EC routing of the Mechelbach River, Luxembourg

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This report describes the EC routing experiments of the Mechelbach river in Luxembourg. EC routing was done to better understand a catchment, where water comes from and what differences there are in water quality. To be able to allocate where the water comes from and why there are differences in water qualities, EC routing field measurements were compared to an analysis of topographical information and land use. The research question therefore was: What is the relationship between topographical information (and land use) and the discharge of different tributaries within the Mechelbach catchment? Topographical information was obtained through GIS analysis, using a DEM of the area to calculate Strahler order, division of sub-catchments and TWI. Also a land use map was made. These were compared to field measurements of EC and discharge. Quite a large spread was observed in the discharge measurements, indicating inaccuracies. Concluding on the research question, topographical information seemed to be mostly related to discharge through land use. The relation between TWI and discharge was highly dependent on the method for calculating TWI values, of which some showed a positive trend as well.

I. Introduction

Measuring parameters in water is usually done to analyse the quality of water. However, it can also be used to quantify water fluxes and to trace back to where the water comes from. To have a better understanding of the catchment, the focus should not solely be on the values of these parameters, but also on the cause of these values. This way, a problem can be solved from its roots instead of only taking care of the consequences.

Environmental tracers observed in water can help to characterise a catchment by identifying fluxes of water and solutes [1]. By going into the field and measuring electrical conductivity (EC) of stream flow at different locations, it is possible to infer where stream flow may originate from and what processes it undertook from rain droplet to river discharge. Combined with discharge observation, the method can be used for allocating where the water originated from through a mass balance. The method to measure EC is quick, reliable and easy, which makes EC a very useful parameter to get to know important processes in the area.

By looking at the topography of a catchment, inferences about the hydrological processes that formed the catchment can be made [2]. One way of linking hydrology and topography is by evaluating the topographic wetness index (TWI), which relates the local slope and catchment area to the water storage capacity at any location. Given that storage strongly governs the flow of water from rainfall to stream flow, the TWI could provide a simple yet useful measure to predict how different areas contribute to discharge within a larger catchment.

Hydrological processes are also strongly governed by land use, both in terms of quantity [3] and quality of water fluxes. This study will therefore also assess the effect of land use on these processes. In this report, this method of allocation by environmental tracers is compared to the contributions from different areas based on topographical information. The main research question therefore is:

Based on environmental tracers in tributary channels, how do topography and land use explain differences in stream flow contributions from different areas within Mechelbach catchment?

Logically, the following sub-questions can be formulated:

- What is the contribution to stream flow from different areas based on topographic information?

- What is the contribution to stream flow from different areas based on land use?

A. Site description

The site of this research is the Mechelbach catchment in Luxembourg (figure 1). The catchment has streams with flows of less then 100 L/s in May. On the map, many tributaries can be seen. In reality, only a few of them contain enough water to form a side stream. At the other locations, no flowing water can be observed, only wetlands.

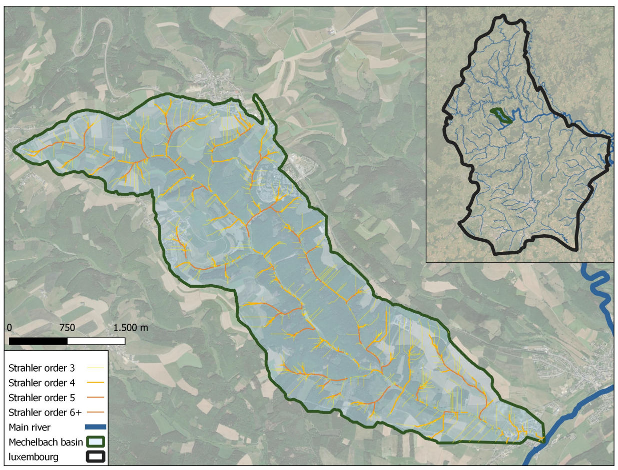

Figure 1. Overview Mechelbach basin

The Mechelbach catchment mostly consists of 3 types of land use: wetlands, forest on hill slopes and plateau. The plateau is often used for agriculture and the wetlands are mostly grasses. Some of the wetlands are very wet and muddy, but a lot of them are more solid grass lands: the soil does not sink while standing on it. An impression of the wetland and forest hills along the Mechelbach river can be seen in figure 2. It can be seen that there is clear distinction between these types of land. Besides the different kinds of landscape, there are more important things in the area that are likely influencing the EC values of water. Some of the nutrients comes from upstream towns. Also, there is a waste water treatment plant (WWTP) in the area, of which the effluent is discharged into the Mechelbach stream.

