A low-cost water quality monitoring system for the Ayeyarwady River in Myanmar using a participatory approach

Thanda Thatoe Nwe Win, Thom Bogaard, Nick van de Giesen

Supplementary Materials I: Description and Assessment of Akvo Water Quality Measurements

Description of the Akvo method

The Akvo water quality measurement system is a simple, low cost and open source, smartphone-based water testing system connected to an online data platform. The innovative water quality testing smartphone applications named Caddisfly and Flow, were developed by the Akvo foundation. Caddisfly is the application of a water quality testing kit combining the simple, low-cost, robust hardware of water quality test strips and sensors; Flow is a field data collection platform through which data can be shared with the people who need to see it. Caddisfly offers different solutions for water quality testing dependent on the parameter which is being tested. One of the options within Caddisfly is an automated way of reading and interpreting strip tests. The test results are geotagged and directly uploaded into the database. The method uses a plastic colour calibration card, on which the test strip is placed, as shown below. The Caddisfly app automatically takes images at the required times, calibrates the phone before each individual test, and then interprets the results (see Figure 1).

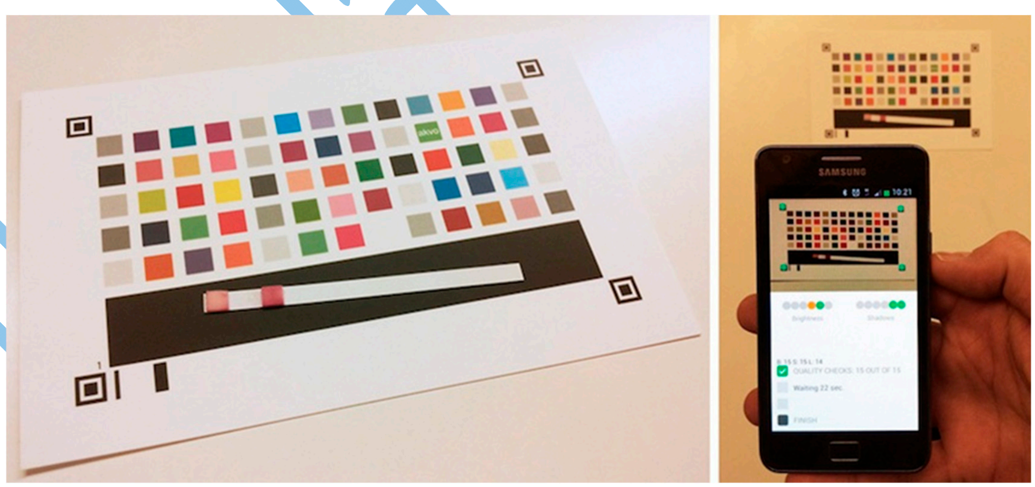

Figure S1. Colour calibration card and Caddisfly mobile app.

In principle, all test strips available on the market can be used, such as arsenic, alkalinity, ammonium, chloride, free & total chlorine, hardness, iron, pH, phosphate, potassium, nitrate and nitrite. Additionally, by connecting an external sensor to the mobile phone Electrical Conductivity (EC) can be measured as well.

Laboratory quality tests

Measuring water quality using indicator strips or added devices using a mobile phone consists of two aspects: the correctness of colour recognition by the camera (physics) and second, the correct chemical concentration as depicted by the indicator strip (chemistry). Rigorous testing of the mobile phone readings was (and still is) performed for every newly added chemical parameter. Hereto, standard solutions over the full range of the indicator strip are prepared and strip readings by the app are compared to the solution concentrations. Some tests have been performed with various mobile phones as camera characteristics differ between phone brands and versions.

Method of test description

For strip test validations the following procedure is followed for different chemical parameters:

1. Prepare standard solutions according to a test strip interval of different concentrations

2. Dip the strip in the standard solutions of each interval and read out the colour values (in Lab) with a desktop colour reader (X-rite i1 pro). These Lab values are embedded in the Akvo Caddisfly software and used as reference values

3. Perform different validation tests with the Caddisfly app, the Colour Reference Card and the subsequent test strip on standard solutions in two light conditions: normal sunlight and bright sunlight (directly in the sun)

4. Compare the results of the Caddisfly app with the standard solutions

Results

In this research, use has been made of EC using an attached sensor and 4 indicator strips: pH, NO3-N, PO4, total Fe. Below the results of the standardised laboratory experiments for validation the strips and EC sensor.

pH

Table S1. Dependency of pH reading on sunlight.

