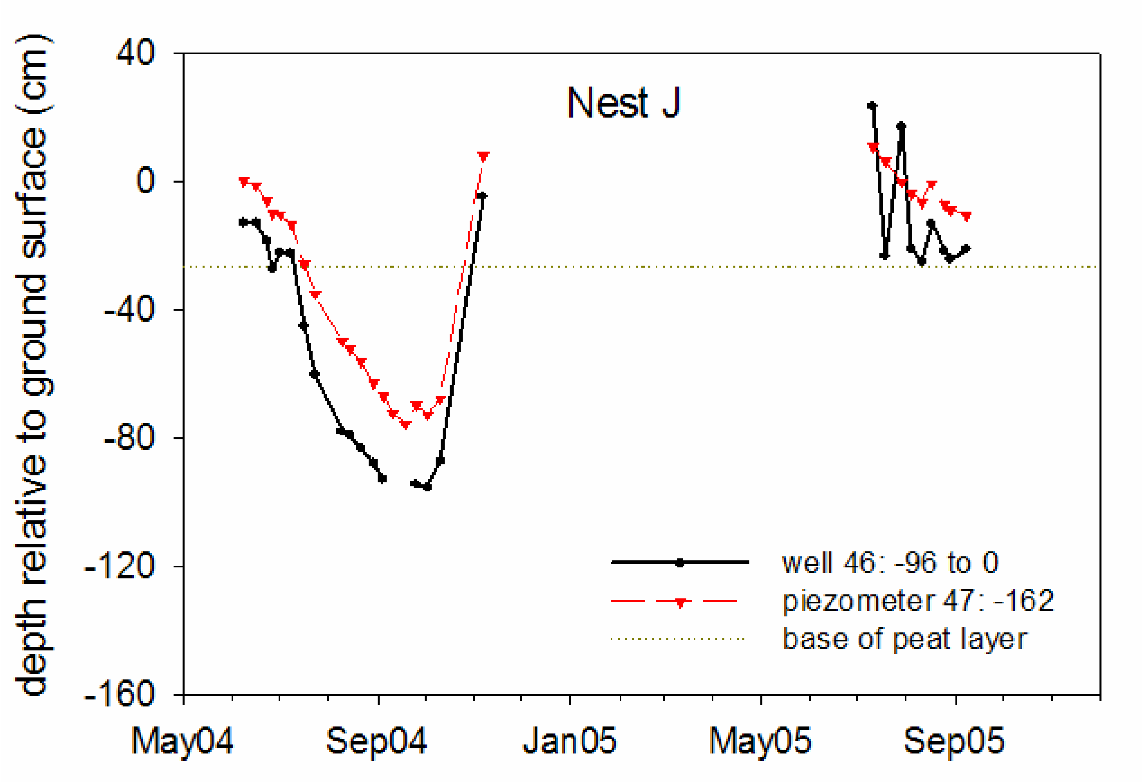

Nest D
depth relative to ground surface (cm)
40
0
-40
-80
-120
-160
May04
Sep04
Jan05
May05
Sep05
base of peat layer
well 36: -92 to 0
piezometer 37: -163
piezometer 63: -209 to -179


Nest E
depth relative to ground surface (cm)
40
0
-40
-80
-120
-160
May04
Sep04
Jan05
May05
Sep05
well 38: -86 to 0
piezometer 39: -136