During the measurements on May 15, 16 and 17 it was dry all the time. In the night of May 15-16, it rained around 0.2 mm for 3 hours. Also in the preceding week of the fieldwork, there had been rainfall in the area of Heiderscheid as well. This caused the rivers to have relatively high water levels compared to other years. This water was assumed to come mainly from storage in the subsurface. The temperature was between 8 and 17 degrees Celsius during the day, lowering down to a minimum of 4 degrees at night.

Figure 2. Wetland and forest

B. Hypothesis

Both topography and land-use provide information on the storage and flow paths of water in an area. Areas with a large storage capacity will store rainwater and distribute it to streams over a longer stretch of time. Given that the weather conditions imply that most of the observed stream flow will come from storage, it was expected to see a positive relationship between TWI and discharge. Similarly, areas with high vegetation cover were expected to generate more baseflow than areas that promote runoff, given their role in slowing down runoff and allowing it to percolate in the soil.

II. Methodology

To answer the main question, both field measurements and a theoretical model must be obtained. How this was done, is described in this section.

A. In the Field

EC values were measured where side streams come together with the main stream. When measuring locations were far from each other, additional EC measurements were taken in between. At some places, the discharge was also measured.

Beforehand, it was not known which streams on the map contain water and which are dry at the moment. Thus, it was not clear upfront where in the field the suitable measurement locations were. Therefore the exact locations on where the measurements were done, are given in the results section.

Location	Downstream EC (µS/cm)	Downstream temperature (°C)	Upstream EC in main stream (µS/cm)	Upstream temperature in main stream (°C)	Upstream EC in side stream (µS/cm)	Upstream temperature in side stream (°C)	Estimated main stream discharge contribution (L/s)	Estimated side stream discharge contribution (L/s)	Comments & observations (For instance: amount of rhodamine used for discharge measurement)
1									
2									
..									

Figure 3. Table field manual

1. Where was EC measured?
When two streams come together, EC was obtained at the following points:

- Upstream, for both the main and side stream the EC was measured as indicated with points A and B in figure 4. The measurement was done at least 1 meter upstream of the point where the two streams came together.
- To obtain the downstream location, first the width downstream was estimated. The location of the downstream measurement is 5 times the width of the stream away from the point where the two streams come together. The downstream measurement is indicated with point C in figure 4. The reason for this is that only from a distance of 5 times the width, the stream can be assumed as well mixed.
- EC was measured at least every 500 meters, so at some points EC was measured, even though no streams come together.

2. Discharge
Discharge was measured using a rhodamine solution. Using this method, a known amount of rhodamine was put into the river. The required concentration was not known beforehand. Under the assumption of 1/ls in the stream, the expected concentration of rhodamine required was 100 µg/L. In the field it was tested if

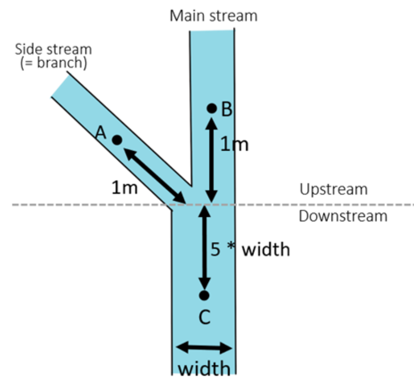

Figure 4. Where to measure EC

this concentration is truly the optimal amount. The rhodamine probes were installed between 5 and 10 times the width of the river downstream of the release point to measure the change in concentration. This is illustrated in figure 5. The probes were installed at a location where the water is flowing (so not a stagnant zone). Putting a known amount of rhodamine into the river and measuring the change in concentration over time allows the calculation of discharge through the relation shown in equation 1 and 2. The concentration over time was measured using a probe containing a fixed response fluorometer [4], which logged to a computer. From this data, the discharge can be calculated using the area under the graph.