	Observed pH in normal sunlight			**Observed pH in bright sunlight**		
	Asus (NSL)	**Moto G4 (NSL)**	**Samsung On5 (NSL)**	**Asus (BSL)**	**Moto G4 (BSL)**	**Samsung On5 (BSL)**
Correlation	0.96	0.97	0.96	0.89	0.90	0.88
Average % Error	-4.53	-2.63	0.54	-0.58	0.20	0.14

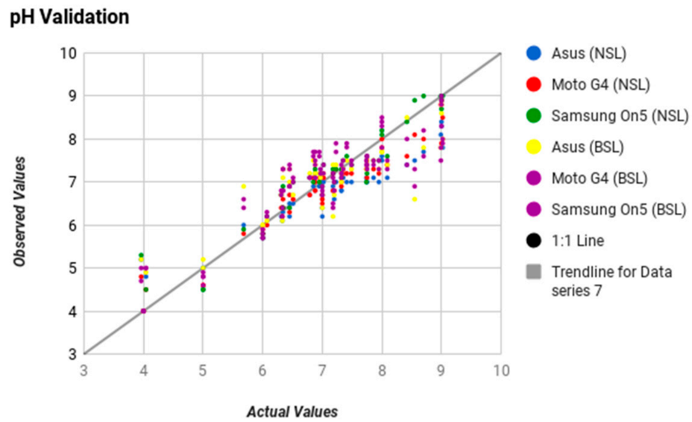

Figure S2. pH Validation.

Nitrate Nitrogen

Table S2. Dependency of Nitrate Nitrogen reading on sunlight

	Observed Nitrate-N Concentration in Normal sunlight (ppm)			Observed Nitrate-N Concentration in bright sunlight (ppm)		
	Asus (NSL)	**Moto G4 (NSL)**	**Samsung On5 (NSL)**	**Asus (BSL)**	**Moto G4 (BSL)**	**Samsung On5 (BSL)**
Correlation	0.90	0.99	0.96	0.92	1.00	1.00
Average % Error	-34.94	-46.99	-44.07	-40.42	-45.78	-42.23

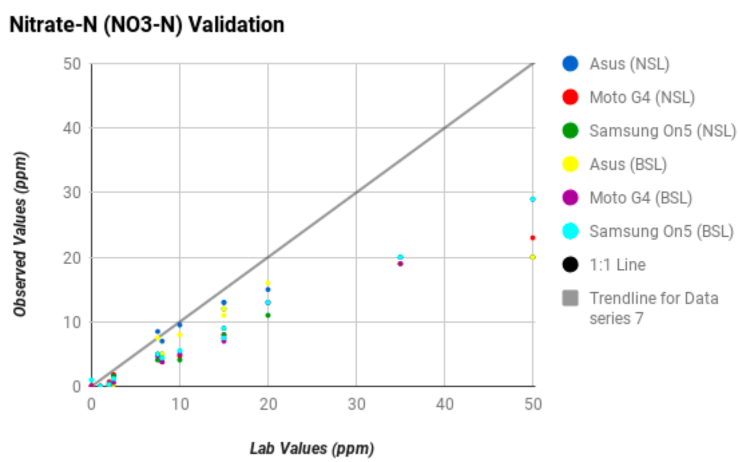

Figure S3. Nitrate Nitrogen Validation.