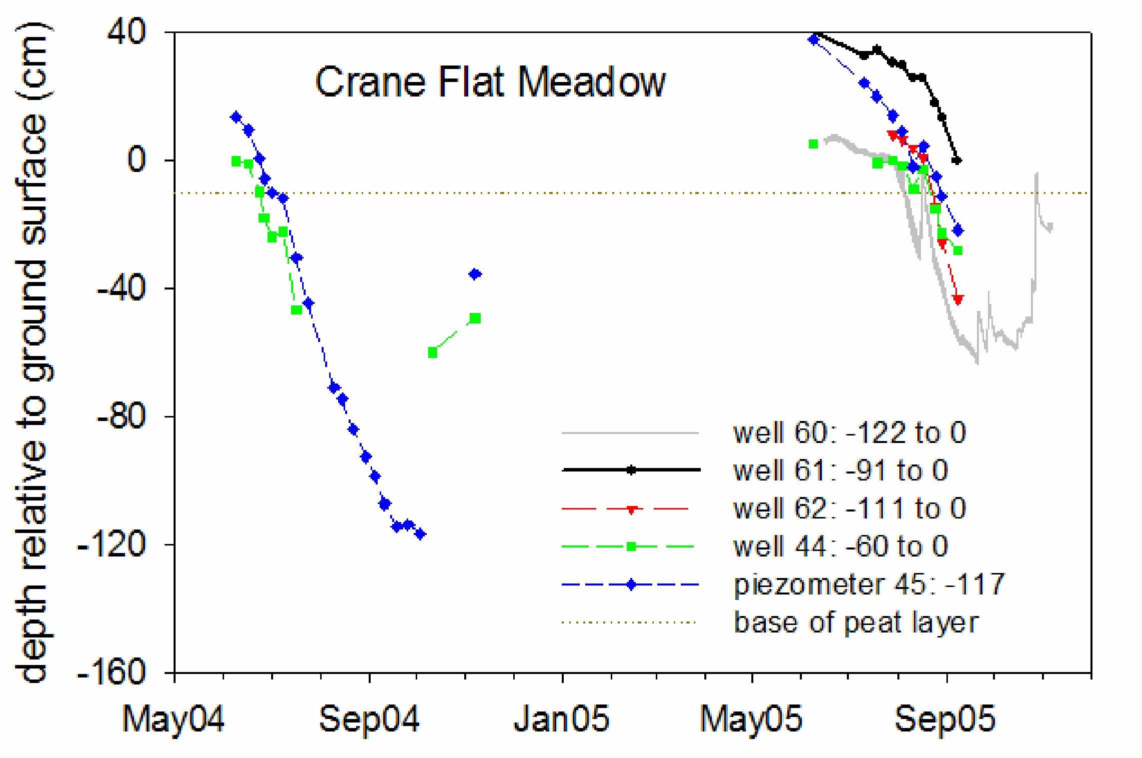

Nest F
depth relative to ground surface (cm)
40
0
-40
-80
-120
-160
May04
Sep04
Jan05
May05
Sep05
piezometer 58: -129 to -99
well 40: -96 to 0
piezometer 41: -150
base of peat layer


Nest G
depth relative to ground surface (cm)
40
0
-40
-80
-120
-160
May04
Sep04
Jan05
May05
Sep05
well 14: -89 to 0
piezometer 15: -63
piezometer 16: -186
base of peat layer

