Effect of temperature on D.O and T.D.S: A measure of Ground and Surface Water Interaction

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ABSTRACT
To statistically quantify ground and surface water interaction using temperature as a tracer and its effect on chemical properties of rivers, a total number of 30 sample points were selected at regular intervals along the profile of the two rivers. Ten points on the upper Oga River, and ten on the Alaro River, the remaining ten on the lower section of the river. Also, a corresponding number of nearby groundwater samples were obtained from a parallel source, for each of the surface water sample points so as to aid comparison. The coordinates of the sample points along the river profile were obtained using a global positioning system (GPS) device. The result of the investigation showed that two of the properties (Total Dissolved Solid and Dissolved Oxygen) of surface water vary significantly while the third (Temperature) does not vary significantly across the river profile extending from the upstream section to the downstream section. It was further observed that the underlying geology in terms of rock types have a significant influence on the properties of the surface water body, this was corroborated through comparison of the groundwater properties against that of the surface water. No significant correlation was observed between temperature and total dissolved solids and dissolved oxygen, thus inferring no form of noteworthy influence from temperature on the considered parameters in this study. The analysis of temperature gradients along a river profile and its effect on water properties provided an insight to the quantitative estimates of rates of interaction through the use of statistics and a possible inferred direction.

KEYWORDS
Groundwater; surface water; interaction; temperature; dissolved oxygen; total dissolved solid

Introduction
Surface water and groundwater were once regarded as distinct resources that could be used and managed independently. The shortcomings of this practice became obvious where sustained depletions of one resource negatively impacted the other (Glennon, 2002). Water that moves between a stream and adjacent sediments carries with it measureable amounts of heat and this can be tracked by quantifying the temperature. Therefore, solar-driven temperature fluctuations at the land surface provide signals. Temperature plays a key role in the health of streams, in terms of quality including the benthic habitat of streambed sediments. Stream temperatures are influenced by exchanges (exchanges include solutes, in addition to water and heat) between streams and nearby groundwater (Surfleet & Louen, 2018). Heat provides a natural tracer of groundwater movement that is readily tracked by measuring temperature. Freshwater aquifers, especially those with limited recharge by meteoric water, can be over-exploited and, depending on the local hydrogeology, may draw in non-potable water from hydraulically connected aquifers to surface water bodies. In some areas, the groundwater can be contaminated by mineral poisons, such as arsenic (Chouvelon et al., 2017).

As water passes through streambed sediments, chemical reactions occur that change its composition and thus affect water quality. Dissolved materials increase due to mineral dissolution. Exchange and other reactions change the relative abundance of materials in solution. Changes in water chemistry can increase toward saturation as water continues to flow through geologic strata. If eventually, groundwater enters the stream, the stream’s chemical composition is affected (Constantz, Cox, & Su, 2003b). Exchanges of water can sometimes be tracked by monitoring the chemistry of water along flow paths. Flow paths can be traced at watershed scales or at the smaller scales of stream banks, sand bars, and local reaches of a stream (Bencala, Kennedy, Zellweger, Jackman, & Avanzino, 1984). Maldaner, Munn, Coleman, Molson, and Parker (2019) and Burow, Constantz, and Fuji (2005) assert that the use of heat as a tracer relies on the measurement of temperature gradients, and temperature is an extremely robust property to monitor (Constantz, 2008).

Exchanges between streams and shallow groundwater systems play a key role in controlling temperatures not only in streams, but also in their underlying lithology. As a result, analyses of subsurface temperature patterns provide information about surface-water/groundwater interactions, and tracing the movement...
of heat leads to a better understanding of the magnitudes and mechanisms of stream/ground-water exchanges (Cremeans, Devlin, McKnight, & Bjerg, 2018) and helps quantify the resulting effects on stream and streambed temperatures and its effect on the chemical properties of the river.

According to Constantz and Stonestrom (2003a) and Jones (2019), chemical tracers are commonly used for tracing flow between streams and ground water. The introduction of chemical tracers in near-stream environments is however limited by real and perceived issues regarding introduced contamination and practical constraints. As an alternative, naturally occurring variations in temperature can be used to track (or trace) the heat carried by flowing water. The hydraulic transport of heat enables its use as a tracer (Kurylyk, Irvine, & Bense, 2019).

