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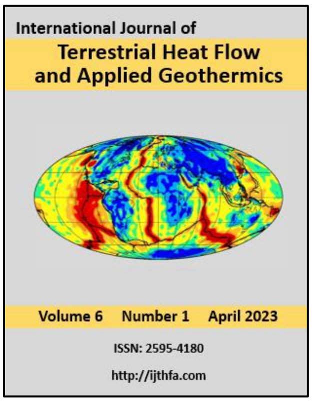

Diurnal Variations in Vegetation Activity affecting Shallow Groundwater Flow identified by Microthermal Measurements

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Abstract

Observations of summer microthermal temperature variations suggest, next to hydrological factors, a significant influence of plant activity on groundwater flow in fractured claystone materials. Variations in groundwater microtemperature were compared to variations in meteorological parameters and electrical potential of plants. With an increase in surface temperature, relative air humidity decreases and an increase in tree electrical potential, measured as the difference between the northern and the southern stem exposure (N–S), can be observed. This increase in electrical potential is concomitant with a change in groundwater temperature of approximately 2 mK. This relationship does not always occur. At high temperatures (+30°C) the decrease amounts to just 1 mK. This fact is related to the change in transpiration of plants, decreased or even suspended at high surface temperatures. A frequency analysis of all data showed a daily frequency of high magnitude in all parameters. Possibly changes in the macro weather situation events were observed in the results of atmospheric pressure, southern electric potential and groundwater temperature. The lag time between changes in electric potential and subsurface microtemperature changes amounts to 17 hours, possibly a result of the electrical potential difference between the northern and the southern exposure of the stem (N–S), and 5 hours, the result of the change in electrical potential difference between the southern and the northern stem exposure side (S–N). A comparison between potential changes and the computed change in gravity resulting from earth tidal effects showed that the correlation between the subsurface temperature variation with up to 2 mK and the change in surface temperature variation does not match directly. Other study shows that the impact of earth tides on subsurface microtemperature variation amounts to ca. 1mK. The effect of groundwater abstraction by mature vegetation is determined at the same range. Atmospheric tides can be correlated with the changes in north and south electric potentials.

1. Introduction

With the advancement of technology, high precision and high resolution microtemperature measurements became available, and what were once regarded as incoherent results are now well defined signals studied and interpreted by different scientific communities (Briciu, 2018; Shimamura and Watanabe, 1981; Shimamura et al., 1984; Jahr et al., 2020; Buntebarth, 1997; Demetrescu and Shimamura 1997; Hamza 1997; Drury, Jessop, and Lewis 1984; Richter and Cruiziat 2002). Geothermal measurements in environmental monitoring are known for their ease of installation, stable and long-term monitoring quality, and low interference with the respective environment. Seismic signals, past weather events, terrestrial and atmospheric tidal signals, as well as plant activity signals could be correlated with systematic changes in groundwater temperature (Briciu, 2018; Shimamura and Watanabe, 1981; Shimamura et al., 1984; Jahr et al., 2020; Buntebarth, 1997; Demetrescu and Shimamura, 1999; Hamza, 1998; Drury et al., 1984; Pinheiro et al., 2021; Buntebarth et al., 2019; Čermák, 1971; Bodri and Čermák, 2011).

The hydrologic cycle is highly affected by changes in vegetation cover. One of the important driving forces in this cycle is transpiration by plants. This process returns approximately 50% of precipitation to the atmosphere, and accounts for over 60% of the evapotranspiration rate. Vegetation is thus exposed to and governed by different meteorological parameters, as well as by the availability of water in the soil and subsoil (Burr, 1947; Chahine, 1992; dos Santos et al., 2017; Good et al., 2015; Kumar et al., 2014; Schlesinger and Jasechko, 2014; Sun et al., 2011; Taiz et al., 2015; Volkov and Ranatunga, 2006). This process can easily explain that woody plants interfere with the groundwater recharge process changing water infiltration rates, evapotranspiration, interception, as well as changes caused by afforestation or deforestation (Le Maitre et al., 1999; Antunes et al., 2018; Acharya et al., 2018; Bense et al., 2013; Kordilla et al., 2012). These studies however did not address the relationship between changes in groundwater microtemperature and plant activity during the growing season (Buntebarth et al., 2019; Pinheiro et al., 2021). Here, we compare short-term, i.e. daily variation of groundwater microtemperature with the ionic flux in a tree.

1.1. Vegetation and Electric Potential

Electric potentials in plants has been studied for some time and has its history summarized in a review by (Schuch and Wanke, 1969). Some studies have shown that despite the periodic daily variation of electric potential in plants (Koppan et al., 2000; Burr, 1947; Gibert et al., 2006; Ansari and Bowling, 1972), there is no direct link to xylem flow (Gibert et al., 2006; Likulunga et al., 2022; Love et al., 2008). Other factors are also responsible for triggering these electrical impulses, such as temperature variations, pollination, and variation in water availability (Fromm and Lautner, 2007). These factors result in varying water content of plants (Likulunga et al., 2022). Soil water abstracted by the roots contains ions and is therefore electrically conductive. This electrolyte is lifted and moves to the top of a tree, creating an electric current that can be determined as an electric potential in the tree trunk (Ansari and Bowling, 1972; Volkov and Ranatunga, 2006).

2. Methodology

To compare plant activity with variations in groundwater temperature and other meteorological parameters, two devices were employed. For the measurement of groundwater temperature, a high-precision thermometer with a resolution of 0.0002 degrees (www.geotec-instruments.com) was used. The instrument is protected by a waterproof box and directly located at the well head of an 80 m deep borehole. A stainless-steel waterproof case protects the calibrated temperature sensor attached at a depth of 40 m. In addition to groundwater temperature, air temperature at the tree was recorded as well.

The electric potential was monitored in a tree specimen of the *Prunus avium* species (Figure 1). The equipment used was LogBox ecoV, manufactured by geeotec (www.geotec-instruments.com). Two pairs of platinum electrodes were placed on two sides of the stem, exposed to the north and south. Vertical distance between the two electrode pairs amounts to approximately one meter, following the protocol of (Koppan et al., 2000). The horizontal distance measures approximately 41 cm. In addition to the north and south electric potentials, relative humidity, and air temperature close to the electrodes, as well as atmospheric pressure were recorded. Frequency analyses were conducted for the monitoring results, employing a python software.