Total Iron

Table S3. Correlation and average error of Total Iron

	Asus (NSL)
Correlation:	0.97
Average % error	-27.24

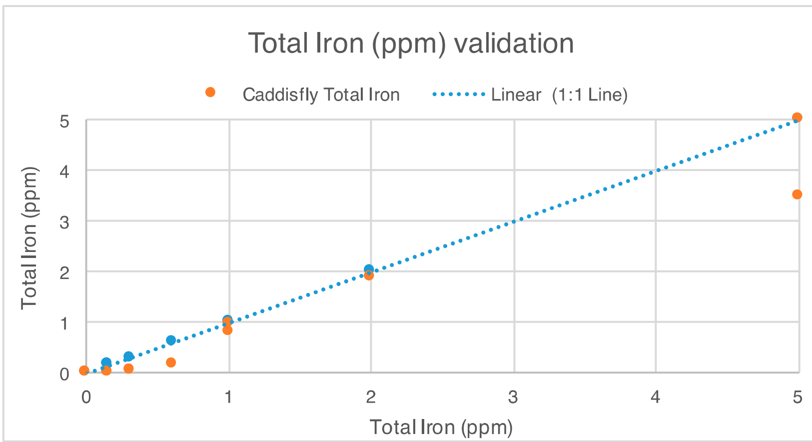

Figure S4. Total Iron Validation.

Phosphate

Table S4. Correlation and average error of Phosphate

	Asus (NSL)
Correlation	0.82
Average % Error	38.52

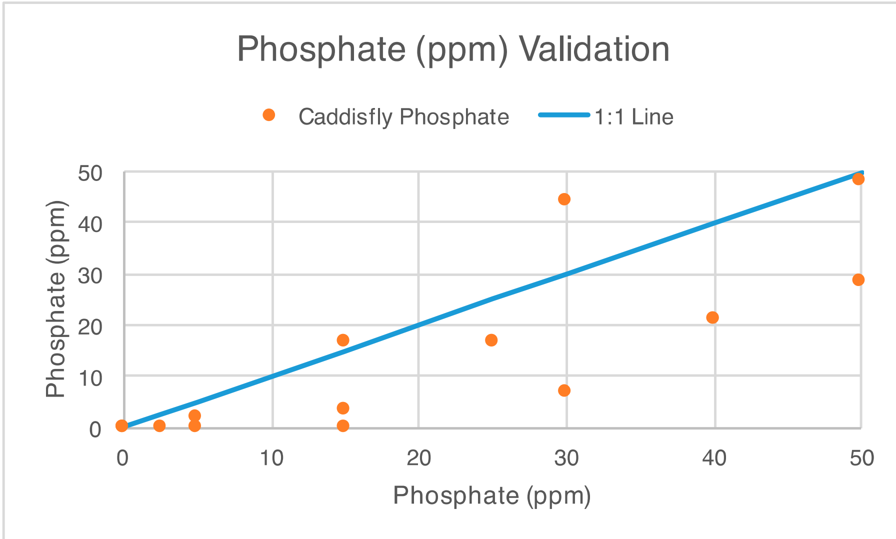

Figure S5. Phosphate Validation.

Electrical Conductivity (EC)

6 devices, 4 EC values (ranging from 200 to 12580 µS/cm)

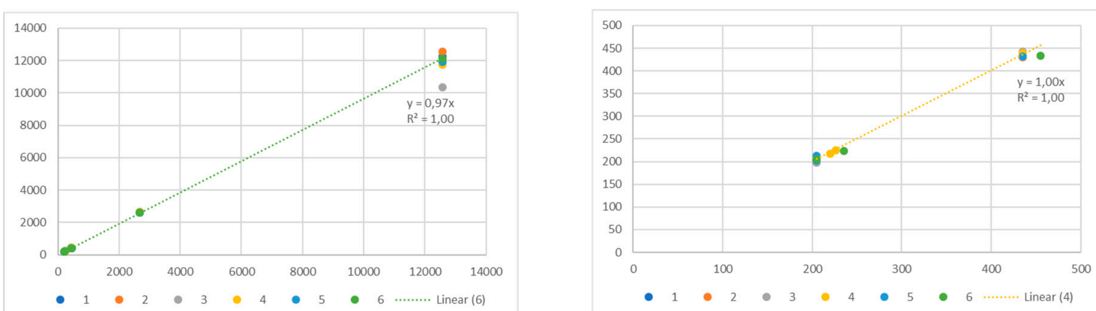

Figure S6. Electrical Conductivity Validation.