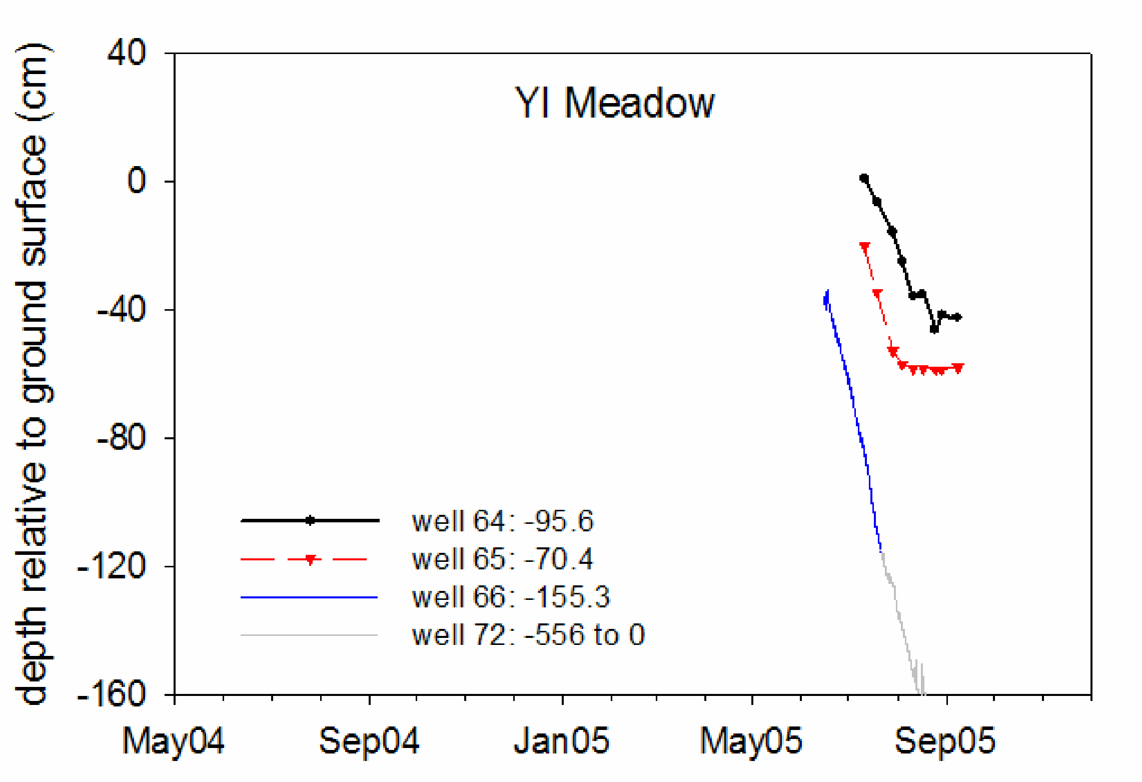

Nest H
depth relative to ground surface (cm)
40
0
-40
-80
-120
-160
May04
Sep04
Jan05
May05
Sep05
well 42: -101 to 0
piezometer 43: -140
base of peat layer