Figure 1 – Prunus avium with installed LogBox ecoV.

3. Results and discussion

Data for groundwater temperature, air temperature and relative humidity, as well as electric potential are presented in Figure 2. To eliminate the effect of atmospheric tides the electric potential was presented as the difference between north and south potential. Earlier results (Buntebarth et al., 2019; Pinheiro et al., 2021) showed a relationship between groundwater microtemperature and surface air temperature, indicating a strong relationship with the onset of the growing season of the plants. In the present data we observe a similar relationship for the summer period (Figure 2). Further, the increase of the electrical potential in plants is synchronized with an increase of surface temperature and a decrease in relative humidity.

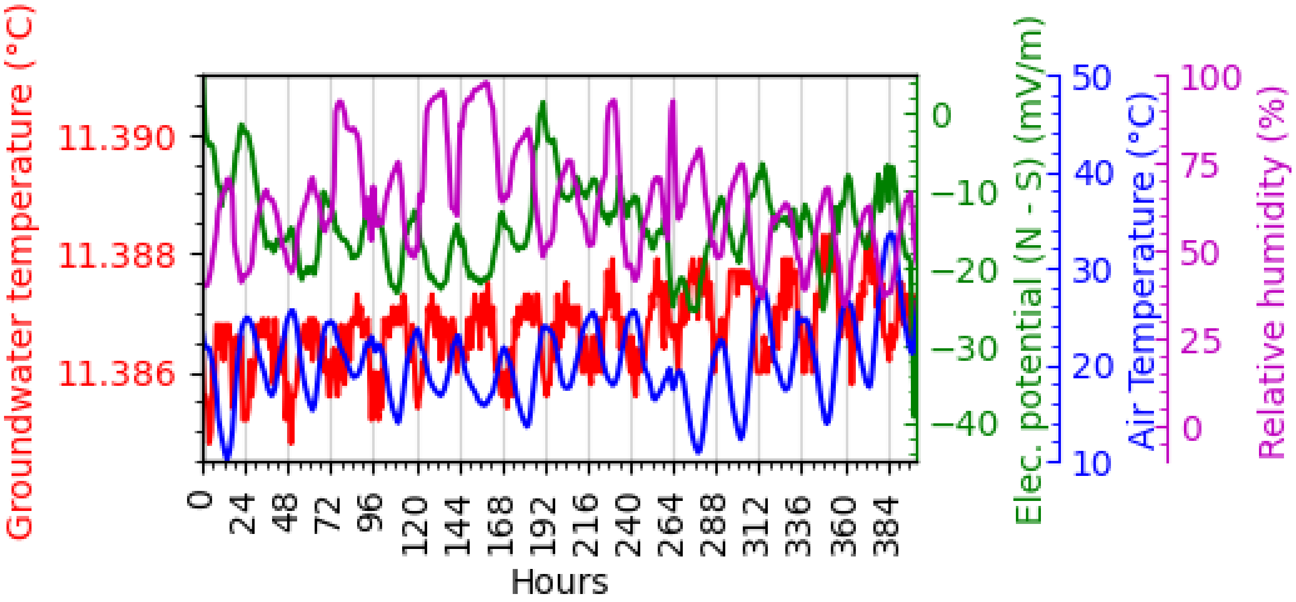

Figure 2 – Original signals: relative humidity, electric potential (N-S), air temperature and groundwater temperature.

A frequency analysis (Figure 3) revealed a diurnal frequency (24 hours) of different magnitude for all variables. This frequency is directly related to solar radiation. Lower frequencies with larger amplitudes were observed for atmospheric pressure, southern electric potential and groundwater temperature (Figure 3). These frequencies represent possibly changes in the macro weather situation. North and south electric potentials (Figure 3) show a half-diurnal frequency (12 hours) and a weak 8-hour amplitude. This frequency is eliminated from the electric potential by subtracting one from the other (Figure 3).

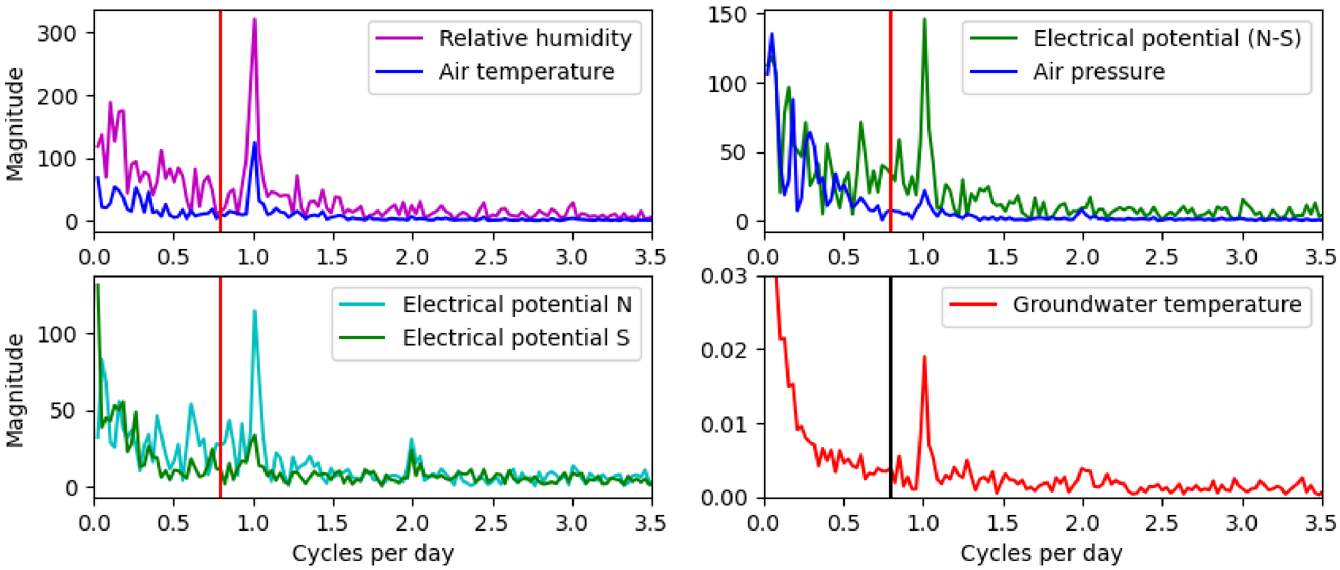

Figure 3 – Frequency analysis of the different variables: relative humidity, electric potential (N-S), air temperature, air pressure, electric potential North (N), electric potential South (S), and groundwater temperature.

