Proof of Concept for a Stilling Tube Water Level Recorder

GEO 511 Master's Thesis

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Abstract

Currently, to monitor exact creek and river levels large installations are needed to avoid wave influences in the data. In this thesis a new tool, the stilling tube water level recorder, has been developed to solve this problem. The new-developed stilling tube is much smaller but has the same advantages as the currently used stilling well, the water level is monitored with a pressure transducer inside a tube that is connected to the stream water through a filter.

Thanks to the much smaller size of the stilling tube water level recorder compared to the current stilling wells, it is very practical in remote areas, as the high mountains, where currently it is very difficult to monitor water levels in creeks. It can be installed at any location that is accessible by foot.

This proof of concept shows that the filtering of the waves with the stilling tube water level recorder is possible and that it provides users with valuable data. Nonetheless, there still are limitations that require a further improvement of the tube, mainly its installation in a creek.

The whole stilling tube prototype has been built only with components that are available on the market and that did not need to be developed for this device. The thesis also contains a construction guidance in which it is described how the stilling well water level is built to be able to rebuild it for own purposes.

Acknowledgements

First of all, I would like to thank Prof. Dr. James W. Kirchner and Dr. Jana von Freyberg at the Department of Environmental Systems Science at the Swiss Federal Institute of Technology who made this thesis possible. They were great support in having ideas, filling knowledge gaps and keeping me up on track. Further, I would like to thank my father, Louis Honegger, who was very engaged in sharing his huge knowledge on materials and workmanship as well as in the finding and discussing of ideas.

Content

1. Introduction

Being able to monitor creek levels is an important source of information in hydrology. Measuring reliable creek level data, on the other hand, is rather difficult since many creeks, do not have a smooth surface, which manipulates the data and leads to a large miss of desired information. The source of error is the uneven surface of the waterbodies; especially in creeks the water surface is dominated by turbulences and waves. There have been done investigations to solve this problem, but the solutions are not yet very user friendly. The USGS, for example, has built stilling wells to reduce the wave impact in the measurements. This well is connected through a small pipe with the creek through which water can flow to adapt the water levels between the creek and the well. The measurements are then taken in the well (Figure 1). (Freeman et al., 2004, Sauer & Turnipseed, 2010)

The current state of the art, with the stilling wells that for example the USGS currently uses, is not satisfying. They are expensive, not practical in remote areas and need unpleasant maintenance. The concept is to design a device that has the advantages of the current stilling well but is far more flexible in its applications. To be able to build a station that can monitor creek level changes in remote areas, it must be transportable by foot, be low in maintenance and at the same time be robust. It needs to somehow separate the sensor from the flowing creek water, so that it is not affected by the current’s waves and it must be able to monitor reliable data. Something that could cover all the expectations is a tube that encloses the sensor and that somehow is able to dampen the movement of the creek level.

The aim of this thesis is (1) to design and present an alternative for the currently used stilling wells that allows to improve hydrological measurements, especially in regions where current usage is limited, as in high-mountain regions considering various general frameworks and (2) a proof of concept demonstrating that the new device is functional. The proof of concept was seen to be working when the stilling well measures what it is supposed to without unexpected and inexplicable errors.

There are some questions that need to be solved in this thesis. The most important of all is:

Is it possible to design a device that is able to monitor creek level changes without the influence of waves represented in the data?

And is it possible to design such a device that is more practical than a stilling well concerning costs, usage in remote areas, simplicity of the construction and of placing it in the field, and maintenance? Based on these questions there are going to be questions on the choice of materials, the finding and minimising of sources of errors and the most practical design in terms of user-friendliness and accuracy of the results.

This report will give the reader an impression on how the stilling tube water level recorder was developed, what thoughts have been made, which materials were used and considered, how it is (re)built, how it behaves in the field, what limitation the new device faces and what it could be used for.

2. Current State of the Research

Measuring water levels has been a big issue in hydrological research for a long time. It is an important factor in both labour and field studies and can still be improved to measure more accurate results and free the path for new fields of study interest. Such measurements are important to understand the dynamics of rivers, lakes and even the sea, for hazard prevention, for economical purposes and many more. During the past decades, many investigations have been done to improve water level measurements, from analogue graphic to automatic digital logging with only a short time span between the logs (Schumann & Muñoz-Carpena 2002). Additionally, there has been a development in the precision, costs and size of the measuring tools (to be named are pressure transducers). A problem that has so far been poorly resolved is the reliable measuring of the water level and volume of smaller creeks, since in these circumstances, the influence of the wave movements is having a strong impact on the result.

There has been shown that there are interesting interactions between the groundwater and the surface-water flows when it comes to snowmelt and plant activity, but these interactions are difficult to measure in the field (Brookfield et al., 2017, Loheide & Lundquist, 2009). To be able to gather reliable data one needs to have very precise measurements with a rather high temporal resolution, but without the impact of the wave movement. Since commonly used perforated PVC tubes do not filter these movements, there is a lot of noise in the result that needs to be smoothed, which results in a loss of important data structure (Schumann & Muñoz-Carpena, 2002, Yuliza et al., 2016, Lundquist et al., 2009).

The United States Geological Survey (USGS) has developed and installed stilling wells, that are able to measure the level of rivers and creeks by building up a well next to the river with a small tube connected to it. With this translation from the small diameter of the tube to the much larger diameter of the well, they manage to almost completely filter the influence of the waves in the river. A big issue with this installation is the cost and space required. The well constantly fills up with particles that are floating in the water and also plant and algae growth is a problem, therefore it must be cleaned regularly. This is time and personnel consuming, especially if it is located in a remote area. The other big disadvantage is that the well requires a lot of space next to the river, a factor that might be expensive as well (Freeman et al., 2004, Sauer & Turnipseed, 2010). Besides the difficulties for some research projects when it comes to financing such a stilling well, it is very impractical for measurements in remote areas. Due to its size and weight, it is necessary that the location is accessible by vehicles. Since also the creeks in the high mountains are of interest when it comes to snow influence and hazard prevention, the disadvantages of the USGS-stilling well become obvious. A further strong disadvantage of such stilling wells is, that they are not movable, since they often are dug directly in the ground at the desired location for the monitoring. Whenever a new creek needs to be monitored, a new stilling well must be built up, instead of being able to relocate an already existing one.

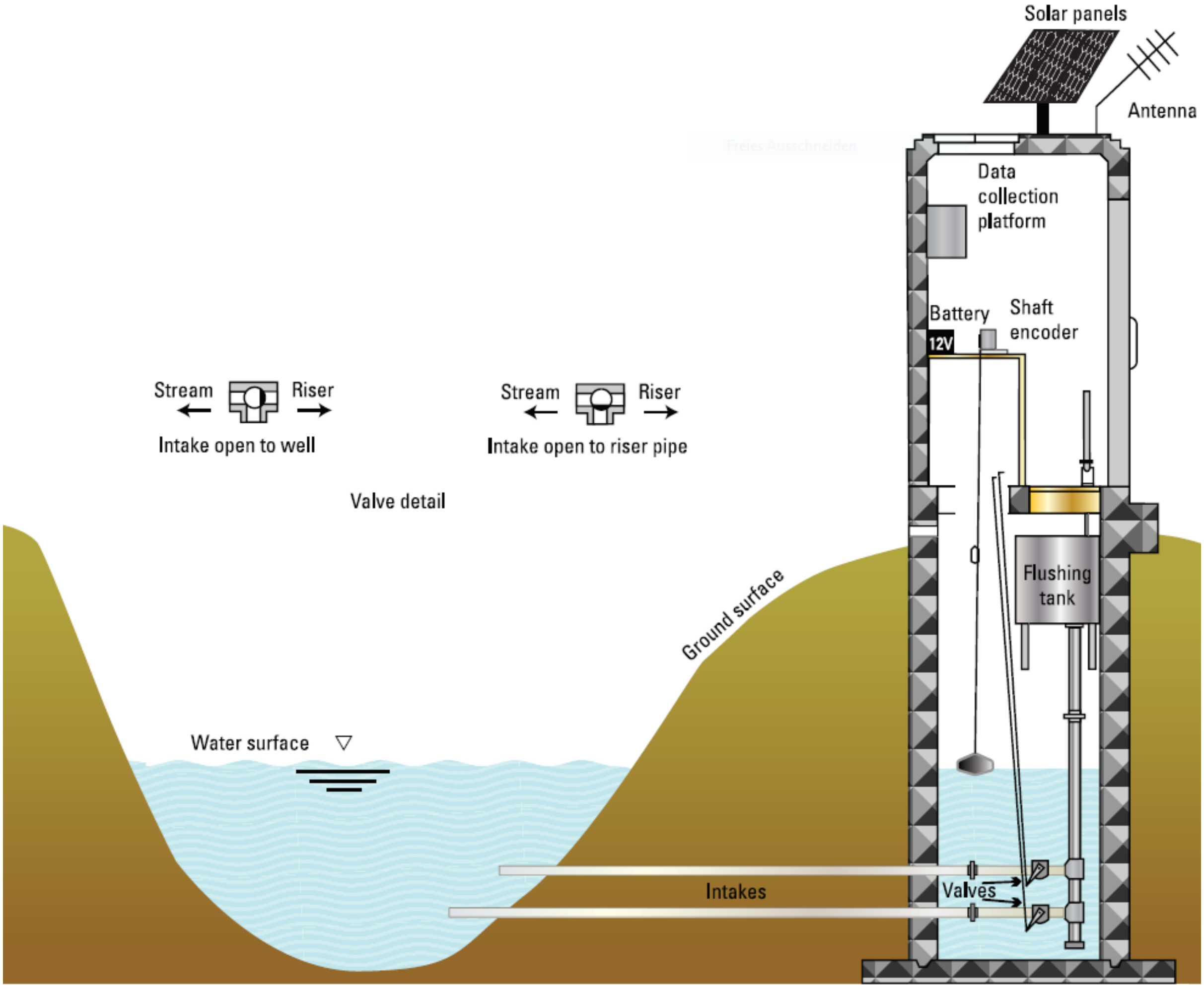

Figure 1: A schematic sketch of a stilling well that is currently used by the USGS (Sauer & Turnipseed, 2010, p. 8).

3. Developing the Stilling Tube

With the current state of the art and the stilling well that, for example, the USGS uses in the back of the mind a new idea needs to be developed. The instrument accuracy of the USGS stilling well is based on the different cross-sectional areas of the little tube leading into a pond with a much larger diameter. Technically this leads to a delay of the water level adaption in the pond, where the sensor is, compared to the water level in the measured creek. The physical background of this delay is the volumetric flow rate, the amount of water can flow through a tube of a certain length and diameter per time, described in the Hagen-Poiseuille equation (Durandi et al., 2011):

$$Q = \frac{\pi * r^4 * \Delta p}{8 * \eta * l} \tag{1}$$

where Q [m^3/s] is the volumetric flow rate, r [m] is the radius of the pipe, Δp [Pa] is the pressure difference between the two ends of the pipe, η [Pa·s] is the dynamic viscosity of the fluid and l [m] is the length of the tube. As visualised in the formula, the radius of the tube has a very strong influence on the volumetric flow rate, if the radius for example is halved, the volumetric flow rate is sixteen times less. In the well and the creek, with their big diameters, the water can flow (and adapt) almost freely, whereas in the tube that connects the two containers, due to its small diameter, the flow of water is very limited. As an imagination; if there is a pond with an area of 1 m^2 and a water level difference between the creek and the pond of 1 cm, a water volume of 0.01 m^3 needs to be transferred through the pipe. If the pipe has a length l of 1 m and a radius r of 1 cm, the volumetric flow rate Q through the pipe is 0.000253 m^3/s ($\eta = 1.52 \cdot 10^{-3}$ Pa·s; $\Delta p = 98.1$ Pa), which means that the needed volume of water needs 39.46 seconds through the tube, when a constant pressure difference is assumed. If the increase of the water level of the mentioned one centimetre comes from a wave rolling over the entrance of the pipe, it is not staying there for a period of around forty seconds, so the water level in the pond has no time to adapt to this level. On the other hand, if the real water level increases by one centimetre, the change would stay for far more than forty seconds, such as the water level inside the well has a chance to adapt to the new level. Hence, what the sensor in the stilling well measures is an average water level for forty seconds, without the influence of waves passing by the sensor (or not) at the very time it takes the measurement.

The idea is to build a tool, which has the same characteristics as the USGS stilling well, but must be installable at different locations, so there must be found another way to delay the water level adaption in a smaller piece of installation. With the idea of a filter tool and a tube in the back of the head, there was a concept to build up on it. The stilling tube will be based on a six millimetres strong LD-PE tube with an inner diameter of 80 millimetres, large enough to fit the pressure transducer in it. To delay the water adaption inside the tube sintered bronze silencers are used as filters. The filter serves as the equivalent to the pipe in the stilling well. Due to the very small diameters of the pores in the filter, the water amount per time that makes its way through the pores is very small compared to the cross-sectional area of the tube's inside which is the equivalent to the pond in the stilling well. At the bottom end of the tube a threaded connector with a cap is welded to the tube with a drilled hole in the cap to mount the filter in it. A complete list of all the considered components and why which component or material was chosen is described in detail in the appendix (Chapter 8.1).

Another important physical factor is the Bernoulli effect (Durandi et al., 2011).

$$\frac{1}{2}\rho v^2 + \rho g z + p = const. \qquad (2)$$

where ρ [kg/m^3] describes the density of the fluid, v [m/s] the velocity of the fluid, g [m/s^2] the gravitational acceleration, z [m] the level difference of the flow and p [Pa] the static pressure of the water at a given point in laminar flow. The second term can be neglected, if the assumption is taken, that the creek at the point of interest is flowing horizontally. In this scenario the formula can be adapted as following:

$$\frac{1}{2}\rho v^2 + p = const. \qquad (3)$$

The term p is the value measured by the pressure transducer in the stilling tube. The tube itself is an obstacle in the river which is compensated in the flow with a higher water velocity around it. This higher velocity in the left part of the sum (dynamic pressure, further called q) of the formula 3 needs to be balanced by lowering the static pressure p, so that the sum stays constant. Hence, if the obstacle is too big and the velocity difference between the free flow and the flow around the obstacle is too big, the resulting water level in the tube is too low compared to the real creek level. The stilling tube should therefore be designed in a way, that it disturbs the water flow as little as possible, meaning it should be as small as possible, especially when it is used in fast-flowing creeks. The other option is to have a turbulent flow at the entrance of the tube, where the filter is.

The other important factor is the dynamic pressure q on an obstacle, in the case of the stilling tube on the filter, which is depending to the second on the velocity of the fluid. A twice as high velocity of the creek, hence, results in a four times higher pressure on the filter, if the filter is directly exposed to the stream in the creek. In other words, if the filter is exposed to a fluid with a velocity higher than 0, the water is pressed in the filter with the pressure q and this pressure is visualised with a higher water level inside the tube than in the creek itself. To avoid this pressure, the filter needs to be placed at a location that is not exposed to water that is moving in a constant direction, for example inside the tube or behind a shield, in turbulent flow.

Now that for all components a decision was taken, a prototype needed to be built to be able to first, test, whether the parts can be fitted together, second, test whether the stilling tube works as it should and third, calculate the time constant, τ-value, of the water level adaption inside the tube.

3.1. Building the Prototype

After the decision of the components, they all needed to be connected to each other. A detailed construction guidance can also be found in the appendix (Chapter 8.2) to be able to rebuild the stilling tubes for own research purposes. This subchapter gives a brief résumé on how the different components are combined to facilitate the imagination of the prototype.