The objectives of the paper are as follows:

- To determine the variation of temperature between surface water and groundwater across the river profile spanning over 10 km.
- To examine the influence of temperature on the dissolution minerals in the river mainly in terms of Total Dissolved Solids and Dissolved Oxygen.
- To ascertain any form of variation in the properties of the surface water across the three zones (upstream, mid/industrial, and downstream sections).
- To examine the hydrogeological cross-sectional properties of the rivers.

**Groundwater–Surface water (GW–SW) interactions**

The term GW–SW interaction defines the interrelationship between the groundwater and surface water resources. Groundwater and surface water resources rely on each other in various ways and sustainable management of these two interlinked resources requires a comprehensive understanding of their interactions. It is essential to understand the various components of the two water resources prior to investigating their interactions. Integrated management of groundwater and surface water resources is required in order to provide for the adequate protection of these resources. Groundwater can be best defined as water that occurs in saturated formations below the earth’s surface. Surface water resource simply refers to waterbodies such as lakes, river/streams, dams, and wetlands that exist on the earth’s surface. Groundwater-surface water interaction mechanism has been widely reported to occur through river/stream bed (Toth, 1963; Winter, 1998). Temperature fluxes and temperature patterns have been exploited to study subsurface flow systems (Sabina, Kinga, & Sławomir, 2020), ranging from irrigation water in rice paddies to geothermal water lying below volcanoes (Schneidewind et al., 2016; Sorey, 1971; Suzuki, 1960).

**Methodology**

**The study area**

This study was carried out in Ibadan, capital city of Oyo state (Plate 1), Nigeria. Ibadan is located on seven hills with an average elevation of 700 feet (200 meters), and about 100 miles (160 km) from the Atlantic coast. It is Nigeria’s second largest city (after Lagos), and located between Lat. 7° 22′N and 7° 56′N of the Equator and between Long. 3° 53′E and 4°E of the Greenwich Meridian. A number of different land use activities ranging from domestic to industrial abound in the Ibadan region (Plate 2). The industries in different regions are involved in diverse manufacturing activities including food and beverage processing, organic chemicals manufacturing, basic steel production, agricultural produce processing and production, auto repair workshops, concrete production, pharmaceuticals, agro-allied chemicals and manufacturing. Effluents from these industries around the study area are collected via a linkage of well-designed drainage system (proper drainage system) where they are channeled into adjoining river (the confluence of Ona and Alaro River). Apart from the industries in the study area, there are also several, agro allied activities, residential estates, and local communities. The two major rivers that flow through the industrial estate are free-flowing and highly turbid, particularly at the points of effluents’ discharge in the industrial zone. River Ona is larger and deeper with huge volume of water than River Alaro. These rivers were investigated over a stretch of distance, a portion of the whole stream profile (approximately 10 km) for water quality parameters.

**Data collection**

The sampling site is a portion (a stretch of about 10 km) of the whole River Ona profile. However, the second river, Alaro, is a tributary of the former. The starting point of the sampling point was at the Eleyele Lake for Ona River and at Oremeje Street for Alaro River. This section was carefully selected on each river and divided into three sections to include the upstream, industrial zones (which is home to a number of industries), and the downstream regions. This division is necessitated by the need to classify and understand the properties of the two rivers at different points based on the different land use type found along the stream profile, taking into account that the work is not targeted at the land use activities which were only
used to classify the study profile into three sections. This research required mainly data on the surface water quality parameters, as well as the stream temperature which was measured on-site in the study area. The quality of groundwater obtained from a groundwater source near each sample point was also tested in order to ascertain the relationship and better explain the interaction between the groundwater and surface water system, thus establishing the influence of geology of the water quality. This understanding is needed so as to establish the influence the two systems have on each other.

A total number of 30 sample points were selected along the chosen section of the profile of the two rivers, ten points on the Ona River, and ten on the Alaro River, the remaining ten on the confluence river. Thus, thirty surface water samples were obtained in the field with that aid of well sterilized 50cl bottles. Also, a corresponding number of nearby groundwater samples were obtained from a parallel number of sources (a shallow aquifer: well), for each of the surface water sample points so as to aid comparison. The coordinates of the sample points along the river profile were obtained using a global positioning system (GPS) device, and then inputted into the ArcGIS environment in generating a map of the study area showing the sample points (Plate. 3).