Quality assessment test using volunteer (TU Delft, the Netherlands)

The tests at TU Delft consisted of synthetic as well as natural water samples. The synthetic water samples, with varying concentrations, were prepared in the lab. The natural water sample was collected from a small river near the TU Delft. The colour of the strip test pad is compared visually with the reference colours chart on the container. Simultaneously, results were also interpreted using the smartphone application. The observed results read by eye and the smartphone application results were both compared to the known concentrations. To control the effect of ambient light condition on the reading of the results, the tests were done indoor (artificial light) as well as outdoor. The concentrations of parameters pH, phosphate, nitrite/nitrate nitrogen and iron were tested in the research.

Method of Analysis

HACH water test strips were used to analyse each parameter. The strips were immersed into the sample according to the instruction for each parameter, and the colour(s) appearing on the strips was (were) compared to the colour in the reference chart of the strips. The observed reading of the results was noted. Each strip was then placed on the colour calibration card and the smartphone application read the colour of the pad automatically and, consecutively, interpreted the result. Laterally, the concentrations of nitrite, nitrate and phosphate for all samples, were determined using Metrohem Ion Chromatography (IC) measurements, the concentration of iron was determined by using Merck Spectroquant NOVA 60 and for the pH concentration INO lab IDS Multi 9420 was used.

In measuring electrical conductivity, an electrical conductivity sensor was connected with a USB cable to the smart phone and the application read the result directly when the sensor was immersed into the sample (see Figure 7). To get the immediate results of electrical conductivity, INO lab IDS Multi 9420 was used.

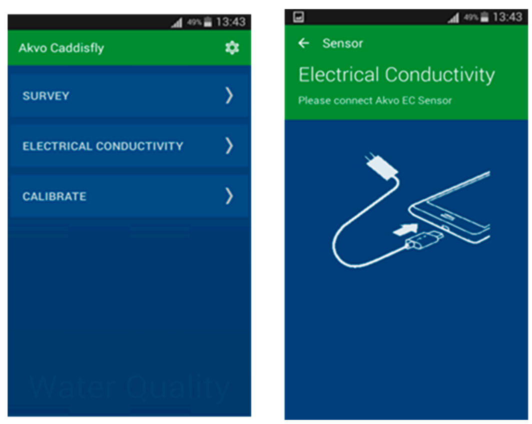

Figure S7. Measurement of Electrical Conductivity by Akvo Caddisfly application.

Results

The results of iron (Figure 8), pH (Figure 9), phosphate (Figure 10), Nitrate Nitrogen (Figure 11) and electrical conductivity (Figure 12) of the quality test at TU Delft are described in the following.

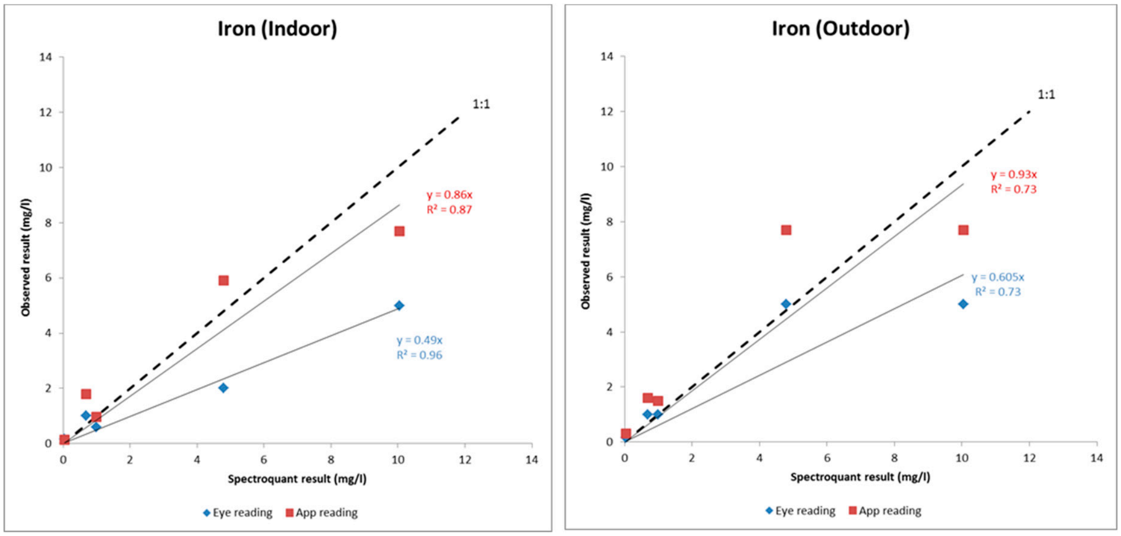

Figure S8. Comparison of iron results from both eye and mobile phone reading to lab test results.