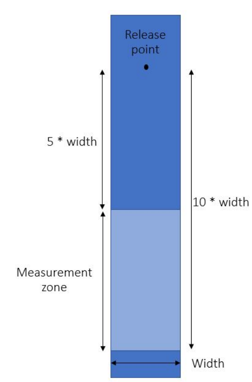

Figure 5. Where to measure discharge

$$\int_{t_0}^{\infty} C(t)dt = k\,(\frac{\mu g}{l} \times s) \quad (1)$$

$$Q(\frac{l}{s}) = \frac{C_{initial}(\mu g)}{k(\frac{\mu g s}{l})} \quad (2)$$

B. Terrain indices

1. Digital Elevation Model (DEM) and Strahler order

A digital elevation model was used in QGIS to generate the stream flow based on the topographical information. The digital elevation model itself is a map showing elevation per pixel, as can be seen in figure 6. With the DEM, a map of how the river flows through the catchment was made. The rivers can be labeled using Strahler order to give an indication of their sizes. This map was used for getting familiar with the area before going there. It shows where the streams can be and gives a good idea of where and how often it is expected to measure. This map can be seen in figure 1, in chapter II. Site description. Besides, the DEM was used to split up sub-catchments. This was useful for explaining differences in EC. When the source of the water is known, one can compare the different types of land use to explain the differences in water quality.

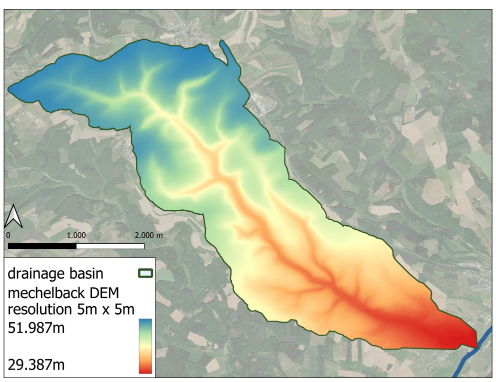

Figure 6. 5m Digital Elevation Model supplied by LIST, Luxembourg

2. Topographical Wetness Index and sub-catchments

The Topographical Wetness Index (TWI) describes a measure of storage. From the DEM the upstream area and the slope angle could be calculated for every pixel. These two metrics were combined with the formula shown in equation 3 to generate figure 7.

For every sub-catchment, the average TWI was calculated. The higher the TWI, the more storage an area can provide in theory. This means that areas with a high TWI provide more water in a situation where only base flow was observed.

$$TWI = ln(\frac{Area}{tan(angle)}) \tag{3}$$

$$Q_1 + Q_2 = Q_3 \tag{4}$$

$$Q_1C_1 + Q_2C_2 = Q_3C_3 \tag{5}$$

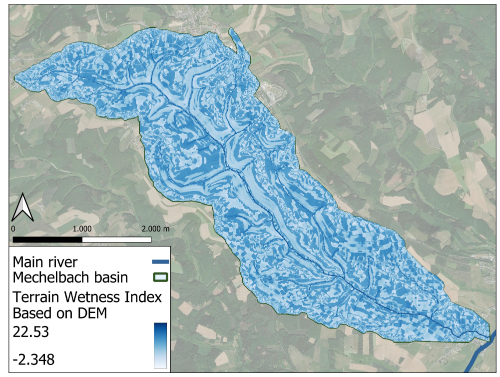

Figure 7. TWI calculated per pixel

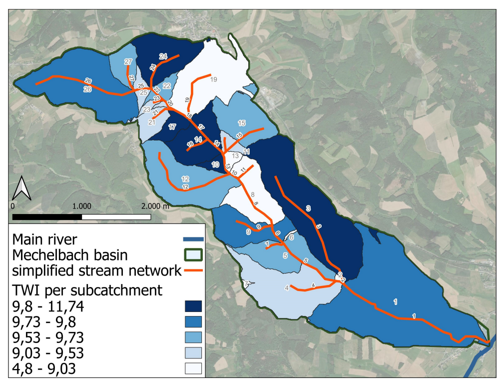

Figure 8. TWI per sub-catchement

C. Processing of measurements

The obtained field results were used to make a map which indicates the amount of water coming from the different sub-catchments. A map showing these sub-catchments based on the DEM and TWI is given in figure 8. Calculations were done with a linear mixing model, using equation 4 and 5. For simplicity it was assumed that all downstream measurements are fully mixed in this model. In reality, this might not be the case because of heterogeneity in natural catchments. An example is given in figure 9. Differences in EC values were used to attribute different fractions of the observed flow to tributaries. Along the stretch of a single channel without visible inflows, different EC values may be observed. We attributed the differences in EC in between confluences to the diffuse inflow of water from the subsurface, of which the EC was also measured.