The main piece of the stilling tube, the tube itself, is 1.70 metres long, which corresponds approximately to the combined length of the pressure transducer and the cable, but without the desiccant. This is necessary to be able to change the desiccant and the connection device without uninstalling the whole stilling tube. The threaded connector and the cap at the bottom of the tube are attached to the tube by hot plate welding, a procedure the melts both, the tube's and the connector's edge before pressing them on each other to let them cool down as one combined piece of plastic. The filter is placed in a hole in the cap at the bottom of the tube towards the inside of the tube. This is to protect the filter from floating material in the creek and to minimise Bernoulli effects and hydrodynamic pressure. However, after the first field test it came clear that an adaption is needed for the filter placement. The result was that the filter from then on was mounted towards the outside of the tube and an additional shield was screwed on the outside of the cap through which the filter is mounted. This is more accurately described in chapter 5.1.1 and chapter 8.2. The costs for one stilling tube are about 2000 Swiss francs for the first device and about 1500 Swiss Francs for additional devices, since the communication device for the pressure transducer can be used for several stilling tubes.

Figure 2: The stilling tube water level recorder. The pressure transducer and desiccant are inside the tube, connected with the cable and the filter is behind the shield at the bottom

In the first test round, mainly the general function of the device and the properties of the different filters were tested, the test in moving water needs to be done in a second step in field tests. The tests of the filter mainly focused on knowing what their time constants are.

4. Testing the Prototype

4.1. The Time Constant (Tau-Value)

The time constant, or τ-value, is based on the dependency of the volumetric flow rate on the pressure difference (Formula 1). During the convergence process, the pressure difference between the creek and the inside of the tube constantly decreases, which has an influence on the volumetric flow rate through the filter. The smaller the pressure difference, the smaller also the flow rate through the filter is. Transferred to the stilling tube this means that the convergence first is fastest and the closer the complete convergence is, the slower the convergence proceeds (due to a smaller pressure difference).

The time constant is a very important factor to describe the function of the filter in the device and to be able to take the best filter for a certain research question. It is obvious, that the larger filters allow a faster adaption inside the tube, but to quantify the differences a mathematical value is inevitable. The time constant describes the amount of time, which is used to converge the water level inside the tube to the creek's water level to 63.2%, which is $1 - e^{-1}$. In a formula it can be described as:

$$v(t) = 1 - e^{-t/\tau}, \tag{4}$$

where v [-] describes the percentage of convergence, t [s] the time since start and τ [s] the time constant. According to the formula, after a time $t = \tau$, the percentage of convergence is $1 - e^{-1}$, after $t = 2\tau$, $1 - e^{-2}$ and so forth. After a time of 5τ the percentage of convergence has reached more than 99%. Hence, the smaller the time constant, the faster the convergence happens (Rowell, 2004).

4.2. Testing

Every prototype needs to be tested to find out whether it works as it is planned to work, for this purpose a test site was installed. The tube was secured with two clamps which were screwed in a wooden immovable pole. At the bottom, a cubic container was placed on the even ground that was partly filled up with water, such as the water level was some centimetres above the sensor. By placing water-tightly closed buckets filled with dry gravel in the water or removing them, an artificial in- or decrease of the water level was implied. For the tests, two buckets were used which allowed the water level to rise exactly 15 millimetres each (Figure 3).

For a first test round, every filter with a thread width from G1/8'' to G1/2'' was once installed and the pressure transducer was set-up as described in its manual. Before the first filter test was started, the water level that the pressure transducer measures was measured with the lid on the tube but without any filter in it, to know when the water level inside the tube has adapted to the water level outside after the mounting of the filter in the lid. This was necessary, because to screw the lid on the tube one must hold the hands underwater which rises the water level. But for testing it is important that measuring is not started before the water levels have equalised. For the first tests every filter was used once until a full adaption to the risen level was reached. When analysing the results, it was obvious that the smaller filters have a much longer adaption time than the bigger ones, which was to be expected. After the last test of the first round, the smallest filter was left in the installation to have an idea of what happens when the filters stay in the water for a longer time period, than just for one test. When testing again three days later, the adaption of the water level with the same filter took much less time. At first this was unexpected and not explicable, since the filters should not vary in their properties. If the filter stays the same, the adaption through the filter must also stay the same, unless the filter is broken. But even if the cause is damages, the change was huge and the filter did not show any visible damage. As a conclusion, something must have happened with the filter itself to allow water to flow through it faster.


Figure 3: The setup for the first tests. The stilling tube is secured to an immovable pillar over a container filled with water. With the two buckets, the water level was controlled. When these were taken out of the container, the water level decreased by three centimetres.

After discussing where that error could come from, a certain possibility could be, that this effect could come from the dry pores of the filter. The filters in the first test round came directly out of the package and therefore they were completely dry. To avoid that error for future tests and to prove that the different adaption times come from the dry filters, they were stored in liquids only from now on. To allow an optimal filling of the pores, first, water was sucked through the filters, to fill up smaller pores than by just laying the filters in water. Additionally, the filters were stored in methylated spirit. Methylated spirit has a smaller density and a much smaller surface tension, which allows it to fill smaller pores easier (Durandi et al., 2011). Also, methylated spirit is perfectly soluble in water so they can be used for testing, and for the final measurements in the field, without any further treatment. A well-appreciated side-effect is that even with a long storage, the liquid that the filters are stored in does not get bad and that there is no algae growth expected in methylated spirit. So, the liquid that the filters are stored in does not need to be exchanged every now and then.

The filters were kept in the methylated spirit for some days before tests restarted to allow an as good filling of the pores as possible. Again, all filters were tested once, but in this test period both, for an increase of the water level and a decrease. After each test, the filters were put back in the methylated spirit as they will be used again for further test executions and, if they produce constant time constants up to some minutes, for tests in the field. Already after the first test round with the wet filters, it was clear without further analysis that the time needed for adaption is much shorter. To ensure that the filters now work constantly and provide the same results at any time, the test with all the filters was repeated several times.

4.3. Test Results

A first result is that the stilling tube works as it is supposed to, the water flows through the filter into and out of the tube. Also, the water level inside the tube adapts to the water level outside after a certain time period. Much more of interest are the results of the adaption times of the different filters. To have a general number to compare the different filters with each other, there can be calculated the so-called tau-value, the time constant, of each filter (Chapter 4.1).

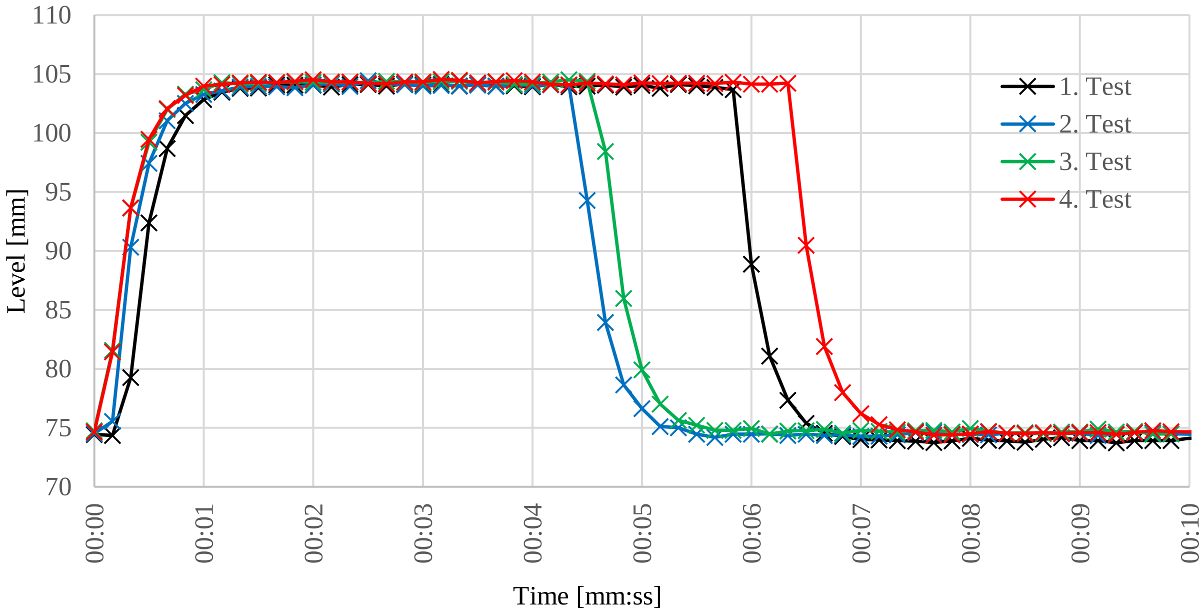

Figure 4: The test results of the G1/2’’ thread filter with an O-ring. It is visible that the different curves are very similar to each other which indicates that the filter works very constant.

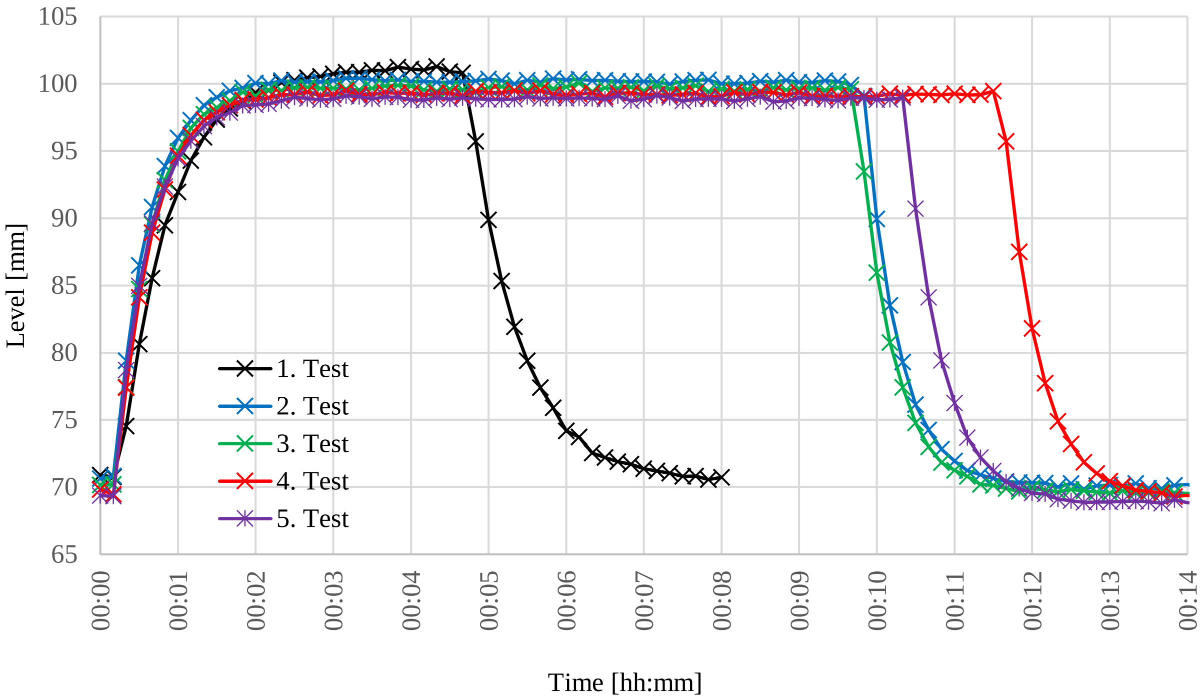

Figure 5: The test results of the G1/4’’ thread filter with an O-ring. It can be observed that in the first test (black curve) the adaption was slower than in the following four tests, so the in- and decrease of the in the first test is a bit less steep than in the other tests. This is caused by the still (too) dry filter that was used in the first test. In the subsequent tests the filters were all stored in methylated spirit and their behaviour is very constant. Figure 4 and Figure 5 represent all the tests of the different filters, the graphs for the other filters are looking mostly similar, with the respective adaption patterns.

At first, there is the visual impression of the test values. It is important that the curves of the different tests are looking similar for the different tests of the same filter type. The original water level has not been the same in all tests which is on purpose and which is not allowed to lead to different results. The adaption will be the same, as long as the absolute change stays the same, no matter what the initial water level is. When having a first visual impression of the test results this seems to be the case for all the filters. However, there is a difference visible for the small filters (Figure 5). There, the first result (black) shows a slower adaption to the new water levels, both when rising and decreasing. The same pattern has been observed with both of the G1/8’’ thread filters, too. Generally, all test results show approximately the same pattern but with different adaption times, so the two shown diagrams (Figure 4, Figure 5) stand as examples for all the tests. The slower adaption with the small filters, most probably, relates to the small pores not filled with water and therefore not transporting water. It seems extremely important to make sure that the filter is fully wettened, especially with the small filters, to guarantee a constant result. The longer the filters have been stored in the methylated spirit, towards the end of the test period, the more constant the results became.

When looking at the graphs (Figure 4, Figure 5) there can be seen, that in the flat parts of the curves, either when the upper or lower water level has adjusted, there is a constant variation of the values, which is not explicable with the experiment. This either comes from real water level changes inside the tube or from changes in the atmospheric pressure difference between the in- and outside of the tube or a malfunctioning of the pressure transducer. A change of water level of this order of magnitude inside the tube is not a very realistic scenario, but a malfunctioning of the pressure transducers or a changing difference of the measured atmospheric pressure between the inside and the outside of the tube are possible and a realistic source of errors.

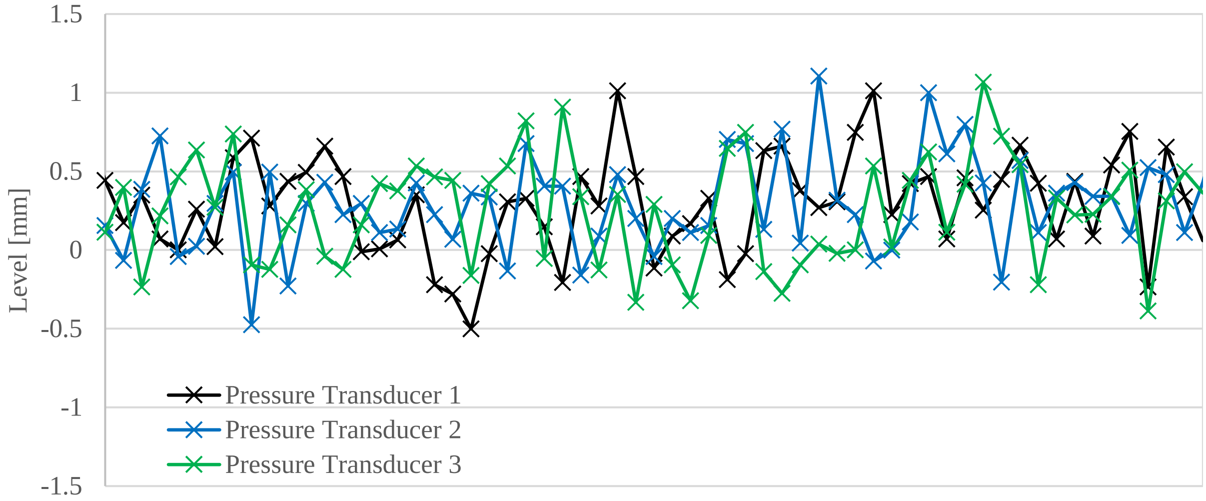

Figure 6: The result of the pressure transducer test with a measurement taken every second for each of the sensors, in this figure as a representative sample of one minute. Three pressure transducers were hung over the back of a chair in a closed room to test whether the irregularities in tests come from the pressure transducers. The sensors are supposed to monitor a constant level of zero millimetres, when in the air, but it can be seen that the values range from -0.5 to +1 millimetres. Also, the oscillations of the curves are not depending from each other, what they would be if there was air movement in the room.