3.1. Geothermal and surface temperature

The variation of groundwater temperature at depths of up to 30 meters is influenced by the daily and seasonal variation of the temperature at the surface. Beyond this depth thermal conductivity is not applied (Tautz 1971; Buntebarth, Pinheiro, and Sauter 2019) and surface temperature variations are not detectable by techniques available today.

Groundwater is clearly affected by vegetation activities (Le Maitre, et al., 1999; Antunes et al., 2018; Acharya et al., 2018; Bense et al., 2013; Kordilla et al., 2012). Studies show that during the dry season some plants abstract water up to a depth of approximately 6 meters (Antunes et al., 2018). In fractured rock materials with high Hydraulic diffusivities (Buntebarth et al., 2019), this effect can be detected also at large depths of several tens of meters. The review by (Acharya et al., 2018) reports that areas with woody vegetation show higher evapotranspiration and therefore a decrease in recharge. It also suggests that infiltration increases in these areas, when land cover allows it. In this study (Figure 2) a temperature decrease of approximately 2 mK with an increase in surface temperature is observed. This relationship does not always apply. In our earlier work (Buntebarth et al., 2019; Pinheiro et al., 2021)we showed that, with the beginning of the growing season, this relationship applies for surface temperatures above 9°C. Figure 4 shows that with temperatures approaching very high values (> 30°C) the temperature difference is less than 2 mK. With very high temperatures and/or prolonged exposure to higher temperatures, stomata tend to close, thus reducing transpiration rates to avoid both excessive water loss and cavitation (Richter and Cruiziat, 2002; Tibbitts, 1979; Taiz et al., 2015). Some studies confirm a higher activity in plants during spring/summer periods compared to that of fall/winter (Burr, 1947; Gibert et al., 2006; Hao et. at., 2021).

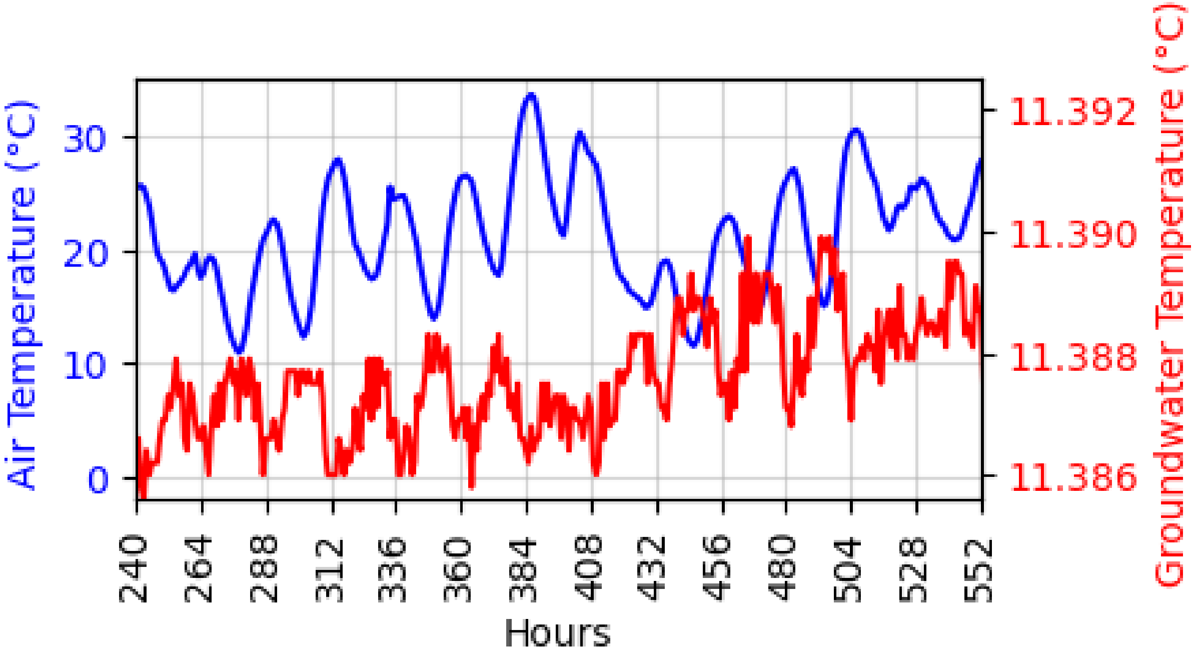

Figure 4 – Original signal: air temperature and groundwater temperature.

3.2. Geothermal temperature and electric potential

The periodic variation in plant electrical potential observed during our study period (Figure 2) was evidenced in other studies (Burr, 1947; Gibert et al., 2006; Hao et al., 2021; Likulunga et al., 2022). There are daily and annual periodic variations. Studies show that the amplitude of the electric potential change is larger during spring/summer periods compared to those of fall/winter times (Burr, 1947; Gibert et al., 2006; Hao et al., 2021), consistent with the results presented here and in our earlier studies (Buntebarth et al., 2019; Pinheiro et al., 2021).

Comparing electric potential (N-S) with groundwater temperature, a systematic relationship becomes obvious. This relationship can be observed in both, the original raw signal (Figure 5) and the frequency analysis (Figure 3). There is a predominant relationship directly correlated to the intensity of solar radiation. From the phase shift the response time between groundwater temperature and electric potential can be determined at 17 hours (Figure 6). In this case, there would be a decrease in groundwater temperature caused by the abstraction of water and after 17 hours an increase in the electric potential. Please note that we consider here the difference in electric potential between North and South exposure positions. For a South - North difference, the phase shift becomes 5 hours. Gibert and co-workers (Gibert et al., 2006) report that there is a temporal difference between a change in xylem flux and the change in electric potential. The electric potential returns to its original value after ca. 8 h, while a zero-sap-flow is already reached after ca. 4 h.

The presence of a measurable electrical potential in dead plants, and a zero-change in potential in plants with reduced transpiration rate indicate that sap flow is not the only mechanism explaining electric potential changes (Hao et al., 2021). Hao relates the electrical potential of plants direct to water content, which resulted in a good hypothesis, especially when we consider that the changes suffered by plants caused by environmental variations can be observed in the variation of groundwater temperature.