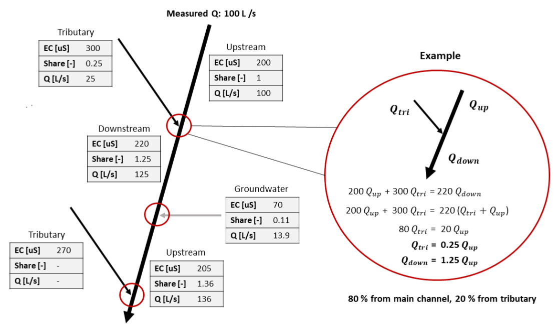

Figure 9. Example of EC routing calculation

D. Land use

The main reason for changes in EC along the stream is differences in land use, as was indicated before. A land use map is required to compare the correlation between different land use types and EC values of sub-catchments (figure 10). This was obtained from the open data portal of luxemburg which has a dataset for the 2018 landuse classification based on INSPIRE data [5].

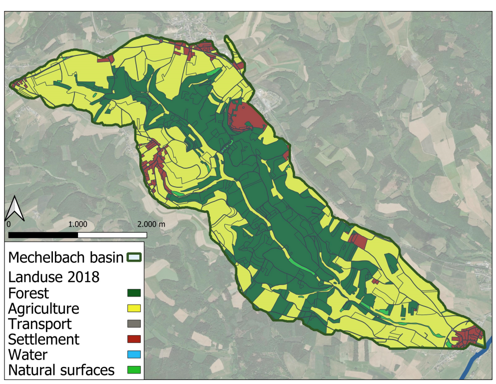

Figure 10. Landuse in 2018

III. Results

A. Measurements

Before visiting the site, it was not known at which locations it was feasible to measure EC and discharge. Therefore it was decided in the field which places are good for doing the measurements (figure 11).

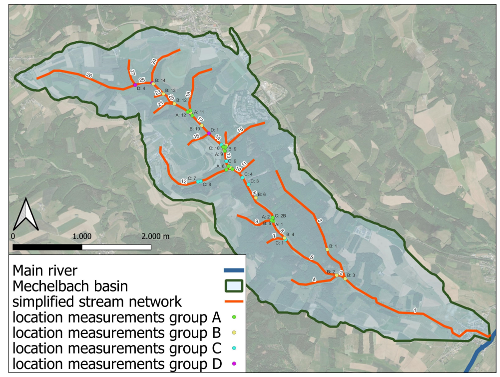

Figure 11. Locations of completed measurements

B. discharge

The amount of rhodamine solution used in the first few experiments was 1 ml of 100 $\mu g/l$ as seen in the left plot of figure 12. This amount was insufficient and thus the experiment was repeated with higher concentrations. After a few more tries in larger streams, up to 100 mL of 100 $\mu g/l$ gave good results, as can be observed in the right plot of figure 12. After analyzing all discharge data, the results were used to compare with the discharge calculations obtained with the mixing model.

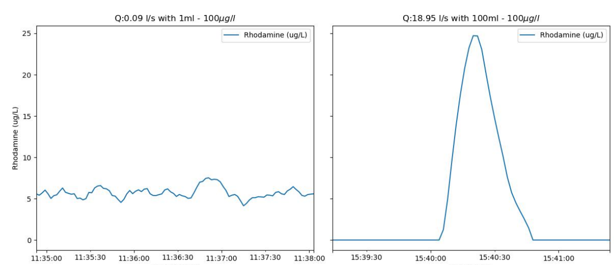

Figure 12. Rhodamine concentrations over time for two different concentrations

C. EC routing

With the equations of the mixing model (4 and 5), the measured EC was used to compute the contribution to stream flow per sub-catchment. For each confluence, it was calculated in percentages how much of the water downstream comes from the main stream and how much comes from the tributary. For sections