To have an idea whether the errors come from a malfunctioning of the instrument or from changing air pressure differences, the instruments were installed in a closed room hanging over a back of a chair to ensure an as similar air pressure as possible. For the test, a measurement every second was taken with three of the instruments (Figure 6). When analysing the results of these measurements, it is visible, that there is a peak-to-peak amplitude of about 1.5 millimetres measured in a closed room that should not have any moving air masses. Theoretically, all the sensors should measure a constant level of zero millimetres, since there is no difference in air pressure when they are hanging in the free atmosphere. Additionally, all the pressure transducers produce other patterns, it is not a common up-and-down of the results of the three sensors. The results do not depend on each other, which means, that every pressure transducer for itself has this remote behaviour. The result of these measurements with a peak-to-peak amplitude of about 1.5 millimetres corresponds approximately to the test results of the device tests (and also to the ±1.75 millimetres accuracy of the pressure transducer stated in the manual (chapter 8.1.1), and thereby explains the inconstancies measured during the tests. Such inconstancies of the measurements are not evitable, which means that either better pressure transducers need to be found or to just be aware of this source of error. For the purpose of a proof of concept for the developed device it is sufficient to be aware of the error, so there was not looked for any better sensors.

		Thread and filter type							
		G1/2’’ O-ring	G1/2’’ hexagon long	G1/2’’ hexagon short	G3/8’’ O-ring	G3/8’’ hexagon	G1/4’’ O-ring	G1/8’’ O-ring	G1/8’’ hexagon
Time constant, τ [s]	1st test	13.142	7.863	17.635	14.746	20.794	36.789	120.139	115.888
	2nd test	13.649	7.156	16.002	14.560	20.978	25.031	72.278	112.178
	3rd test	13.205	7.721	16.249	15.375	20.534	25.202	80.744	85.921
	4th test	12.915	8.248	15.932	15.777	20.180	25.851	89.300	91.212
	5th test						26.397	99.617	95.303
	6th test								99.328
	Average	13.228	7.747	16.455	15.115	20.622	25.620	85.485	92.941

Table 1: The table presents the time constants of the different filters; each value represents one test. The values that are marked red are from the very first test rounds, where the filters were dry or almost dry, these values are not included in the averages to have a representative value for comparison. The filters with an O-ring do always have a smaller time constant than the ones with a hexagon (the short filter with a hexagon has the representative size), which is consistent with the respective pore size (Chapter 8.1.3). Also, the bigger filters have lower time constants than the smaller filters. Surprising is that the smaller filters have a much bigger variability of the time constants than the big ones.

The time constants for the tests with the filters range from around eight seconds with the long G1/2’’ thread filter with hexagon to around 85 and 93 seconds for the two G1/8’’ thread filters (Table 1). It needs to be stated, that the time constants calculated for the smallest filters are much less constant than for the bigger filters. Where this more inconsistent time constants come from is not fully explicable. There is a pattern, that shows that the time constant gets bigger with the tests, which does not correspond with the thesis that the time constant lowers with a longer stay in the methylated spirit. Between the different tests the filters have not been laying in the air so that they could dry out again. A theory is that the small filters are very sensitive to changes by impurities, but since the tests were made in fresh tap water this is hard to believe. What can be said is that the small filters are very sensitive to changes and that one must be aware of that and that this has to be considered and observed in the field tests as well.

At first, only the filters that have a thread smaller or equal to G1/2’’ have been tested because the hole in the lid was cut to that width, so to test the bigger filters a bigger hole first would have needed to be bored. This widening of the hole would be irreversible such that all the necessary tests were conducted and analysed before the hole would have been enlarged. As it is visible in Table 1, already for the G1/2’’ thread filters the time constant is as low as eight seconds, so it was decided that the other filters would not need to be tested, because their time constants will be even faster or at the same time as the ones of the already tested filters. Also, for the stilling tube a time constant of only a few seconds is not very necessary since most of the monitoring has much bigger interval times. However, if there is need for such little time constants, there are filters available at the same company (chapter 8.1.3), that provide a faster adaption of the water inside the tube. They are not yet tested with the stilling tube that is developed in this project, but their time constants will most probably be no more than ten seconds.

5. Field tests

After the tests in a container in silent water the device also needs to be tested in natural environments to prove that it provides users with reliable data. An important question in the field tests is, whether the stilling tube can handle moving water, especially concerning Bernoulli effects and hydrodynamic pressure (Chapter 3).

For the mounting of the stilling tubes in the creeks, brackets that are screwed in wood (or stone) are quite unpractical, so before field-testing the device a solution needed to be found for this problem. An alternative method is to install stakes in the rivers and mount the device with hose clamps to that stake. The stakes need to be strong enough to withstand the water pressure, also when carrying the device and they should be as thin as possible to be able to drive them into the river bed. A good option are metallic tubes; however, these are hard to pound in a river bed due to their large extrusion. A better and as well strong alternative are T-stakes. Such were found in a supplier for horse owners and are normally used as stakes for horse fences. These are available in a good length, around two metres, and have a small metal plate at the lower part of the stake to hinder a moving of the stake when hit in the ground (Figure 7).

Figure 7: The T-stake with a plate at the lower part, which was used for the field tests.

As a result of the field tests it is expected that the filtered tubes show a water level with little to no oscillation above the oscillation produced by the sensor itself (±1.75 mm), or if there is oscillation above this limit, there must be an explanation which is not induced by the function of the stilling tube itself. Also, the results are expected to represent the change of the creek levels, if there is any. Additionally, the stilling tubes are expected to show similar changes of the creek level and not completely independent results, especially if they are mounted at one single T-stake. And last but not least, the filtered stilling tubes are supposed to provide a better result, especially in terms of oscillation patterns in the monitored data, than the reference tube that is not equipped with any filter.

5.1. Riedbach

As a first test site the Riedbach in the Canton of Valais was chosen (46°10′05.784″N 7°49′57.021″E). The Riedbach is a very steep and therefore turbulent creek fed by a glacier, which provides a strong water flow although the summer of 2018 in Switzerland was very dry resulting in generally very low creek levels. Also, there is an intake for a water power plant just below the test site, which allows to have data of the amount of water flowing in the creek and its changes, if needed. For the time of the year, early September, the water flow of the Riedbach was rather high, so the flow was strong and turbulent. Finding a suitable spot to install the device was very difficult. The bed consisted mostly of larger rocks and there were no spots that had a sufficiently deep bed of sand and gravel, which is necessary to be able to drive the stake in the ground. Also, it was challenging to find a place that was safe to work when regarding people’s safety.

A perfect spot would be in a smaller but well-connected pool, allowing a water level that is relatively constant over a certain area to allow the water level to be approximately the same at both sides of the tube and to measure in an area of low stream velocity. If the tube was installed in an area of such a steep creek, that is channel-like, one faces the problem that the water level on the mountainward side lays significantly higher than on the valleyward side. The value for the water level measured in the tube is therefore less reliable than if it is measured in a pool. Also, velocities in channels are much higher than in pools. Additionally, in pools the turbulence of the water flow tendentially is higher, which is better concerning the hydrodynamic pressure and the Bernoulli effect. However, it was necessary to take care not to install the device in a part of the pool that faces strong upwelling forces since upwelling forces artificially rise the level of water inside the tube which affects the measured result (due to the hydrodynamic force showing in the direction of the filter entrance). On the other hand, river dynamics underlie constant changes, so it is impossible to know where exactly up- and downwelling currents will be in an hour, day or week. Especially in mountainous areas the river dynamics may change a lot with an in- or decrease of the creek level.

After all, a suitable but far not perfect spot was found. One T-stake could be drilled in the riverbed but not as save as it could stay and survive in place for a week or two. Only having one stake and wanting to measure and produce results with all four stilling tubes, it was necessary to attach all four tubes to the one stake. It was possible to secure only two tubes to one stake, but the remaining two tubes could be secured to the others that were hanging on the stakes and each other in a way that the whole construction was stable enough to remain in the creek for some hours (Figure 8). With this background, it was decided to only let the instruments run

Figure 8: The installation of the stilling tubes in the Riedbach. All four tubes needed to be secured to one T-stake since it was impossible to drive more than one stake in the riverbed.

for about one hundred minutes with a measurement taken every thirty seconds to at least have some information on whether the devices work as they are supposed to or whether there are general failures that need to be corrected. The four stilling tubes have been installed with three different filters and one without any filter. The tube without any filtering will serve as a reference to have an idea on how the water level is measured without any filtering, and thereby delaying, effect. However, since this sensor is mounted inside a tube, there still is a little dampening of the water level within the cross-sectional area of the tube (~50 cm^2). The other installed filters were the G1/8’’, G1/4’’ and G1/2’’ thread silencers, all with sintered thread and O-ring. These were chosen according to their time constants, such as there is a wide range of time constants represented in the field tests.

In the data of the Riedbach field trip (Figure 9) it can be seen that the stilling tube generally behaves as it is expected and wished, although there are some patterns that require to take a closer look at. An obvious pattern is that the data points for the filtered tubes are far less scattered than the data points of the reference tube without any filter (black). This is as expected, and this is also what a filtered stilling tube, in the end, is supposed to do. But there are some remarkable behaviours that are not expected and maybe also not wished. First, the data curve for the tube with the G1/2’’ thread filter (blue) is the only one showing a typical adaption curve as in the tests at the test site in still water. Although it shows an adaption curve, the adaption takes much more time than in the prototype tests in still water before. The other two filtered tubes (red and green) do not show any continuous adaption at all, which is surprising, because the time constant of the two filters are about 25 and 90 seconds. A normal behaviour for these two would be expected to be a round curve that slowly converges to the actual level of the Riedbach. As it looks like in the data points, first the convergence happens very fast for a minute or two until it abruptly stops, and the river level seems to be completely adapted. Also, the tube with the G1/2’’ thread filter shows a similar behaviour, although the break in the convergence is not as abruptly and there is still a convergence after the break, however slower as before.

These breaks visualise that something must have slowed down the convergence of the level inside the tube to the creek level, in the cases for the tubes with a G1/4’’ thread (green) and a G1/8’’ thread filter (red), to a minimum. But what could induce such a break? Creek water does not suddenly change its viscosity, density, adhesion and cohesion forces which could affect the flow rate through the filter.

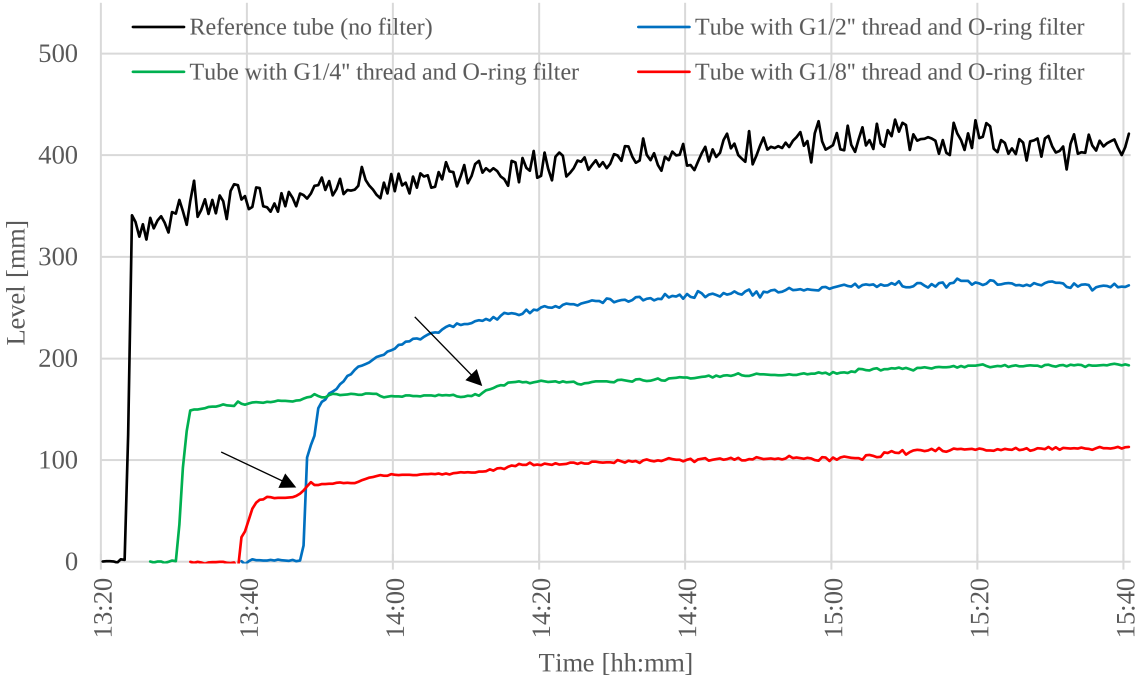

Figure 9: The results of the field test in the Riedbach on 21 September 2018, a measurement is taken every thirty seconds. It is visible that the data of the reference tube without ant filter (black) is much more scattered, compared to the other three tubes. Also, the missing adaption curves for the tube with the G1/4’’ thread and O-ring (green) and the G1/8’’ thread and O-ring filters (red) are clearly visualised. At around 13:50 for the tube with the G1/8’’ thread and O-ring filter (red) and around 14:10 for tube with the G1/4’’ thread and O-ring filter (green) the step in the convergence can be seen (black arrows). This leads to the plausible theory that the filters were blocked by air bubbles that only allowed little to no flow through the filter.

Another irregular pattern found in the green and red curve (G1/4’’ thread and G1/8’’ thread filter) leads to an answer of the above question. In the two graphs of the respective data (marked with black arrows), there are steps visible that do not correlate with each other. Since they do not correlate, it is also not plausible that this is a real behaviour of the Riedbach. Something which was blocking the filter has disappeared for a while and allowed the level inside the tube to converge to the water level outside. However, the absence was only of short duration and little amount. A problem, and probably the explanation of the irregularities, is that the filter is hollow at the bottom. The filter was mounted towards the inside of the tube with the opening towards the bottom, with the idea that the filter is protected through the tube with this installation. What completely has been unconsidered is that with the opening to the bottom, air bubbles can and will be trapped in the filter opening and hinder, respectively block, water flow through the filter. In the case of the tubes with the G1/4’’ and G1/8’’ thread filter the water bubbles that are trapped in the filter must have blocked the filter almost completely and were hardly ever flushed out of the small opening. An additional problem with the filters, in this set-up with the opening towards the bottom, is that to mount the filter in the hole, adapters were used which make the opening of the filter deeper and the beginning of the opening (where the adapter(s) is/are) is not permeable. This also could explain why the data of tube with a G1/2'' thread filter still shows an adaption, while slower than normal. A part of the filter must have been filled with an air bubble, but the filter is permeable until it reaches the outside of the lid since no adapter was needed to mount this filter.

The results of Riedbach are, at least for the three filtered installations, not representative for the final device, since, for known reasons, the setup has changed after that field trip. On the other hand, the reference tube shows very clearly the problems that hydrological measurements are facing in wild creeks. The measured level changes in the reference tube between the different measurements do not correlate with the real water level of the creek. There is no such constant up-and-down of the water level in a creek almost solely fed by glacial melt on a mostly clear and sunny day. The curve shows well the tendency of the creek level change when smoothed, but it is, for example, hardly visible whether the creek level slightly in- or decreases for a short duration. When comparing the curve for the reference tube and the tube with the G1/2'' thread filter it comes clear that a small level change is much more likely to be detected with the filtered tube than with a tube without any filter, or even without any tube at all. If the peak-to-peak amplitude between data points is (much) wider than the real water level change it will disappear completely when smoothing the curve.

5.1.1. Adaptions after Riedbach

A consequence from the field trip to the Riedbach is that the filter cannot be installed with the opening towards the bottom, since the stilling tube will not work properly if air bubbles are trapped inside the filter opening. A simple solution for this problem is to screw the filter from the other side through the lid, such as the opening is towards the top and water bubbles cannot be trapped at any place. But the idea to do it the other way, in the beginning, was to protect the filter from transported material in the water. If the filter now is at the outside of the tube, it also needs to be protected to first reduce the risk of a damage through an impact of transported material in the river and second to the kinetic water pressure which it is exposed to when mounted at the outside.

To avoid those two factors, the filter needs some sort of barrier or shield around it that is higher than the filter itself, but it should not filter the water additionally itself. Also, it must not be secured to the lid airtightly, since then the same problem with the trapped water would occur again. The shield must be very stable, because it is not allowed to break when hit by an obstacle to be further able to protect the filter from other impacts.