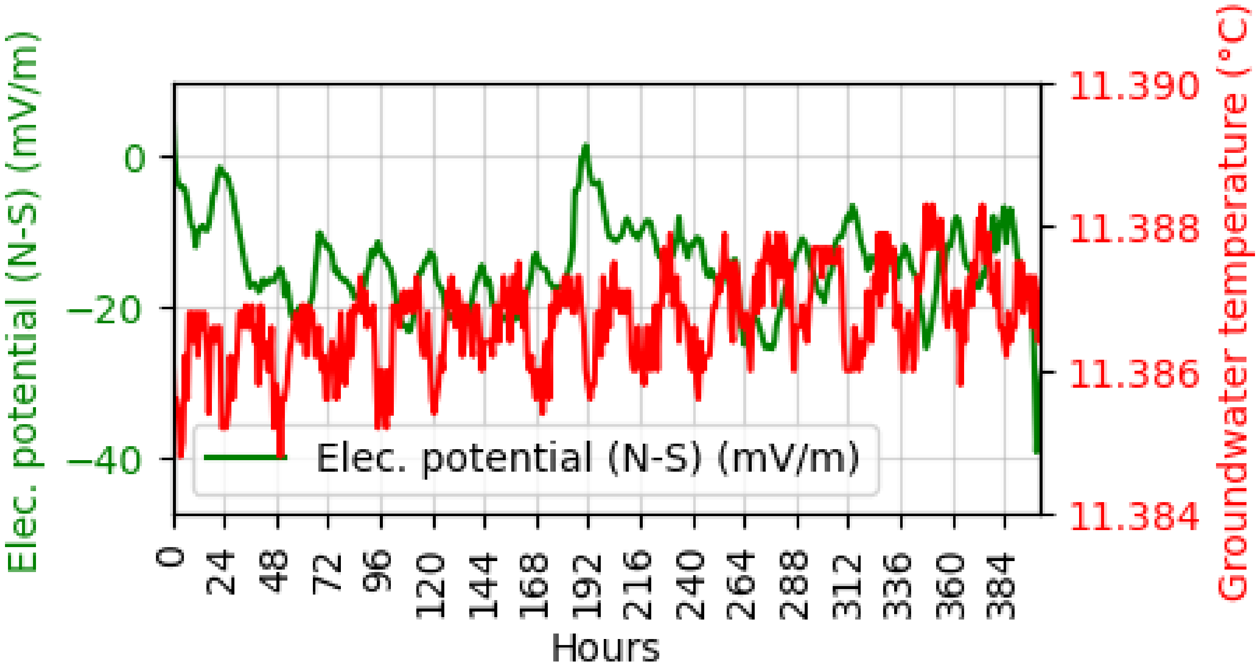

Figure 5 – Original signal: electrical potential (N-S) and groundwater temperature.

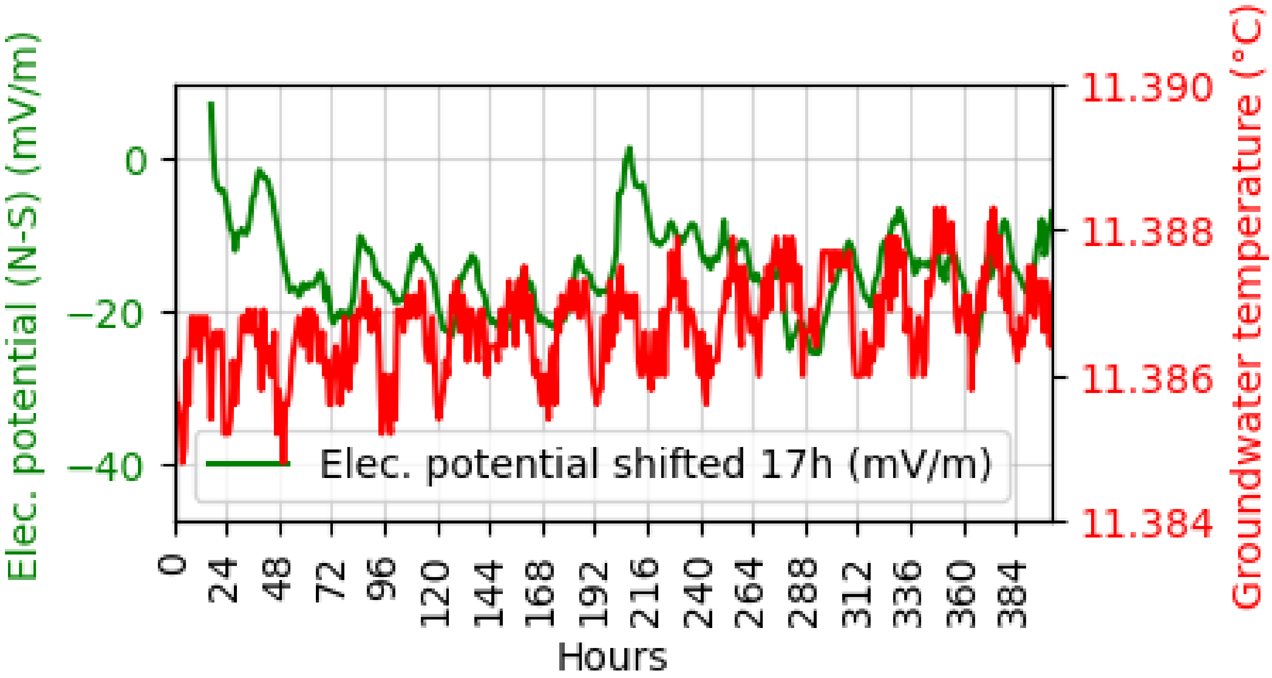

Figure 6 – Phase shift between the different signals: electrical potential difference (N-S) is shifted by 17h compared to groundwater temperature.