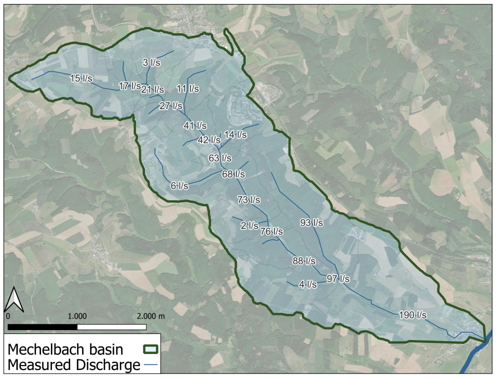

Figure 13. Discharge per sub-catchment obtained by EC routing (in l/s)

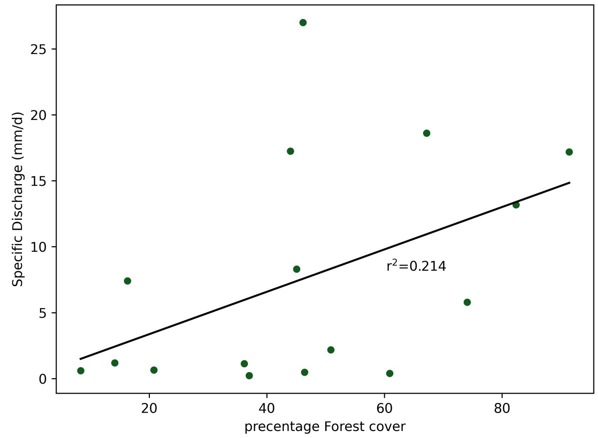

Figure 14. Comparison of specific discharge with % forest cover

with a change in EC value with no visible tributaries, the calculation was done with groundwater as the tributary. Using a starting value of 190 l/s downstream (which was calculated by using one of the values from the measurements obtained with rhodamine), the discharge per sub-catchment can be seen in figure 13. These computed values are compared to the measured ones in table 1.

Table 1. Measured vs computed discharges

#	Measured (l/s)		Computed (l/s)
5	39.14		79.63
6	53.34		75.59
12	4.64	11.1	5.66
14	39.86		41.8
19	8.25	17.38	10.51
22	18.95		20.59
25	29.77		17.24

D. Effect of land use on specific discharge

After full EC routing was done, characteristics of different sub-catchments could be compared to each other. First, specific discharge was compared to the percentage of forest cover (figure 14). A positive trend can be observed, although there was a large spread in the observations. A positive relation indicates that areas with relatively large forest cover generated more stream flow.

In the same way, specific discharge can be compared to the percentage of agriculture cover (figure 15). Here, a negative trend can be observed, again with a large spread. This indicates that agriculture does not have a lot of storage, resulting in relatively lower base flows.

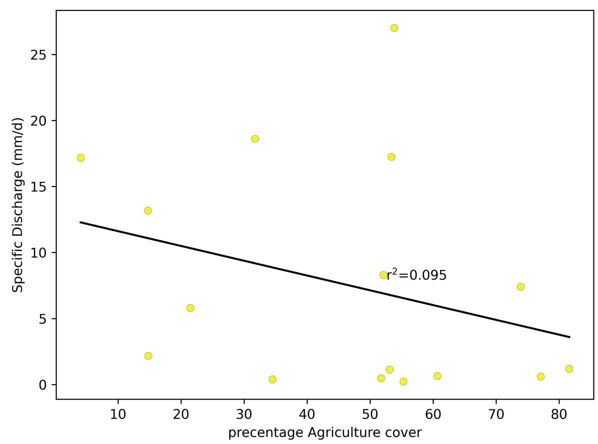

Figure 15. Comparison of specific discharge with % agriculture cover

When the same comparison was made for the percentage of settlement cover and specific discharge, the result looks quite different (figure 16). The highest discharges are all obtained for the areas with the least settlement cover. For higher settlement cover, specific discharge was very small. The relation between the two variables does not seem linear, but a strong negative trend can be observed. This makes sense, because settlements are known for their low storage.