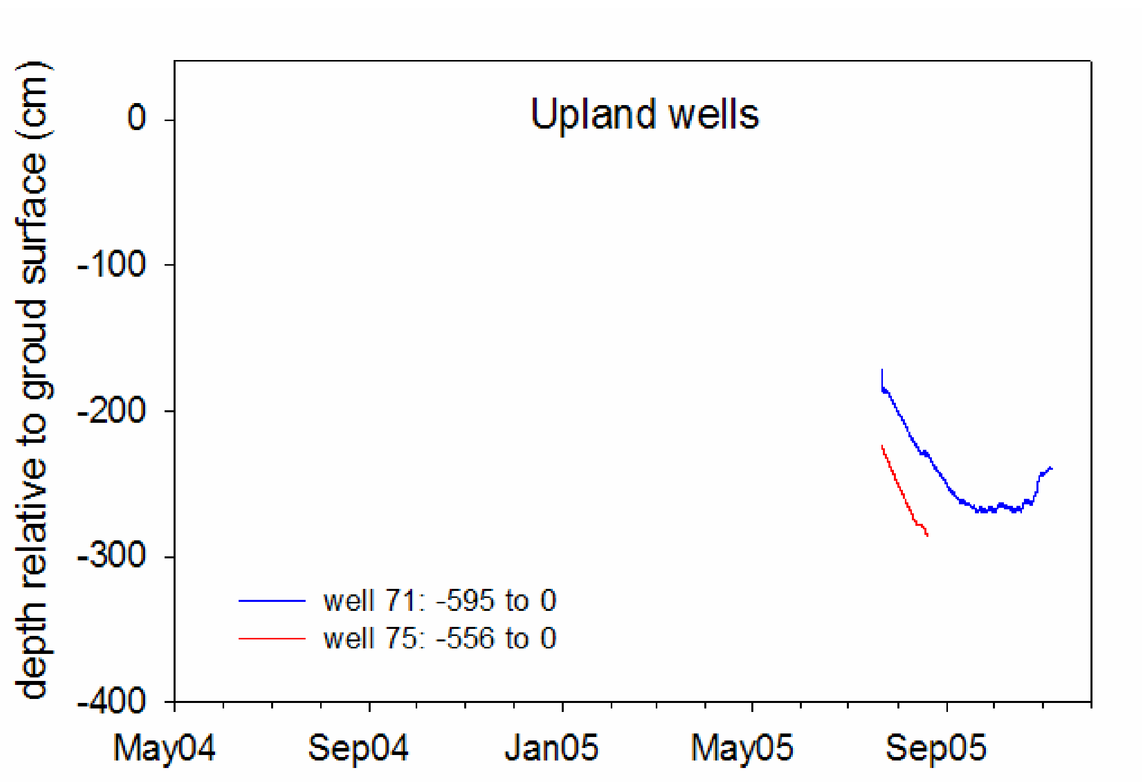


Nest J
depth relative to ground surface (cm)
40
0
-40
-80
-120
-160
May04
Sep04
Jan05
May05
Sep05
well 46: -96 to 0
piezometer 47: -162
base of peat layer

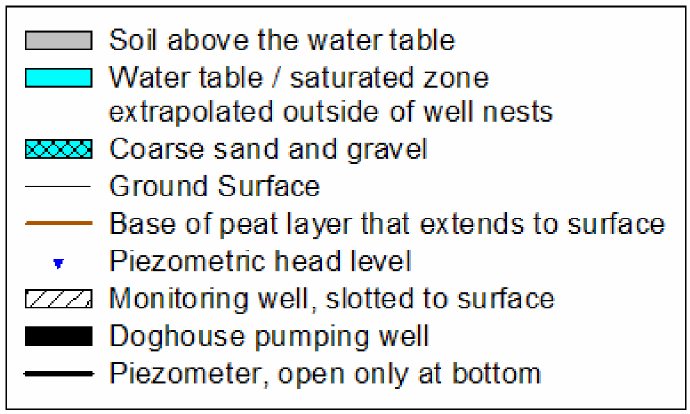
Crane Flat Meadow
depth relative to ground surface (cm)
40
0
-40
-80
-120
-160
May04
Sep04
Jan05
May05
Sep05
well 60: -122 to 0
well 61: -91 to 0
well 62: -111 to 0
well 44: -60 to 0
piezometer 45: -117
base of peat layer