Hence, a shield was produced with a piece of tube that protects the filter, which is now at the outside of the tube. The shield hinders floating material to directly crash in the filter and damage or destroy it, and it is blocking direct flow on the filter. This is supposed to minimise extra forces on the filter that are not induced by the water level itself but by the velocity of the creek water.

5.2. Rietholzbach


Figure 10: The installation of the stilling tubes in the very calm Rietholzbach.

After the adaptions of the bottom lid were made, the next test site was chosen to be the Rietholzbach in the Canton of St. Gallen (47°22′47.724″N 8°59′31.550″E). Compared to the Riedbach in the mountainous Canton of Valais, the Rietholzbach is a very calm and much smaller creek. The site was chosen because it is very close to a research station of the Institute for Atmospheric and Climate Science of the Swiss Federal Institute of Technology (ETH), which also monitors the runoff and creek level, that could provide professionally measured data of the discharge if needed to compare. At Rietholzbach the bed of the creek was muddy, which made it very easy to place the stakes safely in the creek. More of a concern was to find a place in the creek that is deep enough to ensure that the filters are below the water surface even if the water level decreases. This is necessary because the membrane of the pressure transducer should not freeze as it might get destroyed when frozen. Additionally, the tubes may not dam the water artificially to gain representative data which is challenging in an as small creek as the Rietholzbach. At this site, two stakes were installed in the creek with two stilling tubes mounted on both of them (Figure 10). Additionally, the installations were secured with ratchet straps to a bridge to hinder them as good as possible from moving.

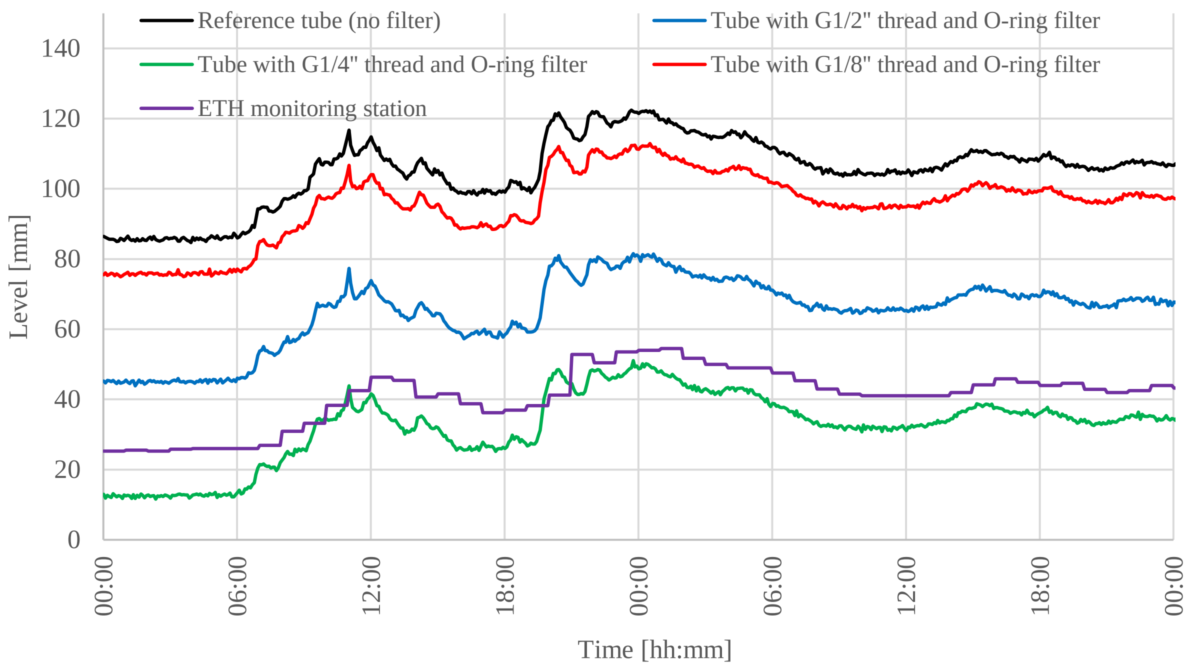

Figure 11: Test results from Rietholzbach between 27 and 28 October 2018, a measurement was taken every five minutes. Even during the rain events, there is no difference in the result of the different tubes. The black line represents the reference tube without filter. The fact that all the tubes produce an almost congruent result shows that also the filtered tubes detect water level changes and that the filters do not hinder an adaption of the water level inside the tube. But it does not show, that the filtered tubes produce better results than the reference tube without a filter. Additionally, there is the data from the ETH monitoring station (purple). These data points are only taken once per hour (at the left of a straight line), but the data pionts confirm the change of the water level, that the stilling tubes have measured.

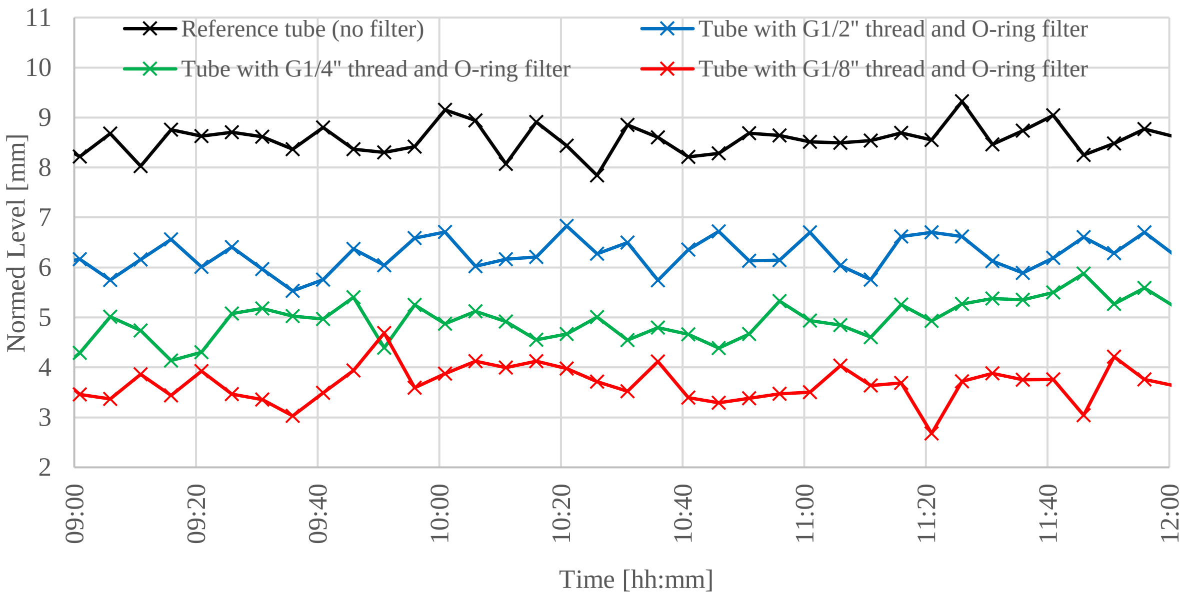

Figure 12: In the normed data it is visible that all four tubes produce scattered data, there is no distinction between the reference tube without a filter (black) and the other ones. The amplitude is mostly below one millimetre, which is within the given accuracy of the pressure transducer, but still more than hoped.

After one week, the data was read out and a first visual analysis has shown that there is not much of a difference between the different tubes. This was surprising, since it meant that the filtered tubes do not provide better data than the reference without any filter. As a consequence, it means that filters and the complex device is not needed in such a creek, but that already the dampening of the reference tube is sufficient. However, a rainy period was expected, which will produce a higher discharge in the very low-flowing creek, so the installation was let in place for another week. After this additional week, the results did not look much different, however, it was clearly visible that the level of the creek has risen (Figure 11).

The Institute for Atmospheric and Climate Science of the ETH also monitors the water level of the Rietholzbach. The provided data is measured once per hour, always at the time on the left side of each flat step in the Figure 11. Their data show a similar behaviour of the creek level, but with a much smaller resolution. This confirms that the stilling tubes measure a reliable water level, at least in calm creeks and not only random values, which is a very important step in the proof of concept. However, in a creek like Rietholzbach it is not necessary to use the filtered tubes, the reference tube is sufficient to monitor data of good quality in such a creek. To prove that the filtered tubes work better than the unfiltered ones, however, it is necessary to test them in more turbulent creeks, too.

In Figure 12 the monitored levels of the Rietholzbach are normed for a period of three hours to see the oscillation between the data points. As in the first tests in still water, there are oscillations with a peak-to-peak amplitude of about one millimetre, a few times a bit more. They are not larger than the stated accuracy of ±1.75 millimetres for the pressure transducer. At least in water with a low velocity, there is no scattering above the sensor's accuracy.

For the next field test(s) it was therefore important to find a creek that is more turbulent, since little turbulent flow does not show any necessity for a filtered tube not to mention prove the improved functionality of the filtered stilling tube compared to the reference tube. As mentioned before, the tube, even without a mechanical filter, does dampen the waves at the sensor's location enough to provide the same accuracy as the filtered tubes. Although the creek only had very small waves, there still were some, especially when water level rose during the rain event.

5.3. Schlichenden Brünnen

Looking for a more turbulently flowing creek, the Schlichenden Brünnen creek was found in the Muotathal in the pre-alpine canton of Schwyz (46°58′23.177″N 8°47′03.336″E). The Schlichenden Brünnen serves as an outflow of a larger karst cave. There a Federal Office of the Environment (FOEN, also known as Bundesamt für Umwelt, BAFU) monitoring station for discharge is situated just at the test site, so professionally measured reference data is accessible. Since the creek just leaves the cave some ten metres above the test site, there is very little human influence as dams, channelling or likely that influences the river's flow.

Figure 13: The Schlichenden Brünnen shows a much rougher creek surface, than the Rietholzbach (BAFU).

Figure 14: The installation in the Schlichenden Brünnen creek. The reference tube and the tube with the G1/4'' thread and O-ring filter are secured to the FOEN monitoring station at the shore, whereas tubes with the G1/2'' thread and O-ring and the G1/8'' thread and O-ring are mounted to the stake in the middle of the creek. The actual flow was much lower than in the picture provided by the BAFU (Figure 13), but the tubes were installed anyway since the creek was not completely still.

On the images provided by the FOEN it is visible that the flow is much wavier that at Rietholzbach, but there is still no white-water. At this location it was much more difficult to place the stakes, resulting in only one stake being set in place. The bed of the river was too rocky with hardly any sand between the rocks. Compared to the mountain creek Riedbach, the rocks were much smaller and round, so that the riverbed was not completely tight, and it was possible to move the stones in the bed with the stake. On the stake that was driven in the riverbed, two tubes were installed, whereas the other two tubes were mounted directly to the monitoring station at the shore of the river. Also here, the installation was left for several days to have an impression of the river's changes. Since the waves in Schlichenden Brünnen were larger than at the Rietholzbach, a more divers result of the different filters and the reference was expected.

A very interesting patter can be seen, when taking a closer look at the data in Figure 15. The different positioning of the filters has a well-visible influence on the monitored creek level change. The two tubes that are mounted to the T-stake and that are place in the middle of the creek (G1/2'' thread filter (blue) and G1/8'' thread filter (red)) have monitored a stronger decrease than the reference tube (black) and the tube with a G1/4'' thread filter (green), although their position is hardly two metres from each other. There are different possible reasons for this difference. First, there can be a change of momentum with the change of the creek level. With a decrease of the creek level, the velocity of the water probably will change and there might also be changes of flow lines that seem to have a very local influence on the creek level. An additional factor could be a source that has its inflow to the creek just above the monitoring station. None of these factors can be neglected, but it states as an example on how difficult it is to monitor reliable creek level data. Only a change of position of about two metres in such a creek, which is relatively calm, can have an influence in the monitored data. In bigger and wilder creeks this factor is going to be even bigger, since there, the currents may change even more with a change of the amount of water.

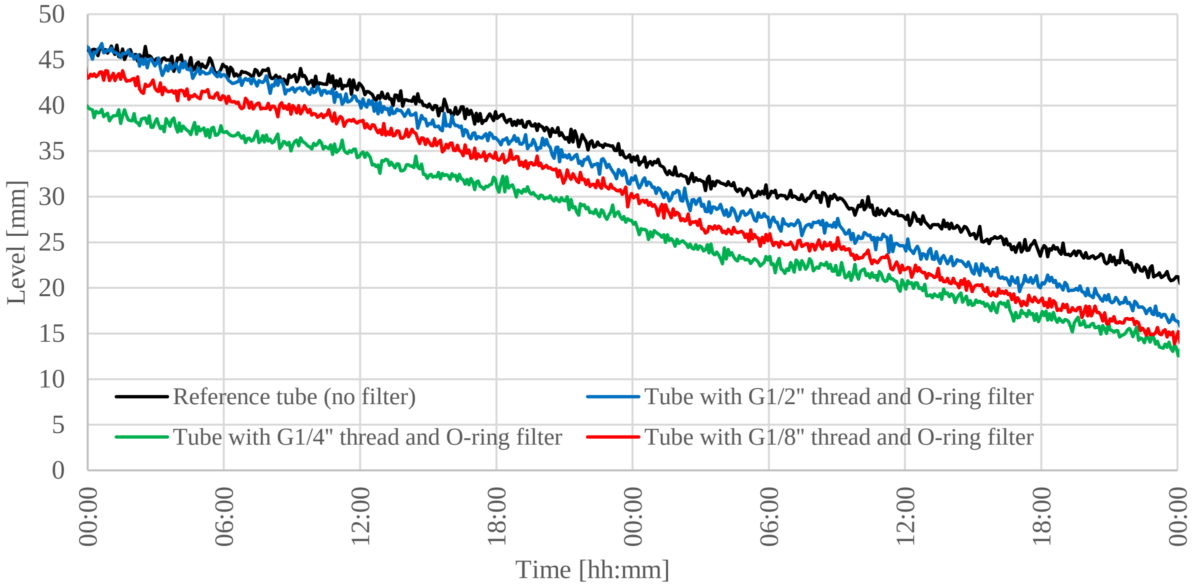

Figure 15: The data from the Schlichenden Brünnen creek from 11 to 12 November 2018 shows principally the same result as at the Rietholzbach, there is no difference concerning oscillation between the reference tube (blue) and the others. Interesting is, however, that the tubes reference tube (black) and the tube with a G1/4’’ thread filter (green) show a different change of the creek level than tubes with a G1/2’’ (blue) and G1/8’’ thread filter (red), which probably is caused by a different momentum of the creek and a water source close to the FOEN monitoring station. The two tubes that show the same result are mounted at the same T-stake, respectively at the FOEN monitoring station.