The data on the stream temperature were obtained from the field using a multi-meter (multiple parameter meter). This particular meter measures all the parameters involved in this study, i.e. Temperature, DO, and TDS. The procedure involved taking temperature measurement along the bank of the river where the surface water is in contact with the land which is one of the interface of interaction between groundwater and surface water, with other being the stream bed. Furthermore, stream temperature was taken in the morning at so as to minimize the influence of solar radiation on the stream temperature. The data on the chemical parameters such as DO and TDS were obtained on-site using the DO/TDS meter at each sample point while following necessary procedure to ensure accuracy. Also, the on-site measurement of the DO was done just as the case is with the stream temperature. The variation of the stream temperature value along the river profile will indicate a form of interaction as stated by Constantz and Stonestrom (2003a).

Furthermore, by comparing the properties of water obtained from the sample point against the properties of a nearby groundwater source (preferably a well), the influence of the underlying geology can be inferred from the relationship established through a comparative analysis of data obtained from both sample source. The choice of a well and not a borehole was necessitated by the fact that the water level of the chosen river of study may not be complemented by the level of the water table of a nearby

Plate 1: Map showing the Study Area (Source: Author, 2017)
borehole due to the position of the underlying aquifers as opposed to that of a well, in other words, a well is dug on an underlying shallow aquifer while boreholes are on deep-seated aquifers. The stretch of a total length of 10 km is validated by the need to have enough sample points so as establish a pattern of temperature variation along the profile, as this variation can be used to monitor groundwater movement as well as direction of flow and movement of groundwater along the stream profile (Constantz, 2008).

**Results**

**Influence of temperature on TDS and DO**

To assess the Stream temperature influence on TDS and DO, the Pearson’s Product Moment Correlation coefficient was used. A negative correlation with values of −0.206 was observed between temperature and dissolved oxygen, and a correlation value of −0.285 between temperature and total dissolved solids. At a confidence level of 95%, a negative correlation
Table 1 which is not significant was observed \((r = 0.206, -0.285; P > .05)\), it can be deduced that temperature does not have a direct influence on DO and TDS. The stream temperature influence on TDS and DO was depicted graphically with the aid of chart. The chart (Figure 1) reveals a form of influence of stream temperature on TDS at sample points with higher temperature values; however, this influence was not statistically significant. Conversely, sample point with higher temperature values is observed to have lower DO concentration levels.

**Temperature difference along river stretch**

The difference in the stream temperature of the two rivers before confluence was considered and hence the Mann-Whitney U-test was used to compare the parameter of these rivers and to ascertain the difference. The values of temperature obtained from both the upstream and industrial (midstream) sections of the two rivers are taken into account. In other words, a total number of five sample points from each zone on each river were selected for this analysis. Thus, a total of twenty sample points \((N = 20)\) were selected,

**Table 1. Influence of Temperature on DO and TDS.**

| Stream temperature | Pearson correlation | Dissolved oxygen | Total dissolved solids |
|--------------------|---------------------|-----------------|-----------------------|
| Sig. (2-tailed)    | .275                | −.206           | −.019                 |
| N                  | 30                  | 30              | 30                    |

Source: Author’s Analysis, 2017.
and were classified into two groups based on the number of rivers involved, and then used in carrying out the statistical analysis.

From the analysis of the provided data, it was concluded that the stream temperatures of the two rivers before confluence do not differ significantly (U = 50, p = 1.00). In other words, since the two rivers reflect the same mean rank, there is not any disparity between the two rivers before confluence (Table 2). The relationship between the two rivers in terms of temperature prior to confluence is also graphically depicted (Figure 2). Also, from Figure 2, below, the statistical analysis is corroborated and it can be observed that there is no much variation in the thermal characteristics of the two rivers before confluence. The chart further reflects that the widest range in temperature levels occurs between the fifth samples of each river, where the temperature at the fifth sample point on Ona River is significantly higher than that of Alaro River. However, on a broader scale, with the incorporation of the twenty sample points (ten sample points on Ona river, ten sample points on Alaro River), variation is not significantly evident.

### Hydrogeological cross-section and river properties

The data obtained were subjected to the test of normality using the Kolmogorov-Smirnov test, it was ascertained that the distribution was normal based on the result of the KS statistics. Hence, in examining the relationship between the type of underlying rock and river properties, a total number of five rock types were identified in the study area, namely (Quartzite, Pegmatite, Granite-Gneiss, Undifferentiated Gneiss and Schist, Biotite Granite), and under this rock types, the parameters of river quality were then categorized into five based on the identified underlying rocks as identified from the geological map. The data for each of the categories were plotted on a chart (Figure 3) to corroborate the analysis and graphically depict the variation. The Analysis of Variance for each of the parameters was then carried out by comparing values of the chosen parameters under the different identified rock type which were coded into numerical variables. In the analysis, the rock type was regarded as the independent/grouping variable or otherwise known as factor, while the parameter under study was the dependent variables. The result (Table 3) of the statistical analysis showed that at a confidence level of 95%, there was a significant variation of stream temperature (F= 4.067, Sig. = 0.011), across the identified rock types. TDS (Table 4) also showed a significant across the identified rock types (F= 4.270, Sig. = 0.009 respectively) across the identified rock types, while there was no significant variation (F=1.343 and Sig. =0.282); of DO across the various identified underlying rock type (Table 5).