3.3. Geothermal temperature and terrestrial tides

Both, groundwater flow (Doan et al., 2006; Toll and Rasmussen, 2007; Wang et al., 2018; Merritt, 1999; Allègre et al., 2016; Hsieh et al., 1988; Acworth and Brain, 2008; Roeloffs, 1988; McMillan et al., 2019) and vegetation activity (Holzknecht and Zürcher, 2006; Fisahn, 2018; Burr, 1947; Zürcher et al., 1998; Zürcher, 2006; Zürcher and Schlaepfer, 2014; Zürcher, 2019) are affected by earth tides. In some studies, the effect of tides must be removed from groundwater monitoring results to be able to better interpret hydrogeological tests (Toll and Rasmussen, 2007). In other studies, hydrogeological parameters can be derived from potential changes induced by earth tides (Hsieh et al., 1988; Wang et al., 2018; Allègre et al., 2016; McMillan et al., 2019). In plants, even in the absence of light, some studies relate the growth of tree stems to lunar phases (Zürcher et al., 1998; Holzknecht and Zürcher, 2006), others report the variation of leaf movement (Fisahn, 2018). There are also reports of a change in the speed of germination with a change in earth tidal forces (Zürcher and Schlaepfer, 2014). Still, none of these studies can explain our observations concerning to the influence of earth tides combined with vegetation activity and atmospheric electricity. In our study we observe a relationship between the change in theoretical earth tidal forces and changes in groundwater temperature and electric potential. For better analysis, groundwater temperatures of different frequencies were separated (Figure 3 - vertical line). Temperatures of lowest frequencies representing changes in the macro weather situation, were removed. Just looking at daily groundwater temperature changes (Figure 7), starting at 15:00, an amplitude of ca. 2 mK is observed, while a variation of about 10 mV/m is reflected in the electric potential changes (Figure 7). A direct relationship between groundwater temperature change and the change in terrestrial tidal forces could not be detected. Furthermore, a semidiurnal variation (12 hours peak) in electric potential was not observed in the frequency analysis (Figure 3). Zhou et al., 2022, used the same geothermometer as employed here and came to the conclusion that the magnitude of the microtemperature variation of groundwater is related to the variation in earth tidal forces amounts to a maximum of 1 mK. This observation is confirmed by our study, showing that the the effect of vegetation and the effect of the tidal are in the same range of variation (Pinheiro et al., 2021; Jahr et al., 2020; Buntebarth et al., 2019).

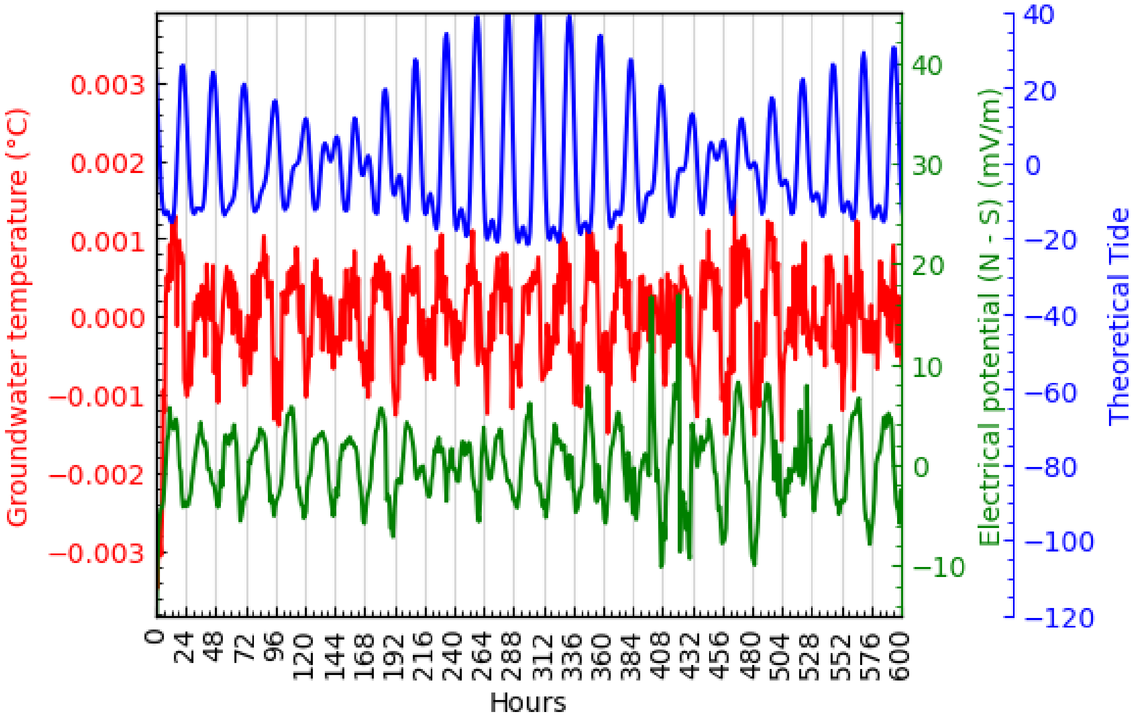

Figure 7 – Inverse frequency analysis: theoretical tide, electric potential (N-S), and groundwater temperature variation

3.4. Geothermal temperature and atmospheric tides

Comparing north and south electric potentials with the surface of the earth is negatively charged. The electrostatic field strength near the earth's surface is about 110-220 V/m and depends on the daily weather conditions (Volkov and Ranatunga, 2006). Atmospheric electricity has long been studied (Elster and Geitel, 1899a; 1899b; 1899c) and exhibits seasonal variation (Harrison, 2012). While land and ocean tides are gravitationally controlled, atmospheric tides are mainly thermally controlled (Lanzerotti and Gregori, 1986; Meloni et al., 1983). In our study the effect of atmospheric tides is observed in north and south electric potentials changes subjected to frequency analysis (Figure 3), also observed by (Le Mouël et al., 2010). Tides in the upper atmosphere are not mentioned by Burr (Burr, 1947), probably because they were not part of the scope of the mentioned work. This semi-diurnal frequency is also present in the atmospheric pressure result (Figure 3).

Groundwater temperature records (Figures 8 and 9), we observe that there is a clear relationship between both parameters. The south electric potential is however more highly affected by weekly interferences, possibly caused by variations in atmospheric pressure (Figure 3).