Both eye reading and the mobile phone app reading underestimate the iron concentration although the latter only slightly. The slope of the regression-line of the results using the app versus the Spectroquant reference ('true') value is 0.86 for indoor and 0.93 for outdoor conditions. On the contrary, the slope of the regression line of the results by eye reading is 0.49 and 0.72 for indoor and outdoor conditions respectively. So, the mobile phone app reading tends to be close to the 1:1 line which means near to the Spectroquant reference results.

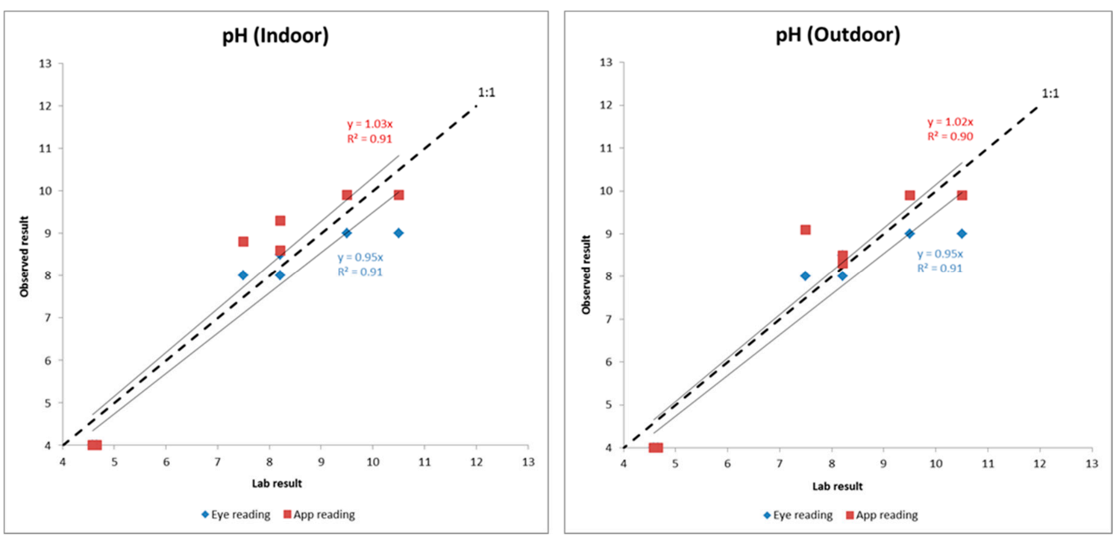

Figure S9. Comparison of observed pH results to lab reference results.

Both eye reading and the mobile phone app reading show very good results for the pH measurements using the HACH indicator strips. In a range from pH=4 to pH=10.5 the eye reading and mobile phone reading have a slope of the regression line with the laboratory reference values of 1:1 and R^2 of more than 0.90. However, it is clear that a deviation of 1 pH-unit is frequently observed.