### Groundwater quality and surface water quality

Further, the TDS, DO, and Temperature of both water sources (river, and wells/boreholes) were compared discreetly to ascertain any significant difference and drawing from the result of the comparison, there is an obvious significant difference in the data recorded for the three parameters from both sources. Groundwater parameters have higher values than those of the surface water; groundwater temperature from the study shows

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**Table 2. Mann-Whitney test statistics.**

| Test statistics | Rank of temperature by river |
|-----------------|-----------------------------|
| Mann-Whitney U  | 50.000                      |
| Z               | .000                        |
| Asymp. Sig. (2-tailed) | 1.000                  |
| Exact Sig. [2*(1-tailed Sig.)] | 1.000        |

Source: Author’s Analysis, 2017.
higher values than surface water temperature (Figure 4), this difference may be attributed to the underground residual heat that can be a result of trapped outgoing terrestrial radiation as well as other geothermal activities (Constantz, Niswonger, & Stewart, 2007). On the contrary, surface water (stream) Dissolved Oxygen was discovered to be higher than the groundwater (Figure 5). The groundwater total dissolved solids also recorded higher values than that of surface water despite the presence of industrial activities along the river, this disparity may be due to the influence of the underlying geology (Rock-type) through the interaction of groundwater and the constituent minerals found in the rock. This finding agrees with literature that groundwater exhibit higher values of TDS than surface water (Sophocleous, 2002; Winter, 1998), and this is a contributory factor to the degree of hardness of groundwater. High TDS affects the taste and odor of water and in general, levels above 300 mg/L become noticeable to consumers. As TDS increases, the water becomes increasingly unacceptable (Fetter, 1992). TDS was surprisingly low at some sample points in the mid-section/industrial zone (Figure 6) despite the presence of industrial effluents; hence, one possible explanation is that the quick flow characteristics of this region reduce the reaction time between water and industrial effluents, thereby retarding dissolution.

Table 3. Analysis of variance for stream temperature across underlying rock types.

|                      | Sum of squares | df | Mean square | F   | Sig. |
|----------------------|----------------|----|-------------|-----|------|
| Between groups       | 22,071         | 4  | 5,518       | 4.067 | .011 |
| Within groups        | 33,918         | 25 | 1,357       |      |      |
| Total                | 55,990         | 29 |             |      |      |

Table 4. Analysis of variance for stream dissolved oxygen across underlying rock types.

|                      | Sum of squares | df | Mean square | F   | Sig. |
|----------------------|----------------|----|-------------|-----|------|
| Between groups       | 24,726         | 4  | 6,182       | 1.343 | .282 |
| Within groups        | 115,031        | 25 | 4,601       |      |      |
| Total                | 139,757        | 29 |             |      |      |

**Figure 3.** Relationship of rock type and river quality parameters across zones. (Rock Type: Qz= Quartzite, Peg= Pegmatite, G.G= Granite-Gneiss, USG= Undifferentiated Gneiss and Schist, B.G= Biotite Granite).

**Figure 4.** Groundwater–surface water temperature comparison.
Variation in river properties

The result of the One-way analysis of variance however indicates differently for each parameter under consideration. Taking the result obtained from the analysis of variance (Table 6) for the stream temperature at a probability level of 5%, it indicates that there is no significant variation ($p > .05$, Sig. = .235) in stream temperature across the three zones (upstream, industrial, downstream), hence a rejection of the null hypothesis that postulates a significant variation of parameters across the three zones. The pattern of this variation is much anticipated as there seems to be no clear difference in the values of temperature as obtained on site in the field. However, from the line chart (Figure 7) below, there is a form of difference across the sample points in each zone, with more variation around the fifth sample point in each zone; with the stream temperature of the upstream having a higher value than the industrial section while that of the downstream section is the lowest.