Altogether, an increase in forest cover seems to increase specific discharge for base flows, while an

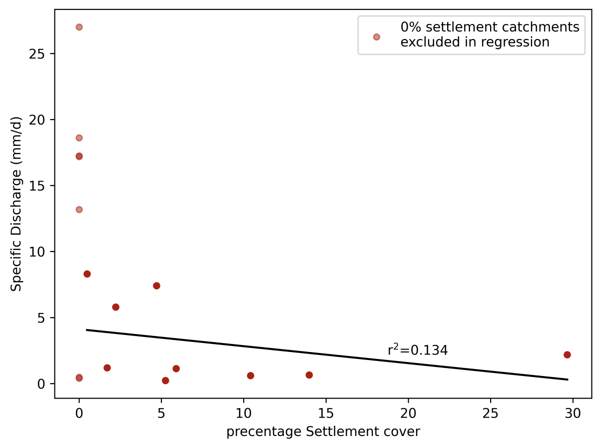

Figure 16. Comparison of specific discharge with % settlement cover

increase in agriculture and settlements cover seem to decrease specific discharge even more during base flow conditions. To be certain that the trends are a real trend and not just coincidence, EC more measurements along the catchments are required. This would yield more data points to prove or disprove the relation.

E. Effect of TWI on specific discharge

Specific discharge was also compared to the TWI of the area. There are many ways to simplify TWI in a model so both the average (figure 17) and summed TWI per sub-catchment (figure 18) are used in this comparison.

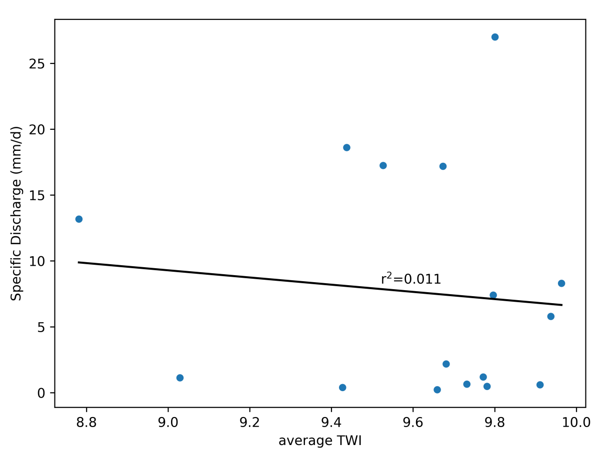

Figure 17. Comparison of specific discharge with average TWI

For summed TWI, the comparison was made with discharge instead of specific discharge. Both graphs show a large spread in results. Meanwhile, the observed trend was different: for average TWI it seems like there was no clear relation, while summed TWI gives a positive relation. One explanation for this could be that an area with both very low and very high TWI shows different behaviour compared to an area with average TWI, but both areas have the same average TWI value. Because of this, the method using summed TWI seems to be a better representation of reality. Also for these variables, a better statistical analysis must be applied to be certain that trends are real an not coincidence.

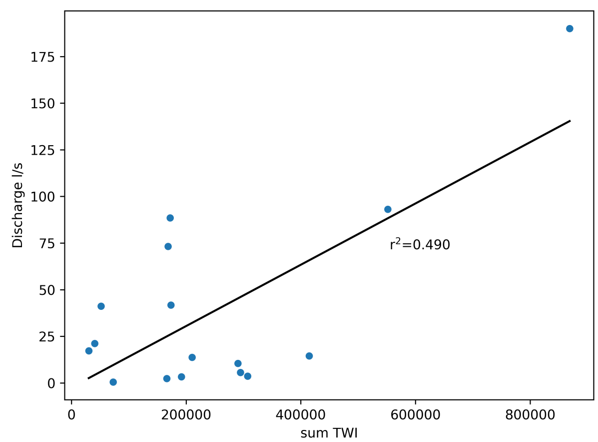

Figure 18. Comparison of discharge with summed TWI

IV. Discussion

A. Analysis of errors

In research involving fieldwork, some degree of measurement errors is unavoidable. This is because of human errors, limited precision of the equipment, and heterogeneity of field conditions, causing the observed system to show small differences in time. Moreover, the way in which our data has been processed and analysed may have caused some degree of error. It is tried to quantify and discuss the main uncertainties in this research.