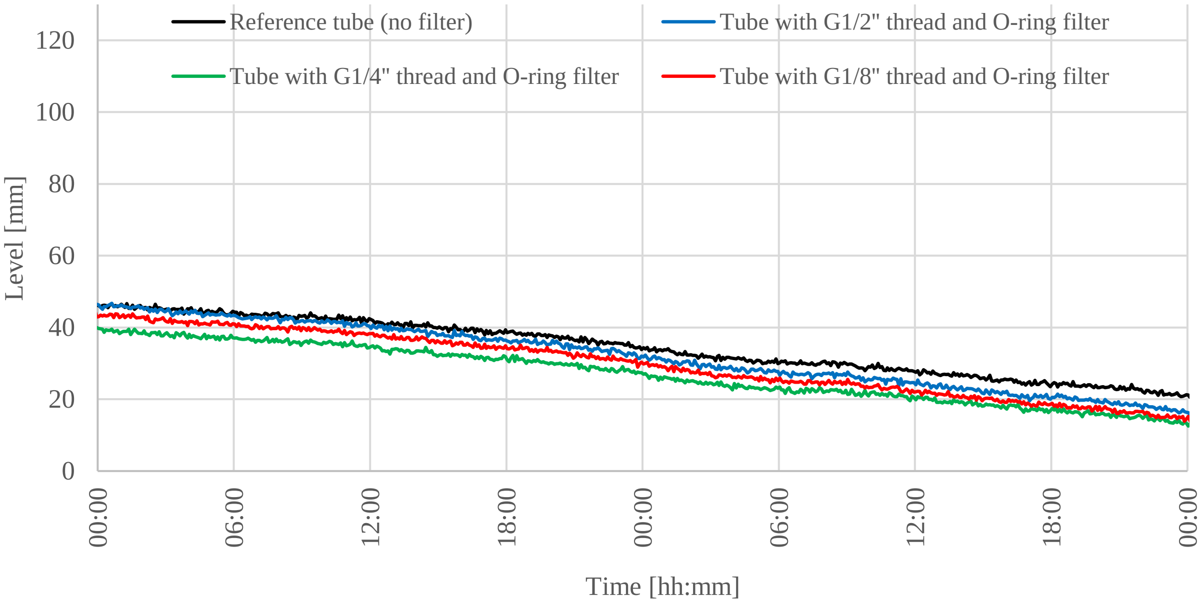

Figure 16: The data from Schlichenden Brünnen from 11 to 12 November 2018 in the same scale as the data from Rietholzbach. The oscillation of the values is at about the same level as in Rietholzbach, which shows the consistency of the measurements.

Also in the Schlichenden Brünnen the small-scale scattering with an amplitude of about one millimetre is observed (Figure 15). In Figure 16 the scale is the same as in Figure 11 and in the two figures the oscillation, also visually, looks similar. It is furthermore possible to measure the oscillation with a mathematical value, the mean absolute difference of the data points. This value is the average of the absolute difference of two neighbouring data points, calculated for the whole measuring period. The higher this value is, the bigger is the change between two points in average. A high value is generally expected for the measurements with the reference tube, since there the water level is not filtered and hence much more affected by the dynamics and waves of the water stream. The smaller the filter, the smaller the value for the mean absolute difference is, in theory. In a creek with an as constant behaviour as in the Schlichenden Brünnen, the value is expected to be below the pressure transducer's accuracy of ±1.75 millimetres. For the logging period in Schlichenden Brünnen, the values for the four different tubes are following:

	Reference tube (no filter)	G1/2'' thread filter with O-ring	G1/4'' thread filter with O-ring	G1/8'' thread filter with O-ring
Mean absolute difference [mm]	0,451	0,473	0,475	0,502

Table 2: The value of the mean absolute difference in average is almost equal for all four tubes. This confirms the visual impression of the graphs and shows that there really is no additional filter effect in the filtered tubes compared to the reference. For such a creek, also an unfiltered tube is sufficient to gain good water level data.

Interestingly, the value rises with the filtering level, meaning that the reference produces the best and the smallest filter the worst value, but on a very small scale such as the influence could be of various sources. The best average is only about 50 micrometres better than the worst value, so they are considered equal. However, every value is smaller than the accuracy of the pressure transducer. As mentioned, the Schlichenden Brünnen creek is too little turbulent flowing to prove the function of the new type of stilling tube, respectively, a stilling tube is not necessary in such a creek to measure accurate results. Concluding, to prove the function of the new stilling tube, they must be tested in a creek that is much more turbulent than the Schlichenden Brünnen.

5.4. Untertalbach

What was needed is a turbulent creek, with a bed that allows to drive in stakes. Since FOEN stations and other hydrological monitoring stations tendentially are at locations where it is comparably easy to measure river properties, which is where river flow is generally laminar, a new field test location was chosen with a priority list. Some must-have criteria were (1) that the creek is turbulent, preferably with white-water parts, (2) the bed allows stakes to be driven in, (3) it does not freeze, (4) it lays on low altitudes, so that not the whole catchment area is covered by snow and (5) it must be accessible by car for testing since carrying four tubes and the other equipment over kilometres is not possible unless with a many people. Point number (4) is important because if the whole catchment is covered by snow early December, in alpine creeks the water level decreases strongly which makes creeks far less turbulent. There are also nice-to-haves, (6) some sort of runoff or creek level monitoring, (7) a short distance to Zürich to avoid long drives, (8) a more or less hidden spot not to attract attention by a lot of people to minimise the risk of theft or destruction of the installations (9) a natural creek without check dams and other creek controlling obstacles and (10) a rain event with much precipitation in the catchment to have a higher flow and more turbulence.

Figure 17: The installation of the stilling tubes in the Untertalbach. The reference tube and the tube filtered with the G1/4’’ thread and O-ring filter are mounted to the stake in the front right, the tube with the G1/2’’ thread and O-ring filter in the front left and the tube with the G1/8’’ thread and O-ring filter on the other shore in the back.

Such a place was found with the Untertalbach near Elm in the Canton of Glarus (46°54′59.066″N 9°11′05.071″E). It is a wild river without any obstacles and a large bed with a high gravel content so that driving the stakes in the bed was not a problem. The snow line in Elm (1000 m a.s.l.) at that time of the year was still 200–300 metres above the test site with a weekend with much precipitation and a rise of the snow line to about 2000 m a.s.l. predicted. A rise of the snow line to that altitude also reduces the risk for a freezing of the sensor to a minimum. There was a lot of precipitation predicted for the test period (plus the snow melt induced by the warmer temperatures and therefore precipitation as rain also in higher areas of the catchment), which was wanted and hoped for, but it also meant that the stakes and stilling tubes must needed to be placed very stable to minimise the risk of natural destruction or even loss. However, the riverbed had perfect conditions for a save mounting of the stakes. There were many pools, also close to the shore which allows to demount the stakes and tubes even if the water level does not fall as low after the rain event as to the state during installation. Three stakes were driven in the in the riverbed to have data from different parts of the river. One was carrying two tubes, the reference tube without any filter and the stilling tube with a G1/4’’ thread and O-ring filter. Close to the opposite shore of the river the tube with a G1/8’’ thread and O-ring filter was mounted to the stake and a bit further up the river at the same shore as the stake with the two tubes the stilling tube with a G1/2’’ thread and O-ring filter was mounted onto the T-stake (Figure 17). The other shore could be reached by a bridge, which was necessary in case the water level, when building back the installations, is too high to allow a safe crossing through the river. To have more data than at the other test sites (where a measurement was taken every fifth minute) the pressure transducers were set to take a measurement every minute. If needed for a better comparison of the results with the data from the other test sites, it is still possible by simply taking every fifth data point.

At the Untertalbach the stilling tubes were left for four days to cover the whole rain event and a bit more to allow the creek to decrease again, which makes the building back of the installations easier. To build up the four devices took about 1.5 hours for two people, much faster than for a single person as in Schlichenden Brünnen. Especially driving the stakes in the river bed is very time consuming as a single person, so it is worth to go on the field trips to place the instruments with two people at least. If only one stilling tube needs to be installed, it will probably take about thirty minutes, if the involved people know what needs to be done and the circumstances are not too difficult. During the monitoring period at the Untertalbach the weather station in Elm measured about 85 millimetres of precipitation as rain (MeteoSwiss, 2019).

At the time the stilling tubes were uninstalled, there were scratches at the tubes and sand deposits on the screws of the hose clamps with which the tubes were secured to the T-stakes, that were about twenty centimetres above the water level. The water level has risen by at least that amount during the rain event and the river must have been was far more turbulent as well. All the tubes were, beside the scratches, without any sign of destruction and no part has been lost during the test period. When screwing off the lower lids that hold the filters, after demounting the stilling tubes, it was visible that silt was transported through the filters and has accumulated in the lid, however, the layer was not thicker than 0.5 millimetres and there were still several millimetres space. The silt can accumulate at least to the thickness of the nut with which the filter is secured. The filter itself was not blocked and when lifting the tubes out of the creek, the water in the tube ran out properly. But the stilling tubes have only been in the creek for four days, so in creeks that carry a lot of silt thicker screw nuts should be used to allow a larger accumulation volume for silt inside the tube. Additionally, some of the silt will be transported out of the tube through the filter again during a decrease of the creek level. It needs to be mentioned that during the tests the filters with the larger pores were used If the river carries a lot of finest materials, the filters with the smaller pores are a first solution, additionally to cleaning the lid regularly. The lid just needs to be screwed off, cleaned in the river water and screwed on the tube again. Compared to the stilling wells used by the USGS (Freeman et al., 2004, Sauer & Turnipseed, 2010) it is much easier, cleaner and faster to clean the new stilling tube, even if it has to be done more often.

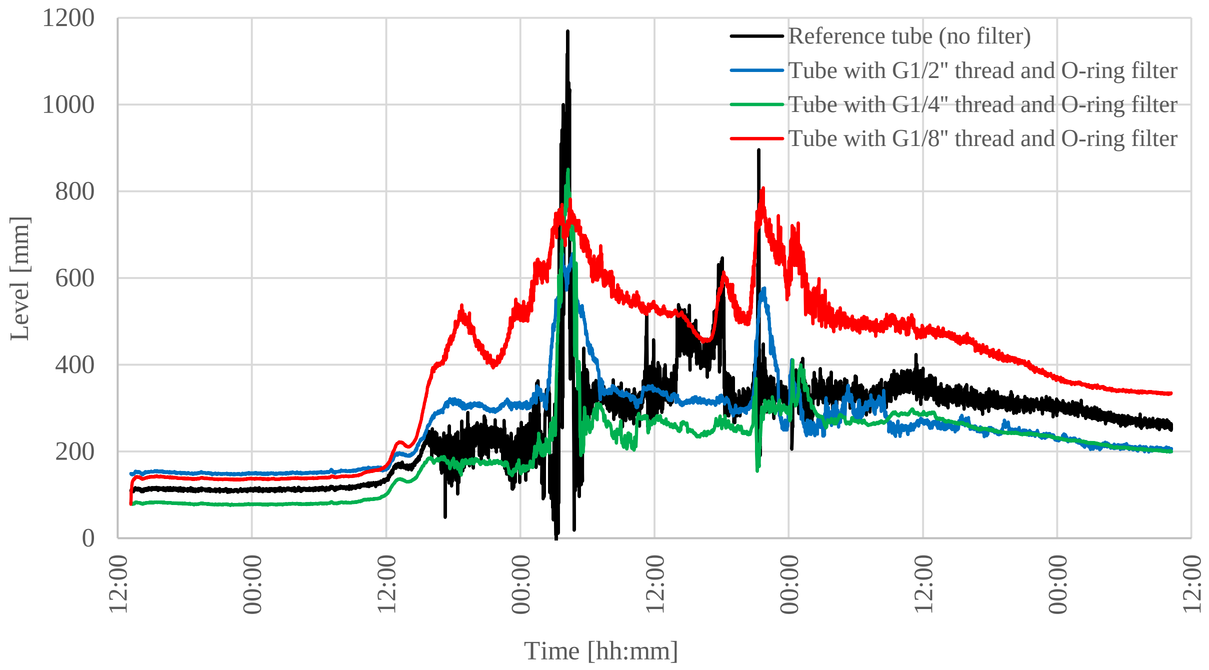

Figure 18: In the results of the monitoring in the Untertalbach between 1 and 5 December 2018 it is very well visible that the reference tube (black) has a much bigger oscillation during peak flow than the other ones. A measurement in this monitoring period was taken every minute. At the right tail of the tube with the G1/8’’ thread filter’s curve (red) the degree of oscillation decreases with a deceasing water level, which is a clear indication that the oscillation is induced by vibrations due to a high water level. Another interesting pattern is that the sequence of lines changes between the beginning and the end of the monitoring period, which shows that the bed of the creek has changed during the peak flow. The behaviour of the creek at the different tube’s locations generally is very different, although the devices were only a few metres from each other. It visualises how difficult it is to monitor reliable creek level data in turbulent creeks.

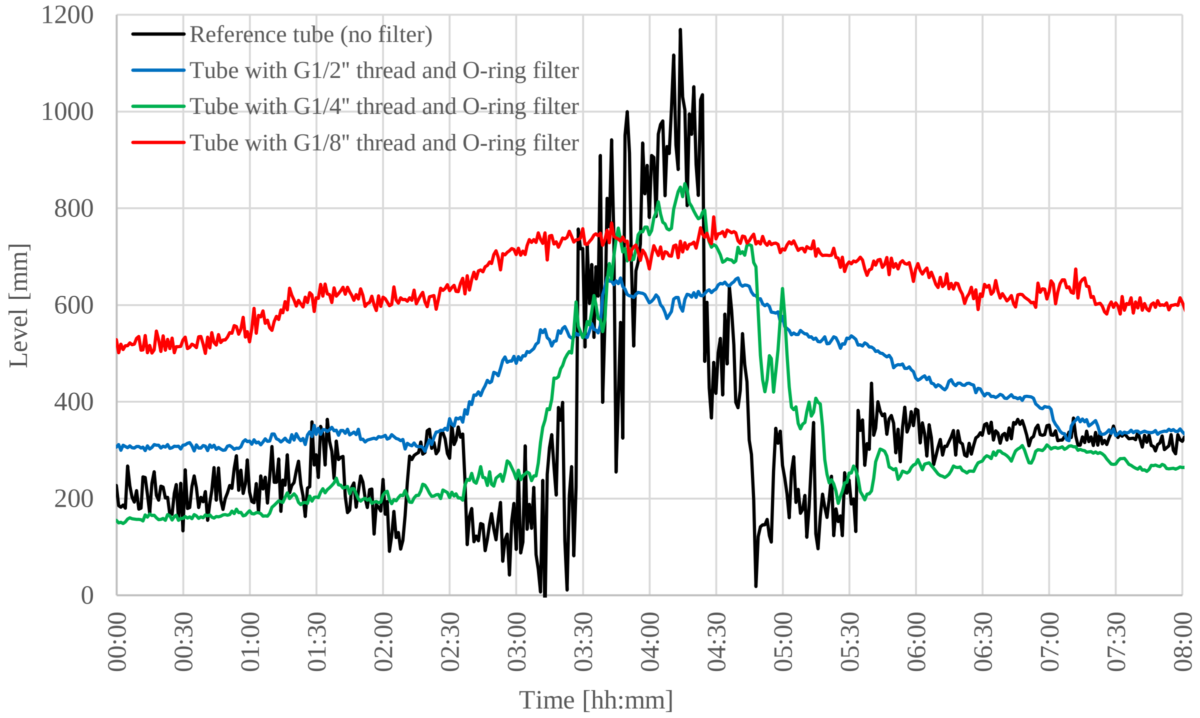

Figure 19: A close-up during the morning on the 3 December 2018 of the peak flow shows the degree of oscillation in the reference tube (black). The reference tube is mounted to the same stake as the tube with the G1/4’’ thread filter (green) and shows a far higher vibration in the data curve than the latter. The tube with the G1/2’’ thread filter (blue) and the tube with the G1/8’’ thread filter (red) have much less oscillation in their data than the reference tube, too, which shows that the stilling tubes with filters are able to dampen the waves much better than the reference tube.

At the beginning and the end, the data curves looked like the ones from the other test sites, all four sensors showed the same behaviour, there was no significant difference between the different tubes (Figure 18). This is surprising because the creek, already at low level is comparably turbulently flowing. But with the rise of the river level, the different tubes showed a different behaviour, there is a clear distinction between the different filters. At the highest peak the scattering of the reference tube’s measurements (black) without a filter is enormous, often several decimetres between two measurements. The tubes with filters face some scattering, too, but far not with the same peak-to-peak amplitude as the reference tube. Part of this scattering is due to vibrations of the tube by the river’s force, but the filtered tubes still show a much better result than the reference tube. The force of the river, and therefore the vibrations, must have been quite big, since the river level has risen during the peak period by forty to sixty centimetres, which was a good test for the material, too. The result shows other interesting patterns, for example the different behaviour of the river at the different locations. Although the tubes were installed close to each other (Figure 17), the river shows a very divers conduct, but all of them are reliable in the matter that they are scattered but with a constant direction of change. A good impression of what a filter can influence is the first big peak on the 3 December around 4 am (Figure 19). The reference tube without a filter and the tube with the G1/4’’ thread filter show the same river level pattern, but the line is far more scattered if no filter is used. These tubes are attached at the same stake, so their pressure transducers are measuring at almost the same location in the creek. While the data for the reference tube show a constant up and down of the river level of some decimetres, the data curve of the tube with the G1/4’’ thread filter is comparably constant with a strong upward and then a strong downward tendency. The oscillation of the data of tube with the G1/4’’ thread filter is almost never more than ten centimetres within a minute.