Furthermore, the result obtained from the analysis of variance for Dissolved oxygen (Table 7) at a probability level of 5% indicates that there is a significant variation ($p < .05$, Sig. = .022) in dissolved oxygen across the three zones (upstream, industrial, downstream). Also, from the chart (Figure 8), there is a form of variation across the sample points in each zone, with the higher values

Table 5. Analysis of Variance for stream TDS across underlying rock types.

|          | Sum of squares | df | Mean square | F     | Sig.  |
|----------|----------------|----|-------------|-------|-------|
| Between  | 282838.200     | 4  | 70709.550   | 4.270 | .009  |
| Within   | 414032.500     | 25 | 16561.300   |       |       |
| Total    | 696870.700     | 29 |             |       |       |

Table 6. Analysis of Variance for stream Total Dissolved Solids across zones.

|          | Sum of squares | df | Mean square | F     | Sig.  |
|----------|----------------|----|-------------|-------|-------|
| Between  | 5.699          | 2  | 2.849       | 1.530 | .235  |
| Within   | 50.291         | 27 | 1.863       |       |       |
| Total    | 55.990         | 29 |             |       |       |

Table 7. Analysis of Variance for stream Dissolved Oxygen across zones.

|          | Sum of squares | df | Mean square | F     | Sig.  |
|----------|----------------|----|-------------|-------|-------|
| Between  | 34.431         | 2  | 17.215      | 4.413 | .022  |
| Within   | 105.326        | 27 | 3.901       |       |       |
| Total    | 139.757        | 29 |             |       |       |
of DO found at the downstream section of the rivers which is after the confluence occurring around New Adeoyo Hospital. The reason for this increase might be attributed to the combined contents of the Upstream and Industrial Section of both rivers prior to confluence.

Finally, with respect to the TDS, there was a variation as depicted by the chart (Figure 7) and this was also corroborated by the significant value obtained as based on the result of the analysis (Table 8) where \( p < .05 \) (Sig. = .000). Further, it can be observed on the chart (Figure 9) that the TDS values for the downstream section are higher than that of the upstream and industrial zone together and this may be concomitant with the fact that the combined flows from Ona and Alaro rivers at the upstream and industrial section upon confluence combine their properties, as well as the combined effects of human activities and the diverse land use activities along the river profile from the upstream till the downstream, thus giving rise to the higher TDS values.

### Conclusion

Temperature is a natural and robust tracer for studying surface water and groundwater interactions. Most previous studies used temperature as independent calibration data for coupled surface water and groundwater models or analyzed the surface water and groundwater interaction pattern by direct visual interpretation of thermal infrared imagery as obtained from the satellite.

The significance of the findings is an offshoot of past researches and efforts made in previous years. It further agrees with literature that there is a constant flux in the continuous interplay between groundwater and surface water. The inflow and outflow of water between the two storages facilitates exchange of materials and nutrients, thus the understanding of the exchanges must be obtained and further researched.
In summary, the measurement and analysis of temperature gradients along a river profile as well as its effects on the properties of the river provide an insight to the quantitative estimates of rates of interaction through the use of statistics and a possible inferred direction of groundwater movement through sediments across the surface-water and groundwater interface. Both the temporal range and spatial extent, over which temperature gradients have been analyzed to use heat as a natural tracer of ground-water movement near streams have been greatly extended by numerous recent case studies. Currently, research is ongoing in the areas such as thermal and hydraulic parameter optimization and time-series analysis of temperature pitches to expand the use of heat as a natural tracer in more complex, highly heterogeneous environments.

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**References**

Bencala, K. E., Kennedy, V. C., Zellweger, G. W., Jackman, A. P., & Avanzino, R. J. (1984). Interactions of solutes and streambed sediment: I. An experimental analysis of cation and anion transport in a mountain stream. *Water Resources Research, 20*(12), 1797–1803. doi:10.1029/WR020i012p01797

Burow, K. R., Constantz, J., & Fujii, R. (2005). Heat as a tracer to estimate dissolved organic carbon flux from a restored wetland. *Ground Water, 43*(4), 545–556. doi:10.1111/j.1745-6584.2005.0055.x

Chouvelon, T., Brach-Papa, C., Auger, D., Bodin, N., Bruzac, S., Crochet, S., ... Munschy, C. (2017). Chemical contaminants (trace metals, persistent organic pollutants) in albacore tuna from western Indian and south-eastern Atlantic Oceans: Trophic influence and potential as tracers of populations. *Science of the Total Environment*, 596, 481–495. doi:10.1016/j.scitotenv.2017.04.048