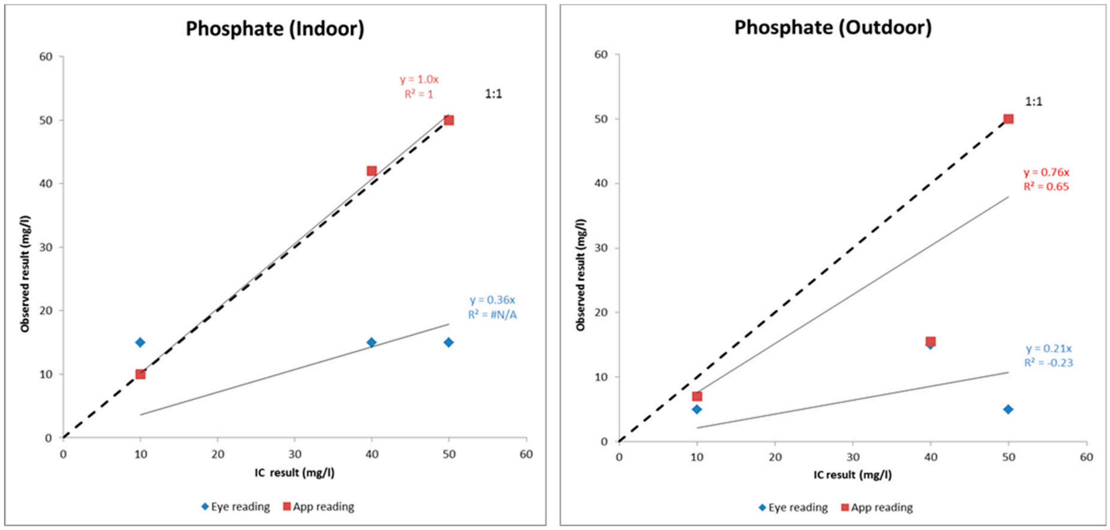

Figure S10. Comparison of observed phosphate results to lab test results.

The results of the phosphate readings are ambiguous, in both cases the eye reading severely underestimate the phosphate concentration, and also the automated reading using the mobile phone app is of under outdoor light conditions. Only the indoor reading using the app are showing correct readings.

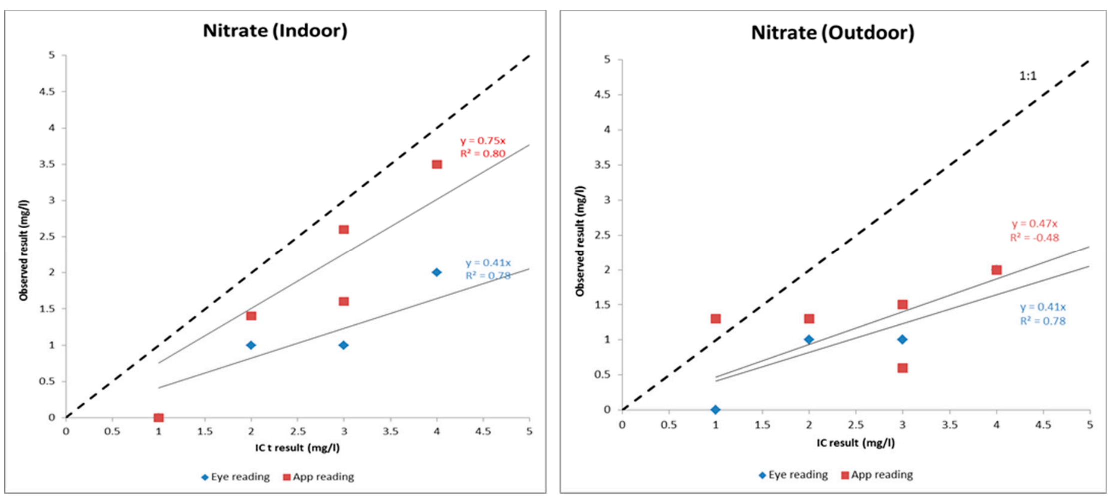

Figure S11. Comparison of observed nitrate nitrogen results to lab test results.

Both in indoor and outdoor conditions for the nitrate test, the slopes of the trend lines of the eye reading results are 0.4. The results obtained with automated reading using the mobile app, the slope is 0.75 in indoor and 0.47 in outdoor conditions. All results show a relatively large scatter as evidenced by low correlation coefficients.

For electrical conductivity, the mobile app measurement results show almost perfect results.

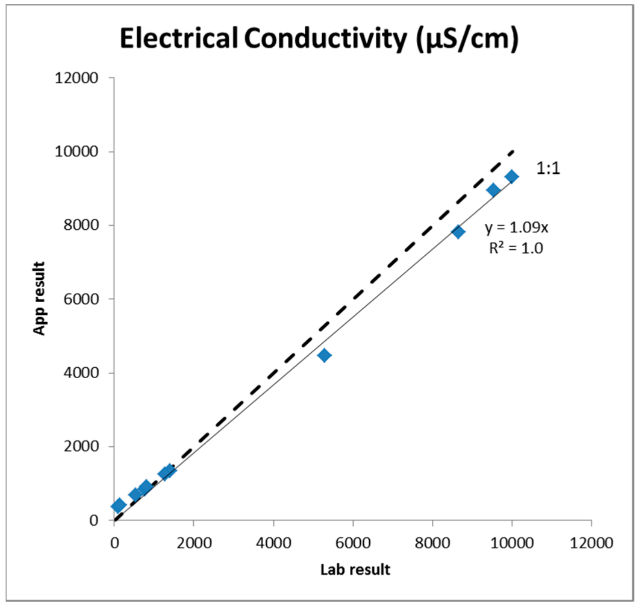

Figure S12. Comparison of Electrical conductivity measurement (app vs lab).