6. Results and Discussion of the Field Tests

As mentioned in the chapters before, the biggest problem was to find a field site with enough turbulence to have a clear distinction between the reference tube without a filter and the filtered tubes. In this chapter, a closer look will be taken at the results from the Untertalbach field site. Here the results look much different than at the other places. Some interesting patterns can be seen, but first a look at the average of the mean absolute difference is taken. Compared to Schlichenden Brünnen, the values of the mean absolute difference differ much more between the three filtered tubes and the reference. Table 3 shows the values for the whole monitoring period and only during peak flow from midnight until 8am on 3 December 2018.

	Reference tube (no filter)	G1/2’’ thread filter with O-ring	G1/4’’ thread filter with O-ring	G1/8’’ thread filter with O-ring
Mean absolute difference over the whole monitoring period [mm]	17.400	3.232	2.249	5.959
Mean absolute difference during peak flow [mm]	56.995	6.202	10.549	13.265

Table 3: The average of the calculated mean absolute differences in the Untertalbach for the whole period of monitoring and during the peak flow from midnight to 8am on 3 December 2018. The value for the reference tube in both periods is much bigger than the values for the filtered tubes, which proves the functionality of the filter. Interestingly, the mean absolute difference during the whole monitoring period is larger for the G1/8’’ thread filter which is the smallest of the tested filters and therefore would be expected to have the smallest value. Reasons could be that this tube was placed in much more turbulent water and therefore was exposed to a higher vibration of the tube or that the filter does not work correctly, but it is not fully explicable. During peak flow the largest filter produces the lowest value for the mean absolute difference, while the smallest filter again has the highest value of the filtered tubes. The main reason, also when comparing with Figure 19, probably is the different exposition to the creek flow and therefore more or less vibration induced by the river.

Different to the measurements at Schlichenden Brünnen, there now is a clear distinction between the unfiltered reference tube and the filtered ones, this is generally what is expected to be seen. But what is very surprising is that the smallest filter produces the highest value of the mean absolute difference of the filtered tubes over both periods, although this filter is supposed to dampen the water level movement the most. So, either the filter did not work correctly or the water inside the tube was moving more than in the other two tubes, or both. Also, the difference is rather big with an almost three to almost four millimetres higher change of water level inside the tube, on average over the whole monitoring period, to the other tubes. A further difference to the other field test stations is that at Untertalbach a measurement was taken every minute, so the values for the mean absolute differences are representing the average water level change within one minute and not within five minutes as at the other stations.

At the beginning and the end of the logging period, again the same pattern as at the other station occurred, there is no big difference in what the pressure transducers of the different tubes measure. The most interesting periods for the purpose of proving the functioning of the new stilling tube are the peak flows. There, the different patterns of the data points show that there is some difference between the four tubes, and therefore the different filters (Figure 19). At the peak, for the reference tube, a very strong oscillation can be observed, whereas the tube with the G1/4’’ thread filter, which is attached to the same stake, has a much clearer data curve. The tubes with the G1/2’’ thread filter and the G1/8’’ thread filter do also have quite clear curves, however, it seems that they experienced different river dynamics compared to the other two tubes, because their curves have a different shape, but they still confirm a rise of creek by several decimetres. The reference tube and the tube with the G1/4’’ thread filter were situated in a pool which lay beneath a small step, so there is a chance that this step reached the location of the tubes during peak flow in a way that the tubes stood in the middle of a smaller ‘waterfall’ and therefore the measured total water level change is higher than the one in reality.

Another interesting period starts on 2 December 2018 at 4pm. This is the time when the reference tube begins to monitor scattered data points. This point, as a reference, is when the water level is a bit more than ten centimetres above the water level in Figure 18. Below this level of turbulence, all four tubes monitor similar water level changes. After 2 December 2018 at 4pm the difference between the reference and the other tubes is obvious. Whereas the filtered tubes deliver results that are more or less constant in the way of not being very scattered, the reference tube only provides a tendency of the change of water level without giving reliable data about the real water level. At very high waterflow, the filtered tube’s data also begin to scatter, but it can be assumed that most of this scattering comes from vibrations inside the tubes, triggered by a higher force of the water and a higher leverage effect. To be able to reduce the vibration induced by the water flow, it is highly recommended, if possible, to install the devices in a way that they are not only secured to the ground at the bottom with a stake in the river, but also to secure them at the top of the stake. This, for example, can be done by mounting the stilling tubes to big rocks in the creek instead of a stake or by fastening them with clamping sets to a bridge or a trunk.

The results from the Untertalbach do not only show different oscillations of the data points measured in the four tubes, but due to the slightly different positions of the tubes in the creek, river dynamics were made visible. There the measured creek level change is by far not similar between the four tubes. This factor is very well visible during the first big peak. The reference tube and the tube with the G1/4’’ thread filter showed an abrupt rise of more than sixty centimetres, whereas the tube with the G1/2’’ thread filter monitored an abrupt rise of about thirty centimetres and the tube with the G1/8’’ thread filter did not monitor any abrupt rise at the peak flow. On the other hand, the data points of tube with the G1/8’’ thread filter show a stepwise rise before the peak flow while the other sensors there did not monitor any significant rise at all. This shows well that the rise and decrease of a creek is strongly depending on the location of the sensor, obstacles like blocks can influence the local creek level significantly. Also, the local flow direction of the stream might vary with a changing river level, which leads to other up- and downwelling locations that can also influence the monitored data.

If the data points of the different tubes are compared between the beginning and the end of the monitoring period (Figure 18), a change of the order of the different levels can be observed. The reason for these differences is a change of the river bed. Since the river bed contains a lot of gravel it is likely that during such a peak flow a lot of material is relocated and accumulated at other locations in the river. It is therefore possible to gain an impression and maybe also a better understanding of riverbed changes when several different stilling tubes are installed close to each other. However, the T-stake and tube can influence the ablation regime as well since they are obstacles in the creek flow that change the velocity and flow line directions of the water around the tube.

6.1. Limitations of the Stilling Tube

As any other tool, the stilling tubes also have limitations that a user has to deal with and be aware of. Some of them have already been mentioned, as the stronger vibrations occurring in high water levels, others are not so obvious from the test results. One of the most important limitations is that the new stilling tube is not able to monitor water depth or flow, it is only able to measure absolute water level changes. This is on one hand due to the pressure transducer that is only able to measure the water head, hence the amount of water above the sensor and not the amount below it. Additionally, it is not possible, for several reasons, to place the sensor at the bottom of a creek. The reasons are that the filter is below the sensor which rises the position of the sensor in the water and that there must be a shield around the filter to protect it from floating material like stones in the water flow. Also, the opening of the shield must not be at the very bottom of the creek to allow the water to flow freely between the filter and the river. If the tube was placed at the very bottom of the creek the water flow to the filter would already be dampened through the shield and small particles would be accumulating in the shield.

Another issue with the new stilling tube is that it needs to be cleaned from time to time to remove the silt that accumulates in the lid. However, compared to the current stilling wells, this is much easier done by just removing the lid's cap and washing it in the creek's water. If this is not done regularly, the tube will still work but the pores of the filter might get blocked up which increases the time constant of the filter.

Challenges that occur with the whole installation can also be induced by the sensor that was chosen. The sensor must not freeze when wet, which needs a good planning of the monitoring in seasons or regions in which temperatures can fall below 0°C. During such monitoring periods the filter must always be below water level in liquid water, even during low flow, to avoid a freezing of the sensor. This can be be a challenge in rivers that carry much less water during winter than in summer, for example in rivers fed by glaciers. As well as too little flow can be a problem, a too high river level can be problematic as well. The range that the instrument can handle is the height of the tube. If the flow is higher, the sensor is not able to measure the correct water level, since there is no longer a connexion to the free atmosphere. Additionally, the desiccant is designed to remove the air's humidity and not to prevent water from flowing into the hose if under water for a longer period. Also, if the installation is mounted to stakes that were driven into the riverbed, high flows might destroy the whole device if the force of water on the stilling tube and stake becomes too high or if it is hit by a massive stone or trunk. Another problem that occurs when the stilling tubes are installed with stakes in relatively high water, is that the data curves will show oscillating patterns, because the installation begins to move in the water due to the leverage forces. This is only evitable (partly) by also securing the stake at its top end or by mounting the stilling tube to a wall or similar. To allow a measuring of larger level differences than the approximately 1.5 metres that are technically possible with the prototypes, it is possible to use a longer tube. There are tubes available up to ten metres per piece (which can, theoretically, be connected by welding to any wished length) and the pressure transducer is available in variations that allow a higher range, if needed, too. However, larger tubes should not be placed in the water with T-stakes, since their length will make them instable. If such long stilling tubes are desired, they should be mounted to a solid wall, where they can be stabilised at different heights and not only at the bottom.

A limitation caused by the pressure transducer is that the data can only be loaded on site, it is not possible to connect the pressure transducer permanently to a computer that would be able to upload data online and at the same time have a desiccant installed which is used to keep the hose dry. With this limitation it is not possible to monitor data and observe the results from an office place, but instead, to download the data from the instrument, a field trip is needed. However, it might be possible to find pressure transducers that allow a constant connexion to a computer and at the same time are able to keep the hose dry. An advantage, however, is that the communication device that can be attached to the pressure transducer is able to communicate via Bluetooth and a mobile phone application can be used to set the logs. So, there is no need to also carry a laptop in the field.

6.2. What can the Stilling Tube be used for?

There are several different usages for the new stilling tube, technically it is applicable at any location where waves hinder a reliable monitoring of the “real” water level. Its original purpose and also what it is developed for is the usage in creeks, where the former stilling wells are used. The improvement compared to the latter is that it is mobile, meaning it does not have to stay at a certain location when once installed, and that it is much cheaper, both in building and maintaining. Due to these characteristics and the results of the field tests it can be very practical in high mountain areas where creeks are wild and stilling wells and other hydrological monitoring installations cannot be built easily. For the current stilling wells, a big well needs to be dug or other huge installations are needed and for most other hydrological monitoring stations a more or less laminar flow is needed do get representing data. Thanks to its easy installing and uninstalling procedure it can also be used for seasonal measurements, however, in creeks with a lot of fine material it needs to be cleaned from time to time. Especially in very wild creeks, where it is very hard to measure reliable water level data, the stilling tube might be the only option to have representative data monitored.

The high sensitivity also allows to detect very small changes in water level, for example very small day/night cycles. Combined with the comparably little financial investments and the possibility to install one stilling tube at different locations it could open up new research fields in hydrology that up to now were much too costly to be researched in.

Even if the stilling tube originally was developed to be functional in creeks and rivers, it can also be used at the shore of standing water bodies like lakes or the sea. In lakes it could be interesting to measure the difference of the water level at opposite locations during strong winds. In such conditions the lake surface would be wavy, which could be eliminated by the stilling tube. In lakes it could be an issue, due to a comparably stable and slowly changing water level, that the bronze filter does not set free enough copper ions to prevent algae growth inside the tube, consequently the concentration of copper ions is not high enough to abolish algae growth. To allow a higher copper ion concentration in the water inside the tube, there could be placed copper pieces or copper wool in the lid. This will not influence the results of the monitoring negatively.

Another interesting field of use for the stilling tube could be the monitoring of tidal changes in the sea. In the sea, the water hardly ever is completely still which impedes good monitoring results. The stilling tube could help to realise better measurements by filtering out the movement of the sea's surface. The pressure transducer itself works for salt water as well but the value for the water density needs to be adapted to the density of saltwater (or brackish water) when starting the measurements to improve the quality of the measurements. However, the stilling tube is not tested in saltwater, so there might be changes in the persistence of the different parts, especially the metallic pieces.

7. Conclusion

The main conclusion is that the new stilling tube water level recorder works. The results show, especially the results from Untertalbach, that the measurements of the filtered stilling tubes are have a much smaller oscillation than the ones from the reference tube that did not have any filter. Mainly in very turbulent creeks the results are much clearer and less involved by large oscillations in the measured water level which come from wave movements. In calmer creeks, however, the need for a stilling tube is questionable. There, no difference between the reference tube and the filtered tubes could be reported. A big question still is the behaviour of the very small filters (G1/8’’ thread), there, against expectations, the oscillation is bigger than with the other filters. Also, the time constants are much less constant than with the bigger filters. A source of this error could be that the filters are much more affected by a drying of the pores which results in a higher time constant. Another theory is that impurities have a much stronger effect compared to the larger filters. This, however, does not explain the higher oscillation during the field test in Untertalbach. On the other hand, the filters with a thread between G1/2’’ and G1/4’’ show very results in the Untertalbach field test with very little oscillation. They still show a bigger oscillation than the noise induced by the pressure transducer itself, but these are explicable with a movement, and resulting vibrations inside the tube, of the stake in the strong water flow. This factor would be able to be minimised by not mounting the tubes on T-stakes but to secure them to a non-movable item as a wall, bridge pillar, or a big rock at both ends of a tube. Generally, the stilling tube water level recorders work very reliably with filters with a thread between G1/2’’ and G1/4’’.

The big advantages of the new stilling tube compared to the stilling wells that are currently used are its small size, simple maintenance, comparably low costs and its possibility to use one device at different locations, it is relocatable. There is no need to dig a big well and it can be placed within an hour at theoretically any place that is accessible by foot. This is also a big advantage concerning the possible usage of the ne stilling tube, it can be used to also monitor creeks in very remote areas, where it is currently difficult to take good measurements. But additional to creeks it can also be used to monitor lake levels or tidal changes in the sea. Besides the usage in creeks, the newly developed stilling tubes can also be used in lakes or the sea to monitor their water levels. In the lakes it could be of interest to monitor the level difference between two opposite shores during strong winds and in the sea, tidal changes can be measured. Generally, due to its easy installation and low costs, the new stilling tube water level recorder could open up new fields of research that up to now were too costly to be researched in. Also, compared to huge installations as the current stilling tubes, there is no need to define a final monitoring location in advance. If a chosen location to monitor water level with a stilling tube is decided to not be good enough, the tubes can simply be installed at a better location.

It is further possible to rebuild the stilling tubes. All the used components are available on the market and none has been solely developed for the construction of the stilling well. How the stilling well is rebuilt and why which material was chosen, and which alternatives there are, is explained in the appendix.

8. Appendix

8.1. Material Decisions

8.1.1. The Sensor

Figure 20: InSitu Level TROLL 500 pressure transducer (InSitu, 2019).

For the whole project a good quality of the measurements is of major importance. The measured results need to represent the truth which means that the values measured need to be very accurate and the resolution should be below a millimetre. With the In-Situ Level TROLL 500 (gauged (vented), 3.5 m range) there was a pressure transducer found that meets the expectations on the sensor. It is a gauged (vented) system which means that, compared to an absolute system, the atmospheric pressure has no influence on the measured result (Figure 21).

In a gauged pressure transducer, the membrane that measures the water pressure is connected to the free atmosphere through a hose, so that on both sides of the membrane, theoretically, there is the same air pressure which allows that only the water level is measured, without any influence of atmospheric pressure. If the measured value was depending of the atmospheric pressure, results will have large uncertainties already when air pressure only changes slightly. This would require a mobile barometer of good quality that additionally needs to be installed close to the stilling tube. Being dependent on two instruments means that errors or uncertainties are accumulating, and that the chance of failure is twice as big.