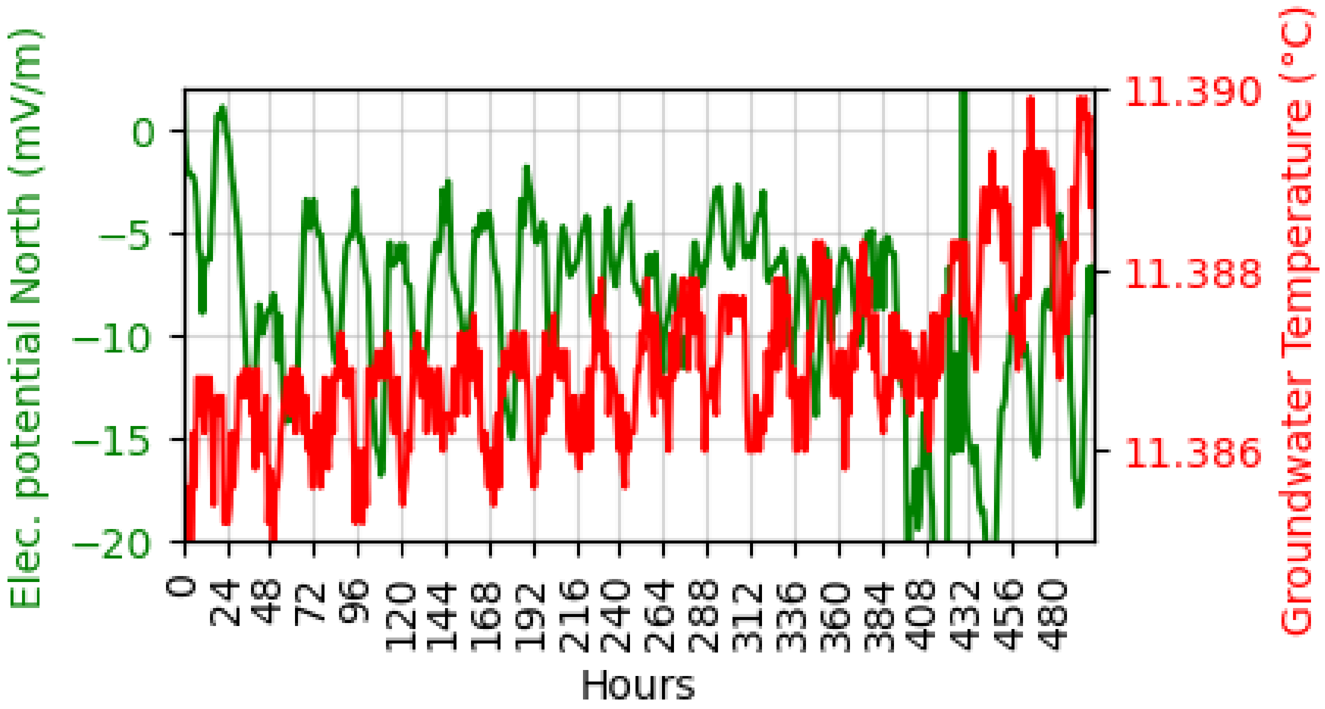

Figure 8 – Original signal: electrical potential North (N) and groundwater temperature.

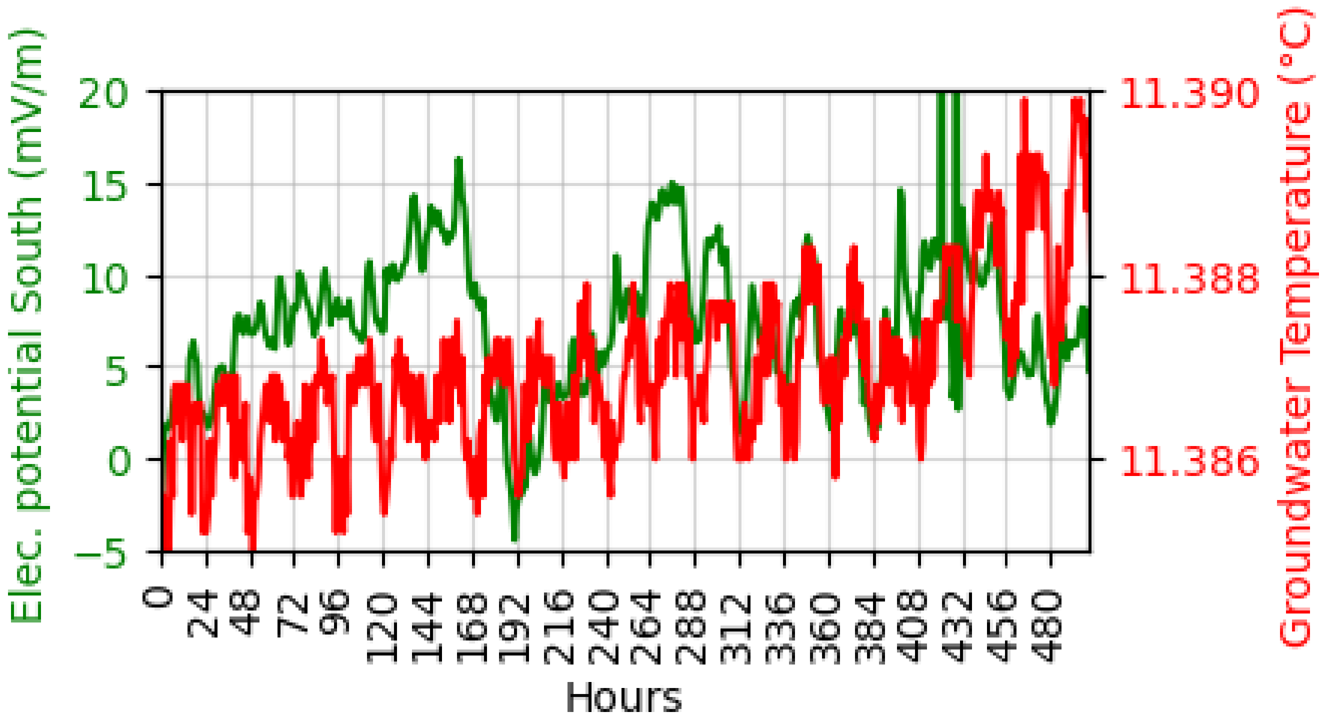

Figure 9 – Original signal: electrical potential South (S) and groundwater temperature.

4. Conclusion

Considering that plant transpiration is responsible for most of the water transfer between the subsurface and the surface, we understand that the explanation of a relationship between groundwater microtemperature and plant activity is plausible. We also understand that the advance of technology, in particular geothermal thermometers allows high temperature resolution measurements previously not available. Furthermore, atmospheric electricity can be a plausible force affecting plant activity.