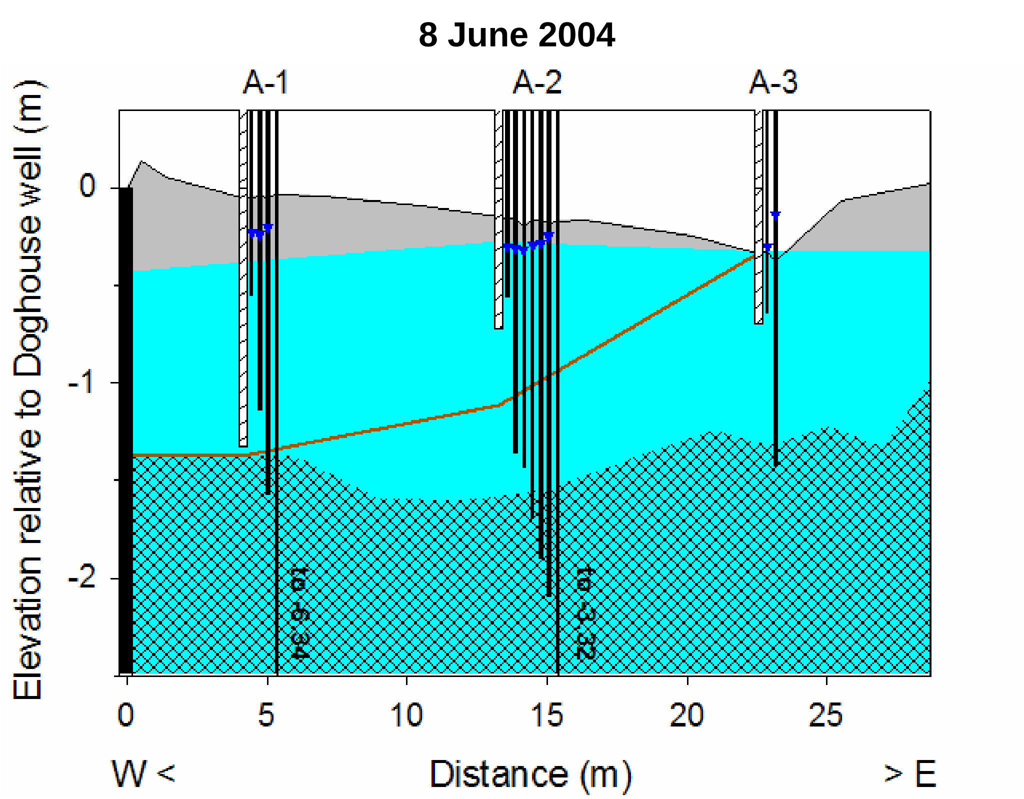

YI Meadow
depth relative to ground surface (cm)
40
0
-40
-80
-120
-160
May04
Sep04
Jan05
May05
Sep05
well 64: -95.6
well 65: -70.4
well 66: -155.3
well 72: -556 to 0

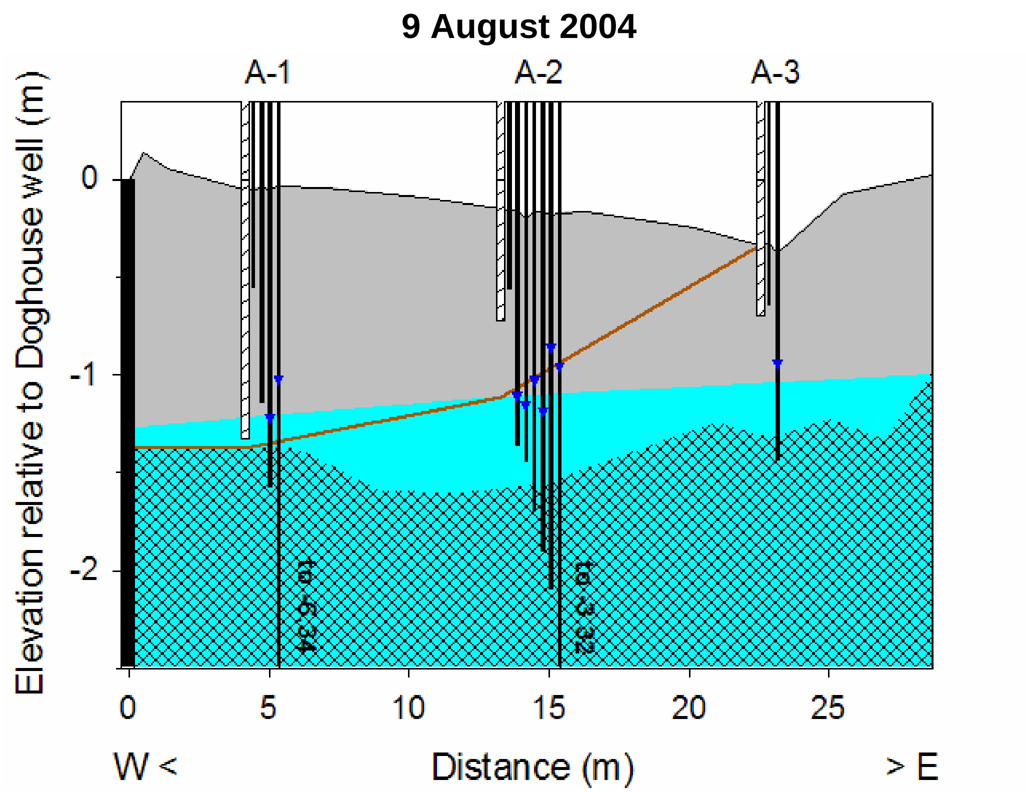

Upland wells
depth relative to groud surface (cm)
0
-100
-200
-300
-400
May04
Sep04
Jan05
May05
Sep05
well 71: -595 to 0
well 75: -556 to 0