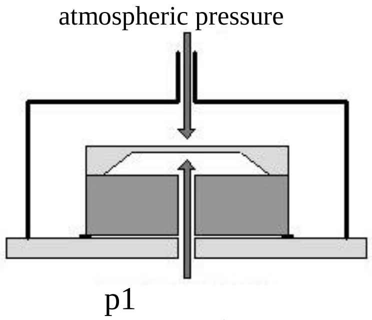

Figure 21: The principle of a vented pressure transducer, on both sides of the membrane, there is a connexion to the atmosphere, from below the pressure on the membrane is the sum of water and atmospheric pressure (p1). In total, the resulting pressure on the membrane only is the water pressure. (FirstSensor, 2019).

The In-Situ Level TROLL 500 pressure transducer, according to its manual (InSitu, 2013), has an accuracy (full scale) of ±0.05% and a resolution of ±0.005% of full scale, or better. With a full-scale range of 3.5 metres this results in an accuracy of ±1.75 millimetres and a resolution of ±0.175 millimetres for the chosen pressure transducer model. Additional to the instrument, the pressure transducers came with a 1.5-metre-long cable and a desiccant to keep the cable dry. With this material it is technically possible to measure rivers levels with a maximum range of about 1.5 metres.

The data itself can be logged directly on the instrument with a maximum of 250’000 data records. To start and stop a logging period and to download the data, there is a device that can be connected to the hose instead of the desiccant. It allows to communicate with the instrument per Bluetooth connexion and a provided mobile app, which is very practical in the field, or connect the communication device per USB-cable to a computer (InSitu, 2013).

A disadvantage of the In-Situ Level TROLL 500 is that it cannot be charged by the user. If the battery runs out of energy, the instrument must be sent back to the company to be recharged. However, the battery is supposed, according to In-Situ (2013), to last for ten years or two million recordings.

Generally, the sensor can be replaced without any problem, if found a better one. The device’s functions are not depending on the sensor, if the sensor and all its required additional parts fit inside the tube’s dimensions. However, all the tests of the prototype and in the field were made with the InSitu Level TROLL 500.

Concerning the costs of the stilling tube, the pressure transducer is by far the most expensive part. All the required parts (level sensor, cable, large desiccant and communication device) cost about 2000.- Swiss francs (CHF), of which about CHF 500.- go on the communication device, which can be used for more than one stilling tube and doesn’t have to be bought multiple times.

8.1.2. The Tube

The tube will be one of the main elements of the new stilling tube. It will be the piece where the creek level will be measured in and it is the piece that needs to be secured to anything to hold the complete installation in place. It is both above and below the water and must withstand in and protect the sensible items mounted inside from the water forces. Ergo, the tube needs to meet several different demands.


Figure 22: Symalit C+S cable conduit “chiaro” (Symalit, 2019).

There are many questions to be solved concerning finding the best tube for this project. Which is the best material? What are the advantages and disadvantages of different materials? What diameter is needed, and which should not be exceeded? Which compromises need to be made? Which factors affect the decision of size and material?

There are some must-criterions that need to be fulfilled. The tube stands in water, which means that the material must be stable in water and is not allowed to, for example, corrode, deform or dissolve. The material should not be eroded too easily since the tube should also be usable in high-mountain areas where creeks carry a lot of floating material as sand or even rocks. It should be stable enough not to crack when hit by a smaller rock transported in the river flow. However, the aim is not to construct a tool, that even survives large debris flows. It should resist UV-light to a degree that it meets the above-named requirements for several months to, preferably but not absolutely necessarily, years. The material needs to be machinable because there will be adaptions needed to mount the filter and the pressure transducer inside the tube. Also, the tube should not be black at the outside to avoid a strong heating in the inside of the tube. This could lead to errors in the result, if the air pressure in the tube changes too much due to the hot air inside the tube, compared to the air pressure at the outside. There are two types of materials that are worthy of consideration: stainless steel and plastics.

8.1.2.1.Plastics

There are many different plastics available but only few are used for tubes. However, there are tubes on the market for various uses. Plastic tubes are used as gutter, cable conduit, to be installed underground, in walls, in the free atmosphere, in concrete and in all possible sizes, shapes and strengths. It was soon clear, that the tube that is needed for the stilling tube does not fit in any of these various combinations of categories. The tube will both, have a part that is in the free atmosphere, a part that is constantly under water and a part that experiences both of it. Plastic tubes for an underground use or in (concrete) walls tend to be stronger than the ones used in the free atmosphere because they meet larger forces. On the other side, these plastics are normally not UV-resistant, since most of the plastics need additives as black carbon to be UV-resistant (Ensinger, 2019), a factor that is obviously not required underground. The first tubes bought to be tested were PVC-tubes. These failed already when sawed in two pieces. They began to splitter which is a clear sign that they will not withstand stone impacts in the river. Also, they do not fulfil the requirement of being machinable. A factor that also allowed a fast cracking is that the strength of these tubes only was a millimetre or two, respectively. Generally, the tubes used in the free atmosphere tend to be of very little strength. First, they are not affected by large forces, and secondly, if they break, they are easy to replace. These factors led to a compromise. UV-instability can be compensated by a bigger strength of the tube, if they must not hold for decades. The tubes of the stilling tube water level recorder can be replaced easily, and they are also not supposed to stand at a place for a decade without any maintenance. There are LDPE-tubes used as cable conduits that have a strength of six millimetres, normally used underground, for example below a road, to protect electric cables from the ground and too much water or in concrete. A strength of six millimetres should be sufficient to prevent the material of being completely destroyed by solar radiation within the time span of some years. Also, it survived the test with a large hammer impact without any destruction, so it will also withstand rock impacts in a river. Additionally, the tubes are available in various sizes in the range between six and twenty centimetres in diameter that is considered optimal for the stilling tube and the tubes have a whitish colour at their outside, which is perfect. An optimal size is as large, that the pressure transducer and desiccant can be placed and secured inside the tube and allowing the cable to be spiralled up the tube to be able to get the desiccant out of the tube at the top of it. This is necessary to attach the communication device without uninstalling the whole stilling tube. The tube, however, should have a diameter as small as possible to disturb the creek flow as little as possible. The first choice was two Symalit "C+S cable conduit "chiaro"" (Symalit, 2018) tubes with an outer diameter of 72 and 92 millimetres, respectively, this results in inner diameters of 60, respectively 80 millimetres.

The next step was to test whether the pressure transducer can be secured in the tubes. It was possible to secure both the transducer and the desiccant in the tubes, but in the smaller tube, it was not possible to simultaneously mount them. The problem in the smaller tube is, that the diameter is too little to be able to spiral the hose that connects the sensor to the open atmosphere enough so that the desiccant reaches far enough into the tube to be secured in place. Also, the smaller tube is too narrow to reach in it with the hand, which makes holding the instruments in place to secure them much more difficult. With these experiences, the decision for the wider tube was made.

8.1.2.2.Stainless Steel

An option, that was not further followed, is stainless steel instead of plastic as the material for the tube. Stainless steel has the big advantage, that it is extremely stable, resistant to UV-light and (probably) less susceptible to vibration (Chapter 6) even with a smaller strength. On the other hand, it is harder to work with, especially when it comes to attach a lid that is connected to the tube per screw thread (Chapter 8.1.4) Also, it is far much more expensive than the Symalit cable conduit. But if the stilling tube needs to be installed in very rough creeks, this might be an option to ensure that the installation doesn't get destroyed even with large impacts of rocks. If the inner diameter of a stainless-steel tube is still eighty millimetres the Symalit cable conduit can be replaced directly by a stainless-steel tube without losing the validity of the test results (Chapter 4.3). The used metal, however, must be stainless steel or any other metal, that doesn't corrode in both water and air and it must also be hard enough not to be deformed by the force of water and transported material. This would need to be evaluated in own tests.

8.1.3. The Filter

Figure 23: Silencers with sintered threads and O-ring (GGT Gleit-Technik AG, 2018).

Finding suitable filters was a challenge. The filters represent the most important part of the stilling tube, since they are the item, that regulates the flow in and out of the tube and so the delay of the water level adaption inside the tube to the creek level outside. Additionally, the filters are used to prevent algae (and other organism) growth inside the tube. To prevent algae growth, copper is used as a toxin, as copper ions, when at high concentrations, lead to algae cells leaking which, consequently, kills them (Nielsen & Wium-Andersen, 1970). As a source for the copper ions the plan was to use a pure copper filter to regulate the water flow between the creek and the tube's inside. When water is flowing through such filters it can take up the copper ions that are needed in the water inside the tube. Every time there is an inflow, the water carries fresh copper ions into the tube. When the water level in the creek lowers and the water flows out of the tube, the consequence is that the supply of copper is interrupted. However, the copper ion concentration of the water inside the tube is not changed.

The disadvantage of the pure copper filters is, that they are not available on the market. No either Swiss or international company listed such in their catalogue so that there was a need for another solution. An alternative for pure copper is an alloy of copper and another metal that has a high copper percentage. Alloys with high copper percentage are bronze and brass, with bronze often having a higher percentage of copper. Looking for bronze filters, a Swiss company was found which sells filters in the size and porosity looked for. GGT Gleit-Technik AG is a company that specialised in sintered filter production and has a wide range of small filters that seem perfect for the project. For testing, two different types of filters were ordered in all available sizes to have an as wide range available as possible. As standard, they sell sintered filters in two different filter classes: CA75 and CA100, however, more filter classes are available on request (GGT, Gleit-Technik AG, 2018)

		Filter class	
		CA75 Silencer with sintered thread and hexagon	CA100 Silencer with sintered thread and O-ring
Thread type	G2’’	Available, but not ordered	Not available
	G1’’	Available	Available
	G3/4’’	Available	Available
	G1/2’’	Available in normal size and long size	Available
	G3/8’’	Available	Available
	G1/4’’	Available	Available
	G1/8’’	Available	Available

Table 4: The available filters in the two types of silencers, that were tested.

At first, all the ‘silencer with sintered thread and O-ring’ (CA100) and ‘silencer with sintered thread and hexagon’ (CA75) with a thread from G1/8’’ to G1’’ were ordered to be tested with the device (however, the G1/4’’ thread sintered silencer with a hexagon has not been delivered in the first order). They consist of bronze balls between 250 and 355µm (CA75) and between 355 and 500 µm respectively letting particles with a diameter no more than 40 or 50 µm, respectively, pass through. This also prevents large particles transported by the stream reaching the inside of the tube and accumulating. Since GGT Gleit-Technik AG follows the DIN ISO norms, their products can also be considered to fulfil certain standards considering uniformity, which allows to expect similar results using different filters of a similar type. If this had not been the case every new filter needed to be tested for its own properties and behaviour in the device before being able to use it.

8.1.4. The Lid


Figure 24: Geberit HDPE threaded connector with screw cap (Geberit, 2018).

The stilling tube is supposed to be maintainable, if needed, without uninstalling the whole device. Also, the filter should be mountable simply in a way that it can be exchanged, if wished. At the same time, it is desirable that there are no moving parts in the final installation in a stream and there should not be any significant waterflow into and out of the tube around the filter during the monitoring. There are different approaches to apply these restrictions, but it is inevitable to have a kind of lid at the lower end of the tube. Realising that, there are two places to mount the filter at, either in the lid itself, or directly through the tube.

To allow an easy maintenance of the tube, for example to clean the tube from accumulating silt, it is desirable to be able to remove the lid easily, also underwater. At the same time there needs to be taken care, that the lid cannot fall off by through the movements and vibrations of the water. To prevent a falling off, either the lid has to fit very tightly, which impedes an easy remove, or it needs to be held to the tube trough threads.

The lid should be removable easily, so the goal was to find a lid that fits on the Symalit cable conduit. Symalit, however, does not provide any threaded lids for their cable conduits, it seems a part like this is not needed in the normal use of a cable conduit. Where threaded lids are definitely required, are when working with water conduits. The lids of water conduits must also be watertight, when the water flows through them in high pressure. On the first sight a perfect solution, but water and cable conduits seem to follow different standards when it comes to the dimension of the tubes, resulting in an incompatibility of the two parts. While the Symalit cable conduit has an outer diameter of 92 millimetres, the closest norm for water conduits is an outer radius of 90 millimetres (Geberit, 2018). This also means, that connecters to a lid have a resulting diameter of 90 millimetres and since the connectors are connected to the tube with a fitting electrofusion coupling, the tube is supposed to have a diameter of 90 millimetres as well. On the other hand, both, connector and tube, are both made of PE plastics, so the decision was to try another way to combine these two parts, for example through plastic welding. The decision fell on the “Geberit HDPE threaded connector with screw cap” with an outer diameter of the connector of 90 millimetres (Geberit, 2018).

8.1.5. The Bracket

To hold the sensor and desiccant in place, brackets are needed. It is important that the sensor doesn’t move inside the tube, not to have a change of water level measured due to a lowering of the sensor in the bracket, for example through small vibrations of the installation. The sensor itself is made of metal, titanium (InSitu, 2013), such as a pure metal clamp might allow a downward moving with gravity of the sensor, even if tightened very tight. To minimise that risk of an error, a rubber-coated bracket is a practical solution. A simple solution quickly found in a supermarket was a bracket that normally is used to hang brooms or likely on a wall. However, when tested in the tube, it came clear that this solution is not satisfying. The brackets were much too hard, as to easily fit the sensors in them when mounted to the tube. Additionally, it is very difficult to fit two small screws trough the two holes in the tube to be able to attach the screw nuts on the threads from outside. However, for testing the installation, the bracket fulfilled its duty, but it was soon clear that an adaption needed to be taken for the final device.

Figure 25: The pipe clamp that was used in the prototype and the construction guidance (Pestalozzi Haustechnik, 2019).

For the final device, pipe clamps were used to secure the pressure transducer and the desiccant in place inside the tube. These are available for different diameters, so that both, the desiccant and the pressure transducer, are tightly secured inside the tube. The are mounted through the tube with bolts that have the same size for both pipe clamp sizes. Generally, all types of pipe clamps can be used and there might be differences between them in different countries, but the prototype and in the construction guidance, pipe clamps are used that need an M8 bolt and therefore a hole in the tube with a diameter of eight millimetres.

8.2. Construction Guidance for the Stilling Tube

This chapter serves as a construction guidance to be able to rebuild the stilling tube. If the dimensions in the sketch (Figure 26) are followed exactly, all the tests are representative for the rebuilt device. There are some dimensions in the sketch that do not need to be copied exactly, these are to be understood as suggestions and their numbers may vary within a certain range. Since the stilling tube prototypes were built in Switzerland, all their parts are available in Switzerland, either in retailers or in the case of the pressure transducer online. Many of the companies are found in other parts of the world as well, or they deliver to a desired location, but it might be that at some places no similar piece of material will be available. In such a case, it is wise to stick as close to the mentioned dimensions, and to test the stilling tube water level recorder with own tests to ensure that is also works with the chosen, different, parts.