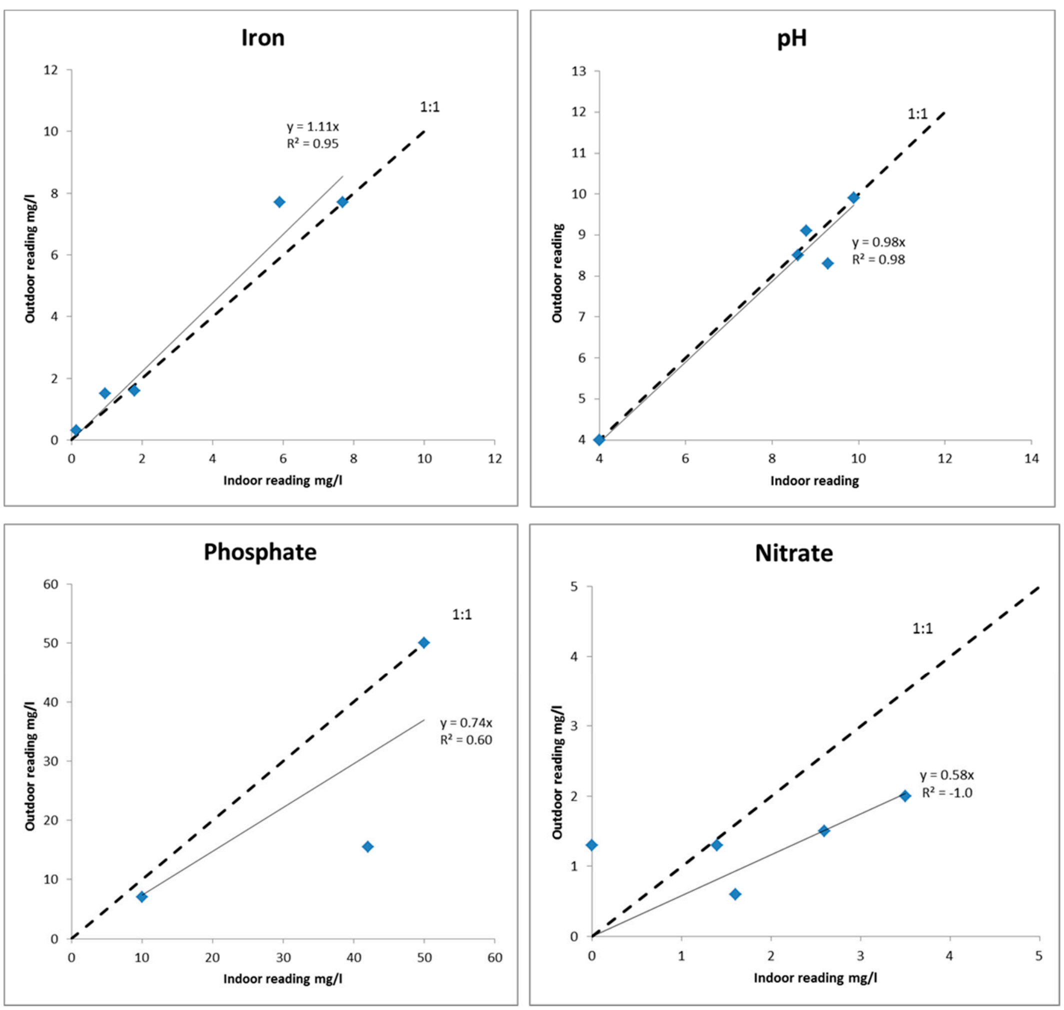

Figure S13. Light Sensitivity analysis.