The uncertainty in EC measurements were quantified by comparing measurements that were done by different groups in the same location. By dividing the standard deviation of the two to four measurements of one location and dividing by the mean of these values, an average uncertainty of 2.14 percent was calculated. for reference, the uncertainty of the values 90, 100, and 110 would be 10 percent. In a similar manner, the uncertainty of each fraction of stream flow (see figure 9) was calculated to be 20.5 percent. This ten-fold increase in the relative error is somewhat surprising, as this is purely the result of processing the data from single measurements to an EC routing. It is observed that the main contributors to this large relative were tributaries with a relatively small contribution, especially when one or more group's data suggested a flux of water that was not supported by other observations. To further demonstrate the potential errors created through routing the stream flow, a calculation example is given in table 2. As can be seen, a relative error of 5 percent upward in every EC measurement would lead to a routing error of more than 10 percent. We have aimed to limit this effect by calculating the contributions of the three components of a confluence per group and taking the mean of these values afterwards. However, to significantly reduce the errors that were visible in the flood routing, additional measurements could help to balance out the outliers.

Table 2. Calculation example EC error to fractions error

	up-stream	tributary	down-stream
EC (real)	200	300	220
EC (measured)	210	315	242
fraction (real)	0.80	0.20	1
fraction (measured)	0.70	0.30	1

In order to quantify how much water came from which sub-catchment, discharge measurements were done. Unlike EC, measured discharge data showed large errors. The rhodamine method failed a few times because the required amount of rhodamine was not known beforehand. Also, for some of the rhodamine measurements that did seem to have the right amount the results varied for the measurements done at different times at the same location. While we were able to discard the measurements that were clearly not performed correctly, there were still large differences. At two locations, the value of one of the measurements was more than double the amount of the other. We were not able to determine if this was because of actual differences in flow or because of a measurement error. It has to be noted that the discharge measurements only affect our analysis to a limited extent, as we only used discharge measurements in one location. The value used when taking one reference point to calculate the discharge from each tributary, following the EC routing, does not change the relative differences of specific discharge between sub-catchments. In 'Recommendations' we discuss how to move forward with rhodamine discharge measurements in the context of this research.

In order to assess the quality of the EC routing as a whole, we compared how the discharge that was assigned to each sub-catchment using flood-routing to actual discharge measurements done in these locations. As these discharge measurements were limited to major streams, we are not able to address the effectiveness of flood routing to determine the inflow from smaller tributaries in the same manner. A major error may lie in the propagation of errors in the routing fractions computed at each confluence, as one reference discharge value is used. As can be seen in table 1, the routed discharge sometimes shows a very small error with respect to local discharge measurements, while at other times the error is very large. One explanation for these results is that the EC routing indeed is a robust way to assign flows to different streams. Alternatively, one could conclude that this is merely a coincidence. Whether the differences are the result of faulty discharge measurements or the propagation of errors in the EC routing is difficult to conclude. This underlines a limitation of our research.

The obtained EC measurements seem to be of good quality. It was known beforehand that the streams at the village and WWTP should have a high EC value, which was indeed the case on all days. Also, groundwater was measured two times and for both measurements the EC value was low, as was expected. For most locations that were measured multiple times (on different days), the EC values were similar. Small differences are to be expected, especially because it had rained during one of the nights. Together with the uncertainty caused by different people handling the EC meters, results from different groups did not differ significantly. The biggest difference in EC values at the same location was at the WWTP.

One reason for the changes in observed discharge and EC is the different times at which it was measured. Comparing the data of different days, the EC values at the same locations had quite small differences in general except around the WWTP. In discharge, differences are quite large. Because it was raining during the night of May 15-16, it makes sense that there is more water in the catchment afterwards, increasing the discharge. In the WWTP the parameters can be even more variable: effluent concentrations and amounts may vary constantly. Because of this, values of the different days cannot directly be compared to each other. To reduce the uncertainty, it is best if all measurements are done in one period with the least amount of changing conditions possible. It can also help to do further research into the effluent of the WWTP, since this has far more variable parameters than the other streams. It might be feasible to install a constant logger there, so that large changes can be allocated.