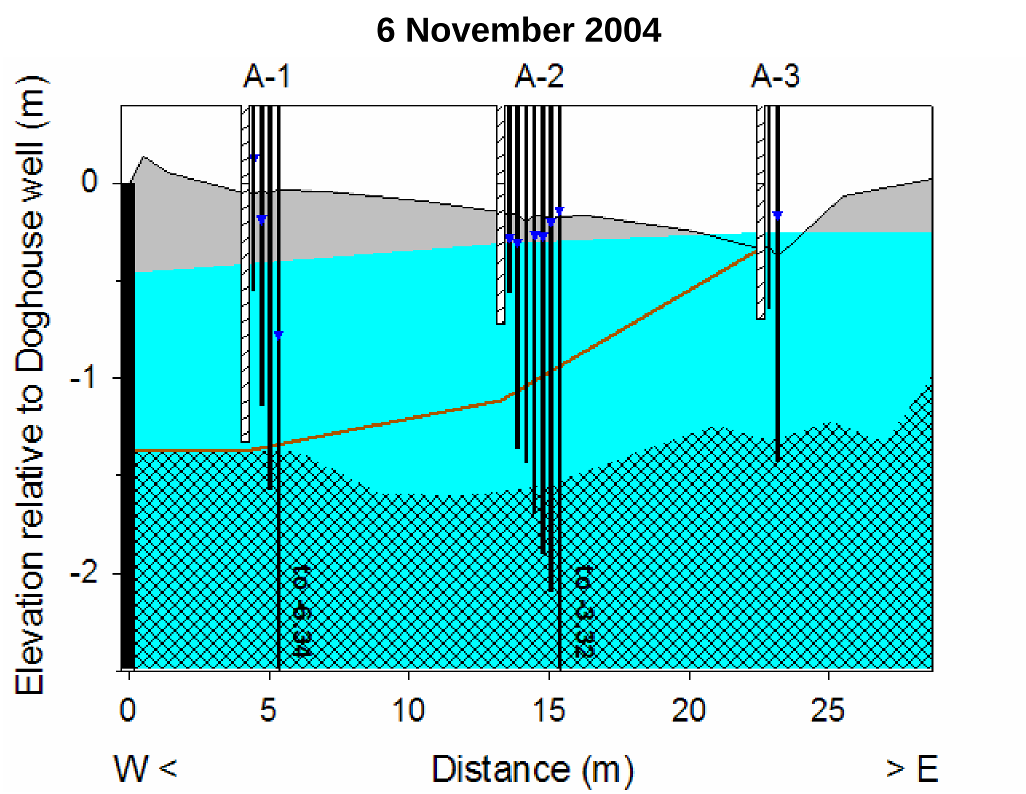
# Appendix C

Cross-sections of transect A.