Finally, we do not exclude the presence of other forces acting on natural processes. The use of conceptual models, and especially of boundary conditions, separating, for example, surface and subsurface phenomena, are widely applied and allow to explain the system response to changes in the environmental conditions. However, an interdisciplinary interaction is required to be able to explain the functioning of a system affected.

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References

Acharya, B., Kharel, G., Zou, C., Wilcox, B., Halihan, T. 2018. Woody Plant Encroachment Impacts on Groundwater Recharge: A Review. Water. vol. 10(10). p. 1466.

Acworth, R. I., Brain, T. 2008. Calculation of barometric efficiency in shallow piezometers using water levels, atmospheric and earth tide data. Hydrogeology Journal. vol. 16. pp. 1469-1481.

Allègre, V., Brodsky, E.E., Xue, L., Nale, S.M., Parker, B.L., Cherry, J.A. 2016. Using earth-tide induced water pressure changes to measure in situ permeability: A comparison with long-term pumping tests. Water Resources Research. vol. 52. pp. 3113-3126.

Ansari, A.Q., Bowling, D.J.F. 1972. Measurement of the Trans-Root Electrical Potential of Plants Grown in Soil. New Phytologist. vol. 71. pp. 111-117.

Antunes, C., Chozas, S., West, J., Zunzunegui, M., Diaz Barradas, M.C., Vieira, S., Máguas, C. 2018. Groundwater drawdown drives ecophysiological adjustments of woody vegetation in a semi-arid coastal ecosystem. Global Change Biology. vol. 24(10). pp. 4894-4908.

Bense, V. F., Gleeson, T., Loveless, S.E., Bour, S.O., Scibek, J. 2013. Fault zone hydrogeology. Earth-Science Reviews. vol. 127. pp. 171-192.

Bodri, L., Čermák, V. 2011. Borehole climatology: a new method how to reconstruct climate (Elsevier).

Briciu, A.E. 2018. Diurnal, semidiurnal, and fortnightly tidal components in orthotidal proglacial rivers. Environmental Monitoring and Assessment, 190(3), p.160.

Buntebarth, G. 1997. Microtemperature signals of the Earth's Crust. In: 5th International Congress of the Brazilian Geophysical Society (pp. cp-299). EAGE Publications BV.

Buntebarth, G., Pinheiro, M., Sauter, M. 2019. About the penetration of the diurnal and annual temperature variation into the subsurface. International Journal of Terrestrial Heat Flow and Applied Geothermics. vol 2. pp.1-5.

Burr, H.S. 1947. Tree potentials. The Yale journal of biology and medicine, vol.19(3). p.311.

Čermák, V. 1971. Underground temperature and inferred climatic temperature of the past millenium. Palaeogeography,Palaeoclimatology, Palaeoecology. vol 10. pp. 1-19.

Chahine, M.T. 1992. The hydrological cycle and its influence on climate. Nature. vol 359. pp. 373-380.

Demetrescu, C., Shimamura H. 1999. Groundwater microtemperature measurements in Romania. pp. 142-146. *Microtemperature Signals of the Earth's Crust*.

Doan, M.L, Brodsky, E.E., Prioul, R., Signer, C. 2006. Tidal analysis of borehole pressure - A tutorial. University of California, Santa Cruz, 25, 27.

dos Santos, M.A., de Jong van Lier, Q., Van Dam, J.C., Freire Bezerra, A.H. 2017. Benchmarking test of empirical root water uptake models. Hydrology and Earth System Sciences. vol. 21. pp. 473-493.

Drury, M. J., Jessop, A.M., Lewis, T. J. 1984. The detection of groundwater flow by precise temperature measurements in boreholes. Geothermics. vol. 13. pp.163-174.

Elster, V.J., Geitel, H. 1899a. Beobachtungen über die Eigenelectricität der atmosphärischen Niederschläge. Terrestrial Magnetism and Atmospheric Electricity. vol. 4. pp. 15-32.

———. 1899b. Über die Existenz electrischer Ionen in der Atmosphäre. Terrestrial Magnetism and Atmospheric Electricity. vol. 4. pp. 213-34.

———. 1899c. Weitere Versuche an Becquerelstrahlen. Annalen der Physik. vol. 305. pp. 83-90.

Fisahn, J. 2018. Are there tides within trees? Ann Bot. vol. 122. pp. 735-739.

Fromm, J., Lautner, S. 2007. Electrical signals and their physiological significance in plants. Plant Cell Environ. vol. 30. pp. 249-257.

Gibert, D., Le Mouël, J.L., Lambs L., Nicollin, F., Perrier, F. 2006. Sap flow and daily electric potential variations in a tree trunk. Plant Science. vol. 171(5). pp. 572-584.

Good, S.P., Noone, D., Bowen, G. 2015. Hydrologic connectivity constrains partitioning of global terrestrial water fluxes. Science. vol. 349. pp. 175-177.

Hamza, V.M. 1998. Models of short-lived thermal pulses generated by tectonic fluid flows in the upper crust. *Microtemprature Signals of the Earth's Crust*, edited by: Buntebarth, G., Zellerfeld, Germany, Papierflieger, Clausthal.

Hao, Z., Li, W., Hao, X. 2021. Variations of electric potential in the xylem of tree trunks associated with water content rhythms. Journal of Experimental Botany. vol. 72(4). pp. 1321-1335.

Harrison, R.G. 2012. The Carnegie Curve. Surveys in Geophysics. vol. 34. pp. 209-232.

Holzknecht, K., Zürcher, E. 2006. Tree stems and tides – A new approach and elements of reflexion (reviewed paper). Schweizerische Zeitschrift fur Forstwesen. vol. 157. pp. 185-190.

Hsieh, P.A., Bredehoeft, J.D., Rojstaczer, S.A. 1988. Response of Well Aquifer Systems to Earth Tides: Problem Revisited. Water Resources Research. vol. 24. pp. 468-472.

Jahr, T., Buntebarth G., Sauter, M. 2020. Earth tides as revealed by micro-temperature measurements in the subsurface. Journal of Geodynamics. vol 136. p.101718.

Koppan, A., Szarka, L., Wesztergom, V. 2000. Annual fluctuation in amplitudes of daily variations of electrical signals measured in the trunk of a standing tree. Comptes Rendus de l'Académie des Sciences-Series III-Sciences de la Vie. vol. 323. pp. 559-563.