B. Discussion of results

While comparing the specific discharge against topography and land use, we were not able to conclude significant relationships. Nevertheless, some rough trends were observed in the results. Specific discharge was used to omit the obvious effect that the surface area of a sub-catchment has on the water it discharges. While a rough positive relationship between the summed topographic wetness index and discharge can be observed, this was not possible for the comparison between the specific discharge and average TWI. As the latter two are merely divisions of the former two by the surface area of the sub-catchments, this is a contradiction. This mainly points towards limitations into make meaningful statements on the investigated relationships. Nevertheless, we may also conclude that the TWI is not a good index to predict differences in streamflow contribution from different areas within a catchment. The average TWI shows that, as a result of averaging over a catchment, local shapes that have large implications for the storage and flow paths of water remain overlooked. Instead, the TWI often converged towards a similar number for each sub-catchment. It should therefore be considered to assess the topography of a catchment with a more in-depth terrain analysis or by using other indices, such as drainage density or average slope [3].

The most visible trend was observed when comparing specific discharge to forest cover, which shows that areas with more forest cover likely generate more stream flow. While this coincides with our expectations, it has to be noted that while in the field, forests were mainly observed on hill slopes with bedrock being only up to a few metres below the surface. Since we expected to observe base flow coming from storage, this somewhat coincides with our expectations. Instead, following the precipitation that occurred in the week before our arrival, we may have observed that subsurface runoff and preferential flow at timescales of days to weeks were the dominant flow paths. Following this line of reasoning, using the TWI to predict stream flow may have been a better predictor when discharge of intermediate timescales can be ruled out as a dominant flow path.

For figure 13, the average distribution was taken for confluences with multiple measurements. For most of the confluences, the distribution is as follows: around 85 to 100 percent of the discharge comes from the main stream and and around 0 to 15 percent comes from the tributary (or groundwater). This makes sense because tributaries usually have a smaller stream flow than the main stream. The biggest exception to this is the confluence most downstream, as the discharge doubles downstream of the confluence. No multiple measurements were done for this part, so it is hard to say whether this is in the right order of magnitude.

C. Recommendations

Overall, we would recommend to perform this research more extensively to obtain more robust results. The most important improvements in accuracy could be made by improving the quality of the discharge measurements. This can be achieved through improving the rhodamine method or using a different kind of discharge measurement. Because of an underestimation of the expected stream flow, the rhodamine was too diluted on the first day of fieldwork. More accurate predictions beforehand could therefore reduce the number of 'trial and error' outliers that were produced on this day. More frequent discharge measurements can improve accuracy as well. Firstly, this could be achieved by gaining experience with using the equip-

ment, so that more measurements can be done within one day. This could also be achieved by making use of a logging device instead of a laptop, as this is easier to handle in the field. Secondly, a longer measuring campaign will create a larger sample size. Other discharge measurements that could be considered are salt dilution coupled with EC measurements or a simple bucket filling measurement. If discharge becomes more reliable, the accuracy of EC and mixing model can be measured more precisely.
With a more extensive analysis of the hydrological system, one could also make a better distinction between the flow paths of the water. This could be done by characterising the subsurface more elaborately for each sub-catchment or by analysing a hydrograph created with daily discharge measurements in combination with precipitation data [6]. Lastly, conducting this study on a larger scale will enable researchers to find significant relationships between the data and draw more certain conclusions.

V. Conclusion

In this report, we have aimed to find relationships between topography and land use data and observations on stream flow from different tributaries using environmental tracers. While some trends could be observed from scatter-plots, no significant relationships were found. For the topographic wetness index, the reason for this may lie in the chosen index being inappropriate or limitations in our measurements. Among land use types, forest was most strongly related to discharge, which could imply that the dominant flow path was subsurface runoff and preferential flow at an intermediate timescale. Using EC routing to attribute discharge to different areas within a larger catchment was found to be a robust method. By doing this, it becomes possible to create an overview of the catchment and compare sub-catchments. The measurements of discharge, however, were less certain. The reason for this mainly lies in the limited number of observations which, in turn, is a result of the effort required to do these types of measurements within a limited amount of time. In order to better understand the hydrology of this catchment in the context of this study, we therefore recommend further studies to take place on a larger scale. This would allow more measurements to be done and a more detailed description of the landscape and processes.

Acknowledgments

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Appendix

GIS files and further details on the analysis methods can be found at github.com/daafip/tracer-experiment-luxemburg.