Constantz, J. E. (2008). Heat as a tracer to determine streambed water exchanges. *Water Resources Research, 44*(4). doi:10.1029/2008WR006996

Constantz, J. E., Cox, M. H., & Su, G. W. (2003b). Comparison of heat and bromide as groundwater tracers near streams. *Groundwater, 41*(5), 647–656. doi:10.1111/j.1745-6584.2003.tb02403.x

Constantz, J. E., Niswonger, R. G., & Stewart, A. E. (2007). Analysis of temperature gradients to determine stream exchanges with ground water. In D. O. Rosenberry & W. James (Eds.), Field techniques for estimating water fluxes between surface water and ground water (pp. 4–D2). LaBaugh. http://pubs.usgs.gov/usgspubs/tm4D2

Constantz, J. E., & Stonestrom, D. A. (2003a). Heat as a tracer of water movement near streams. In Constantz J. E. & Stonestrom D. A. (Eds.), Heat as a tool for studying the movement of groundwater near streams (Vol. 1260, pp. 1–6). U.S. Geological Survey Circular. https://pubs.usgs.gov/circ/2003/circ1260/pdf/Circ1260

Cremeans, M. M., Devlin, J. F., McKnight, U. S., & Bjerg, P. L. (2018). Application of new point measurement device to quantify groundwater-surface water interactions. *Journal of Contaminant Hydrology, 211*, 85–93. doi:10.1016/j.jconhyd.2018.03.010

Fetter, C. W. (1992). *Contaminant hydrology* (pp. 458). New York, NY: Macmillan.

Glennon, R. (2002). *Water follies: Groundwater pumping and the fate of America’s fresh waters*. Washington, DC: Island Press.

Jones, W. K. (2019). Water tracing in karst aquifers. In Encyclopedia of caves (pp. 114–115). Academic Press. https://doi.org/10.1016/B978-0-12-814124-3.00134-5 doi:10.1016/B978-0-12-814124-3.00134-5

Kurylyk, B. L., Irvine, D. J., & Bense, V. F. (2019). Theory, tools, and multidisciplinary applications for tracing groundwater fluxes from temperature profiles. Wiley interdisciplinary reviews. *Water, 6*(1), 1329.

Maldaner, C. H., Munn, J. D., Coleman, T. I., Molson, J. W., & Parker, B. L. (2019). Groundwater flow quantification in fractured rock boreholes using active distributed temperature sensing under natural gradient conditions. *Water Resources Research, 55*(4), 3285–3306. doi:10.1029/2018WR024319

Sabina, J. K., Kinga, S., & Slawomir, S. (2020). Tracing multiple sources of groundwater pollution in a complex
carbonate aquifer (Tarnowskie Góry, southern Poland) using hydrogeochemical tracers, TCE, PCE, SF6 and CFCs. *Applied Geochemistry*, 104623.

Schneidewind, U., van Berkel, M., Anibas, C., Vandersteen, G., Schmidt, C., Joris, I., . . . Zwart, H. J. (2016). LPMLE3: A novel 1-D approach to study water flow in streambeds using heat as a tracer. *Water Resources Research*, 52(8), 6596–6610. doi:10.1002/2015WR017453

Sophocleous, M. (2002). Interactions between groundwater and surface water: The state of the science. *Hydrogeology Journal*, 10(1), 52–67. doi:10.1007/s10040-001-0170-8

Sorey, M. L. (1971). Measurement of vertical groundwater velocity from temperature profiles in a well. *Water Resources Research*, 7(4), 963–970. doi:10.1029/WR007i004p00963

Suzuki, S. (1960). Percolation measurements based on heat flow through soil with special reference to paddy fields. *Journal of Geophysical Research*, 65(9), 2883–2885. doi:10.1029/JZ065i009p02883

Toth, J. (1963). A theoretical analysis of groundwater flow in a small drainage basin. *Journal of Geophysical Research*, 68(16), 4795–4812. doi:10.1029/JZ068i016p04795

Winter, T. C. (ed.). (1998). Groundwater and surface water: A single resource (Vol. 1139). DIANE Publishing Inc. https://pubs.usgs.gov/circ/circ1139/pdf/circ1139.pdf

Surfleet, C., & Louden, J. (2018). The influence of hyporheic exchange on water temperatures in a headwater stream. *Water, 10*(11), 1615. doi:10.3390/w10111615