Kordilla, J., Sauter, M., Reimann, T., Geyer, T. 2012. Simulation of saturated and unsaturated flow in karst systems at catchment scale using a double continuum approach. Hydrology and Earth System Sciences Discussions. vol. 9. pp. 1515-1546.

Kumar, R., Shankar, V., Jat, M.K. 2014. Evaluation of root water uptake models – a review. ISH Journal of Hydraulic Engineering. vol. 21. pp. 115-124.

Lanzerotti, L.J., Gregori, G.P. 1986. Telluric Currents: The Natural Environment and Interactions with Man-Made Systems. The Earth’s electrical environment, National Academy Press, Washington, DC: 232-57.

Le Maitre, D.C., Scott, D.F., Colvin, C. 1999. A review of information on interactions between vegetation and groundwater. Water SA. vol. 25. pp. 137-152.

Le Mouël, J.L., Gibert, D., Poirier, J.P. 2010. On transient electric potential variations in a standing tree and atmospheric electricity. Comptes Rendus Geoscience. vol. 342. pp. 95-99.

Likulunga, E., Clausing, S., Krüger, J., Lang, F., Polle, A. 2022. Fine root biomass of European beech trees in different soil layers show different responses to season, climate, and soil nutrients. Frontiers in Forests and Global Change, vol. 5.

Love, C. J., Zhang, S., Mershin, A. 2008. Source of sustained voltage difference between the xylem of a potted Ficus benjamina tree and its soil. PLoS One. vol. 38(8). p. e2963.

McMillan, T.C., Rau, G.C., Timms, W.A., Andersen, M.S. 2019. Utilizing the Impact of Earth and Atmospheric Tides on Groundwater Systems: A Review Reveals the Future Potential. Reviews of Geophysics. vol. 57. pp. 281-315.

Meloni, A., Lanzerotti, L.J., Gregori, G.P. 1983. Induction of currents in long submarine cables by natural phenomena. Reviews of Geophysics. vol. 21(4). pp. 795-803.

Merritt, M.L. 1999. Estimating Hydraulic Properties of the Floridan Aquifer System by Analysis of Earth-Tide, Ocean-Tide, and Barometric Effects, Collier and Hendry Counties, Florida. U.S. Department of the Interior, US Geological Survey. Rep. 03. p. 4267.

Pinheiro, M., Buntebarth G., Polle A., Sauter M. 2021. Short- and long-term variations in groundwater temperature caused by changes in vegetation cover. International Journal of Terrestrial Heat Flow and Applied Geothermics. vol. 4. pp. 127-134.

Richter, H, Cruiziat, P. 2002. A brief history of the study of water movement in the xylem. Online document. Essay, 4.

Roeloffs, E.A. 1988. Hydrologic Precursorsto Earthquakes:A Review. Pure and Applied Geophysics. vol. 126. pp. 2-4.

Schlesinger, W. H., Jasechko, S. 2014. Transpiration in the global water cycle. Agricultural and Forest Meteorology. vol. 189. pp. 115-117.

Schuch, M., Wanke, R. 1969. Die zeitliche Variation der elektrischen Stromungsspannung auf kurzen Mefistreden im Torfboden als Folge kapillarer Wasserbewegungen. Beitrag zur hydrologischen Dekade der Unesco. Zeitschrift für Pflanzenernährung und Bodenkunde. vol. 122(2). pp. 112-128.

Shimamura, H., Ino, M., Hikawa, H., Iwasaki T. 1984. Groundwater Microtemperature in Earthquake Regions. Pure and Applied Geophysics, 122. pp. 933-946.

Shimamura, H., Watanabe, H. 1981. Coseismic changes in groundwater temperature of the Usu volcanic region, Nature, 291(5811), 137-138.

Sun, G., Alstad K., Chen, J., Chen, S., Ford, C.R., Lin, G., Liu, C., Lu, N., McNulty, s.G., Miao, H., Noormets, A., Vose, J.M., Wilske, B., Zeppel, M., Zhang, Y., Zhang, Z. 2011. A general predictive model for estimating monthly ecosystem evapotranspiration. Ecohydrology. vol. 4(2). pp. 245-255.

Taiz, L., Zeiger, E., Møller, I.M., Murphy, A. 2015. Plant physiology and development (no. Ed.6). Sinauer Associates Inc.

Tautz, H. 1971. Wärmeleitung und Temperaturausgleich: die mathematische Behandlung instationärer Wärmeleitungsprobleme mit Hilfe von Laplace-Transformationen. (Verlag Chemie).

Tibbitts, T.W. 1979. Humidity and Plants. BioScience. vol. 29. pp. 358-363.

Toll, N.J., Rasmussen, T.C. 2007. Removal of barometric pressure effects and earth tides from observed water levels. Ground Water. vol. 45. pp. 101-105.

Volkov, A.G., Ranatunga, D.R. 2006. Plants as environmental biosensors. Plant Signaling & behavior. vol. 1(3). pp. 105-115.

Wang, C.Y., Doan, M.L., Xue, L., Barbour, A.J. 2018. Tidal Response of Groundwater in a Leaky Aquifer – Application to Oklahoma. Water Resources Research. vol. 54. pp. 8019-8033.

Zhou, J., Pan, E., Sun, E., Xu, J., Chen, X. 2022. Temperature Variation in a Homogeneous Sphere Induced by the Tide-Generating Force. Pure and Applied Geophysics. vol. 180. pp. 747-754.

Zürcher, E. 2006. Chronobiology of trees: Synthesis of traditional phytopractices and scientific research as tools of future forestry. In: International Conference on Endogenous Development and Bio-Cultural Diversity. Geneva, Switzerland.

———. 2019. Water in Trees, An essay on astonishing processes, structures and periodicities. Substantia. vol. 3. pp. 75-87.

Zürcher, E., Cantiani, M.G., Guerri, F.S., Michel, D. 1998. Tree stem diameters fluctuate with tide. Nature. vol. 392. pp. 665-666.

Zürcher, E., Schlaepfer, R. 2014. Lunar Rhythmicities in the Biology of Trees, Especially in the Germination of European Spruce (Picea abies Karst.): A New Statistical Analysis of Previously Published Data. Journal of Plant Studies. vol. 3(1). pp. 103-113.