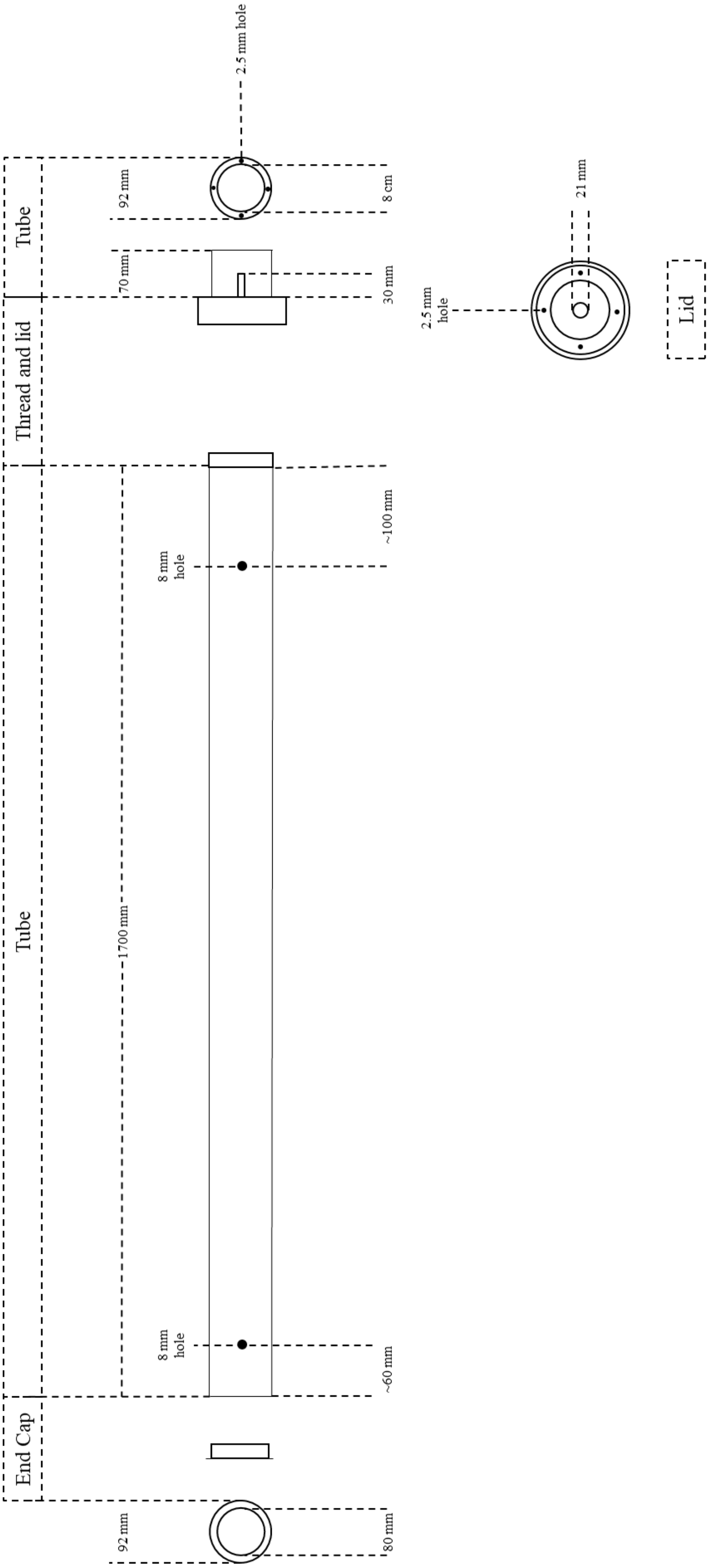

Figure 26: Detail drawing of the stilling tube with the relevant dimensions.

8.2.1. Material

Amount	**Material for tube**
1	InSitu Level TROLL 500 pressure transducer including hose and desiccant
2 m	Symalit C + S cable conduit “chiaro”, 92 mm x 80 mm
1	Geberit HDPE threaded connector with screw cap, 95 mm x 1/6’’ thread
1	Symalit end cap, 92 mm x 80 mm
1	Rubber-coated pipe clamp, Ø 25-30 mm, M8 thread
1	Rubber-coated pipe clamp, Ø 15-19 mm, M8 thread
2	M8 x 20 mm hexagon bolt
2	Washers for M8 bolt
4	3 mm x 25 mm counter-sunk screws
1	T-stake, 2.1 m
min. 2	Hose clamp, Ø 87-112 mm
Amount	**Material for filter**
1	Desired filter
1	G1/2’’ nut
1	Reducing nipple, G1/2’’ x G3/8’’ (external thread x internal thread), if filter thread ≤ G3/8’’
1	Reducing nipple, G3/8’’ x G1/4’’, if filter thread ≤ G1/4’’
1	Reducing nipple, G1/4’’ x G1/8’’, if G1/8’’ filter thread
	Tools needed
	Lathe
	Drilling machine with 8mm and 2.5 mm twist drill bits
	Saw
	Screwdriver for 3 mm x 25 mm screws
	13 mm wrench for M8 x 20 mm hexagon bolt
	Hot welding plate
	Slotted screwdriver

Table 5: The complete list of all the materials and tools, that are needed to construct the stilling tube water level recorder.

8.2.2. Production of the Stilling Tube

8.2.2.1. Cutting the Tube

The tube needs to be cut in three pieces, a long piece, which serves as the main body of the tube and two shorter pieces, one for the filter protection, which will be screwed onto the lid and one which is welded to the threaded connecter. The pieces' lengths are 1.64 m, and two times 6 cm.

Figure 27: The tube is sawed in three pieces. It is important that the cuts are perpendicular to the tube for the next working steps.

8.2.2.2. Cutting the Trenches in the Filter Protection

To allow air to flow out of the filter protection at the outside of the lid, trenches need to be cut in one of the 6 cm long tube pieces. The trenches have a depth of 3 cm and are also cut with the saw. The width of the trenches is the strength of the saw blade (2 mm). For the four trenches, two more or less perpendicular cuts are needed to apportion the trenches. There are also four red lines on the tube, which are nice to use as a reference for the cuts. For safety reasons, it might be wise to construct a holder for the tube piece, to be able to keep the hands away from the saw blade.

Figure 28: Cutting the trenches. To have an apportion of the trenches, it is easiest to cut where the red lines of the tube are. Also take care of the fingers, here a wooden construction was built to safely work on the piece and to not need to have the fingers too close to the saw blade.

8.2.3. Cutting the Threaded Connector

Also with the saw, the threaded connector is cut into two pieces. For the stilling tube, only the thread is needed and the other parts of the connector are too small in diameter to be connected to the tube. It is important not to cut in the thread, but slightly behind it, since otherwise the cap cannot be screwed completely on the thread.

Figure 29: The threaded connecter and the cap come in one piece (left). In this step, only the threaded connector (middle) is used. The cut is behind the thread, where the diameter is slightly smaller than at the thread itself.

8.2.4. Preparing the 2nd 6 cm long Tube Piece for Welding

The 2nd short tube piece (not the one with the trenches) needs to be welded to the thread form step 3. The outer diameter of the tube is 92 mm whereas the outer diameter of the thread, at the place where it is cut, only is 90 mm. The lit, which is threaded at the inside will not fit over a tube with a 92 mm diameter, so it is necessary to reduce the tube's diameter by at least two millimetres. This is done with a lathe. One end of the tube is clamped in the lathe and rotates, at the other end, the plastic will be removed layer by layer. All in all, the tube needs to be

Figure 30: With a lathe, the outer dimensions of the tube can be reduced. Theoretically, it is enough to remove 1 mm of the tube, but to be sure, it is better to remove 2-3 mm, in case the tube is not perfectly round.

reduced by about 2-3 mm (resulting in a diameter loss of 4-6mm) for about 2 cm depth. Whether it is reduced enough or not can be tested, by putting the lid over the black part of the tube. If it completely fits over the reduced part of the tube, it is enough, if not, the tube needs to be reduced a bit more.

8.2.5. Welding the Prepared Tube Piece and the Thread together

Take the reduced part of the tube from step 4 and the thread from step 3. These two parts will be welded together. It is important to weld the cut edge of the thread and the reduced side of the tube together. For the welding a hot welding plate is needed, which needs to be heated up to about 200-220°C. When the hot welding plate has heated up, the two pieces need to be held on the plate, one per side. The two pieces now need to be held in place with little pressure until a small bead appears at the both edges of the tube and the thread, respectively. Now the two pieces can be pressed on each other with little pressure for some seconds until they hold together.

Figure 31: When the temperature of the hot welding plate is between 200 and 220°C the two pieces that need to be welded together, can be held on each side to the plate.

Figure 32: When there is a small bead at the edge of the tube (left) and the thread, the two pieces can gently be pressed together until they hold.

8.2.6. Welding the Tube and the Piece from Chapter 8.2.5 together

In this step, the long tube needs to be welded to the piece from step 6. The procedure is exactly the same, hold the two pieces on the welding plate until a bead appears on each and hold them together until the weld is hard. It is important to weld the two tube pieces together and not the thread. The result looks much nicer, if the red stripes are continuing over the weldseam.

8.2.7. Drilling the Holes for the two Rubber-Coated Pipe Clamps

To finalise the tube, only the two holes for the rubber-coated pipe clamps need to be drilled. These are needed to be able to mount the pressure transducer and the desiccant in the tube. Both pipe clamps use the same bolts, such as the two holes are similar. In this step it is not very important to stick to exact dimensions, since the pipe clamps can be mounted to the pressure transducer and the desiccant in a range of about ten centimetres, depending on where the holes are. Since the desiccant is about eleven centimetres long, it is suggested to place the hole for the desiccant approximately six centimetres from the top of the tube. For the pressure transducer itself, which is about 21 centimetres in length, a placement for the hole at about ten centimetres from the bottom is suggested. The only place where the holes should not be drilled is directly on the weldseals, not because that they would then break, but it is more difficult to tighten the bolt, when it lies on the weld. In this case, the hole should rather be drilled a bit lower and not higher, to facilitate the mounting of the pipe clamp. To make the mounting to a stake easier, it is wise to drill both holes above each other and not twisted around the tube. For the bolts a hole

Figure 33: The holes are drilled with a normal drilling machine and an 8 mm drilling bit (left). Afterwards the M8 bolts with a washer fit tightly through the hole (middle and right) and can be connected to the pipe clamps. Also, the pipe clamps can be placed higher or lower on the desiccant and pressure transducer to have an optimal placing of them inside the tube. After the adjustment of the pipe clamps, the desiccant and the sensor are mounted inside the tube.

of eight millimetres is needed that can be drilled with a normal drilling machine and the respective drill bit. By drilling the two holes in the tube, the tube is finished, now only the lid has to be prepared to finalise the complete stilling tube.

8.2.8. Drilling the Hole for the Filter in the Lid

To place the filter in the lid a hole must be drilled in it. The hole for the filter should be in its centre to make a replacing of the filter as easy as possible. There are two ways to drill the hole in the filter, one is to use a standard drilling machine with the respective drilling bit, or to drill the whole with a lathe. With our prototype, the hole was drilled with the lathe for the practical reason, that there was no fitting drilling bit available. The hole needs to be as big, that a G1/2'' thread will fit through it without any play. An important note is, that a G1/2'' thread does not have a diameter of 0.5 inch (=1.27 cm), but 2.1 cm. So, the hole that is drilled in the lid must have a diameter of 2.1 cm, here exact working is inevitable to have a proper tightening of the filter. As mentioned, this is again done with a lathe, the lid is secured in the lathe and at first a hole is drilled with a large enough drilling bit, depending on the size of the lathe chisel. Afterwards, this hole is enlarged in the lathe to the desired width by cutting the lid's plastic outwards with the lathe chisel. To find out, whether the hole has the desired diameter, it can be tested with one of the G1/2'' filters.

Figure 34: At first, a hole needs to be drilled with a large enough drill bit (depending on the lathe chisel's size), to be able to position the chisel in the hole and enlarge it to the desired width.

8.2.9. Screwing the Shield to the Screw Cap

This is probably the most complicated part of the whole production of the stilling tube. The idea of this part is to screw the shield, that protects the filter from impacts, on the outside of the screw cap. In this step, exact work is very important since there is very little space.


Figure 35: Remove the ring seal with a slotted screwdriver.

The ring seal in the cap has the same size as the tube, so it is possible to screw the tube to the cap with screws placed under the ring seal. At first, this seal ring needs to be taken out of the cap, preferably with a big, slotted screwdriver.


Figure 36: The dimensions of the tube are marked at the outside of the cap (top). Afterwards, the four points are marked 3 mm towards the centre, where the holes for the screws are going to be drilled though (bottom).

Afterwards, the tube needs to be placed centric at the outside of the cap to mark its dimensions there. Knowing that the tube’s strength is six millimetres, now four points can be marked for the drilling holes at three millimetres towards the centre. At these points, the holes are drilled through the cap to connect it to the tube with screws. The holes are drilled perpendicular with a 2.5 mm drill bit. The other end of the holes should all be in the recess of the ring seal, if worked properly.

At the inside of the cap, where the screw heads are placed, a counterbore needs to be drilled with a larger drilling bit to be able to place the ring seal properly again. To have a lead for the srew in the tube as well, there also holes need to be drilled. since it is very difficult to drill all four holes at the correct place, at first only one of the holes is bored. This hole needs to be placed in the centre of the wall at the side of the tube with the trenches. It is very important that this bore hole is parallel to the wall of the tube so that the screw is not leaving the tube. After the first hole is drilled, the first screw can be screwed in. The tube and the screw cap now hold together, which makes it easier to mark the location for the other

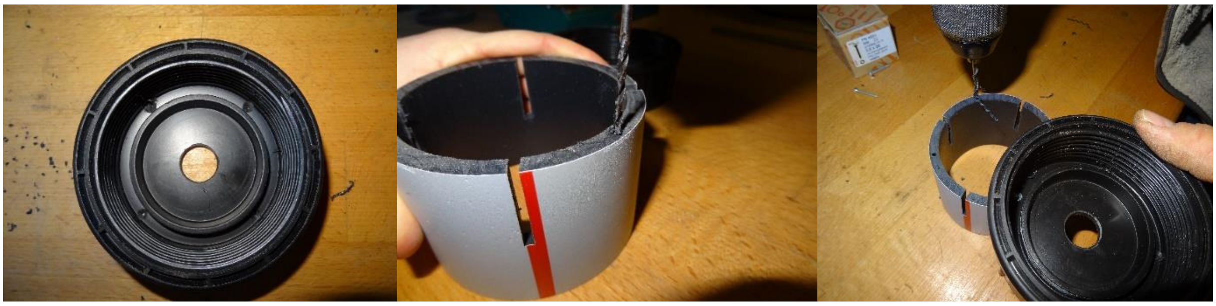

Figure 37: At first, holes and counterbores are drilled in the cap with a 2.5 mm drill bit (left). Then, one of the holes is drilled into the tube piece in the centre of the wall also with a 2.5 mm drill bit (middle). Afterwards, the tube and the cap are screwed together with the first screw, before the other hole positions are marked on the tube through the holes of the cap. At last, the other holes are drilled in the cap, where the marks are (right).

drillings in the tube. To do this, the tube is located centric over the cap and the other positions are marked through the cap. To drill the holes, the tube can be rotated again away from the cap, so that the three marks are free. These holes are now drilled the same way, like the first one. When all the holes are drilled, the tube again is rotated centric over the cap and the remaining screwes can be screwed in. After all the screws are in place, the ring seal can be fitted in its place again and also the cap is ready to be mounted on the thread of the stilling tube.

Figure 38: The remaining screws are screwed in left) before the ring seal is set in place again (middle). The cap can now be screwed on the tube to finalise the tube (right).

8.2.10. Preparing the Cap for the Top of the Stilling Tube

To finalise the stilling tube, only the end cap at the top end of the tube is missing. This cap is needed to prevent animals and dust from entering the tube and also ensures, that the pressure transducer inside the tube is not affected by pressure changes due to wind. The cap must not be airtight so that no under- or overpressure results inside the tube when the water level is changing. Hence, air must be able to pass the top cap of the tube, but preferably nothing else. To ensure that air is able to pass by the cap, little notches are cut in it. The notches allow a very decent airflow

Figure 39: The top cap with one notch in the front. It is suggested to cut more than one notch per cap, in case that one block for some reason.

between the inside and outside of the tube, but still prevent animals and dust to enter the tube’s interior. The notches can be cut in the cap with a sharp knife and don’t have to be big. The suggestion is to cut several of these, in case that one blocks for any reason.

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Personal Declaration

I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

Zürich, 29.01.2019