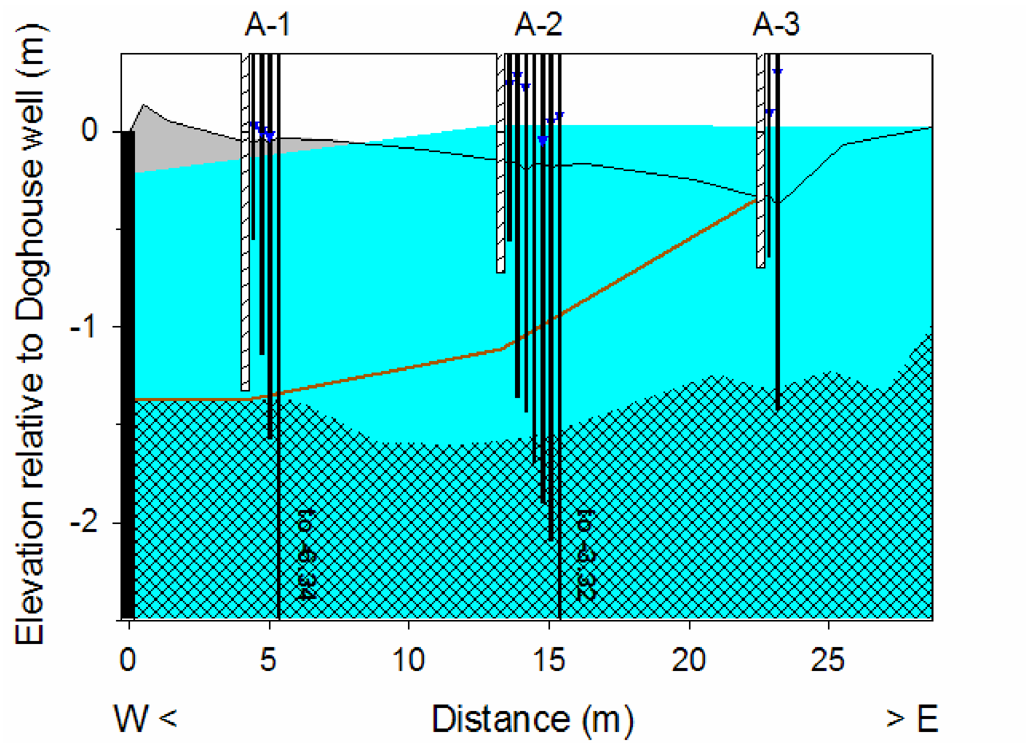


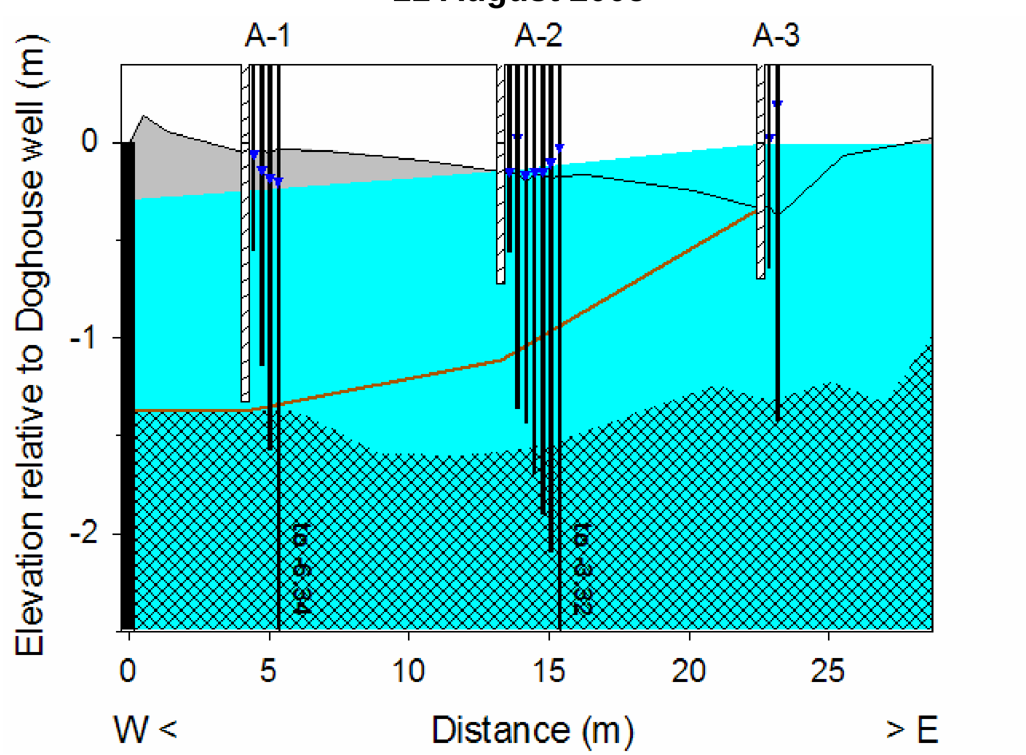

9 August 2004
A-1
A-2
A-3
Elevation relative to Doghouse well (m)
0
-1
-2
to -6.34
to 3.32
0
5
10
15
20
25
W <
Distance (m)
> E

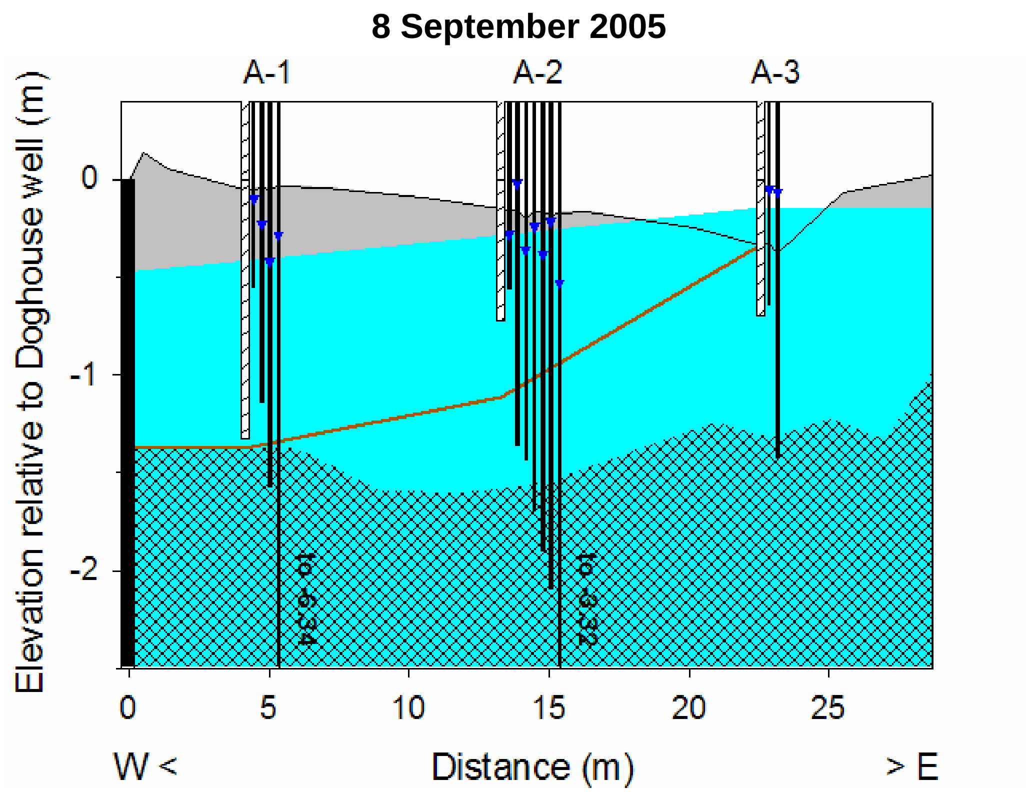

6 November 2004
A-1
A-2
A-3
Elevation relative to Doghouse well (m)
0
-1
-2
to -6.34
to 3.32
0
5
10
15
20
25
W <
Distance (m)
> E

**11 July 2005**




**11 August 2005**




8 September 2005
A-1
A-2
A-3
Elevation relative to Doghouse well (m)
0
-1
-2
to -6.34
to -3.32
0
5
10
15
20
25
W <
Distance (m)
> E