Conclusions

It has been shown that the EC device connected to the mobile phone returns very reliable results in all tested conditions (validation lab and lab-based practice tests). The indicator strips are reported to have generally a 10-25% error margin which is also what was found in our results. The automated colour reading using the mobile phone performs better or equally to eye readings and seems not much affected by light conditions. Secondly, in the tested range of concentrations all strips show positive linear relationship with the 'true' values, however several strips show structural underestimation of the concentration values (slope far below 1:1 line). Moreover, the spread of the results around the trendline shows the inaccuracy of the strip, indicator, tests.

This leads to the conclusion that the EC sensor is reliable. Although the indicator strips have a low accuracy (large error from 'true' value) they do show trends if the differences in concentrations are larger then the error range of the measurements. With our test set-up, the precision (how close serial measurements are together) could not be assessed. This is the limitation of the indicator strips that should be taken into account when interpreting the results.

In the light sensitivity test analysis for mobile app, iron and pH results show almost no deviation but more than 25 % deviation in nitrate test and 70 % deviation in the phosphate test.

Both eye reading and phone application reading give close results in pH and iron tests and both eye and app readings are close to the lab results. In reading phosphate and nitrate nitrogen results, although eye and app reading results are quite similar, both results are far from the lab results in outdoor test, but app reading results are close to the lab results in indoor test. Indoor and outdoor readings do not differ from each other in the tests of pH and iron. In conclusion:

- The smartphone application can read colour strips as well as direct eye observation. But some strips seem to have some light dependency.
- The smartphone application of phosphate and nitrite nitrogen reading needs to be improved, or the quality of the phosphate and nitrite nitrogen strips needs to be checked. But there is linear relationship with increasing concentrations.
- Direct observation is not sensitive to light conditions and the smartphone application performs well wherever the reading is taken: indoor or outdoor. Seems some dependency of light for some strips.
- Electrical conductivity results are reliable compared to the real results gotten from high end equipment.

Supplementary Materials II

Table S4. The results of the monthly water quality measurements

pH		Ec		Nitrate		Iron		Transparency	
DWIR low water survey	*volunteer*	*DWIR low water survey*	*volunteer*	*DWIR low water survey*	*volunteer*	*DWIR low water survey*	*volunteer*	*DWIR low water survey*	*volunteer*
8.4	6.5	102	89	0.1	0.1	0.34	0.39	30	28.1
7.2	5.8	97.3	89.4	0.45	2	0.8	0.15	27	24
7.11	8.6	100	82	0.45	2	0.02	0.15	27	24
8.26	7	128	130			0.31	0.1		
7.34	6.5	120	114.2	0.1	0.2	0.23	0.03	39	39
6.25	7.4	158	166	0.3	0	0.01	0.24	20	19
7.9	7	200	212	1.6	0.5	0.5	0.28	30	29
8.4	8.4	185.3	311	0.1	0.1	0.71	0.15	35	37
8.1	9	220.6	138	0.9	1.1	0.3	0.08	20	20.1
7.4	9	185.6	202	0.1	0.1	1.65	0.08	15	14
7.53	8.4	200	206	0.5	0.7	0.21	0.24	29	28.1
7.38	7.3	160	153.7			0.26	0.04	10	9.2
7.2	7					0.78	0.02	10	9.2
8.31	8.5					0.54	0.1	15	14.1
7.3	7					0.74	0.1	15	15
6.8	7					1.5	0.88		
7.26	8.7					0.44	0.45		
7.9	8.4					0.57	0.54		
7.33	7.4					0.45	0.42		

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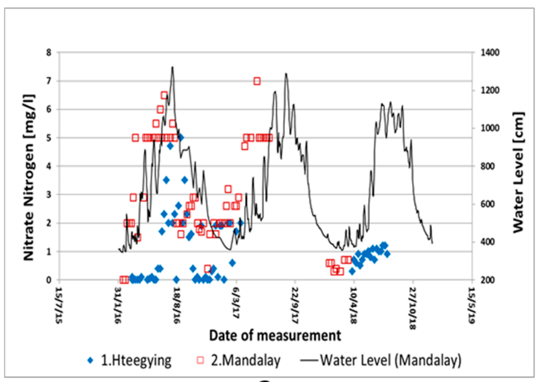
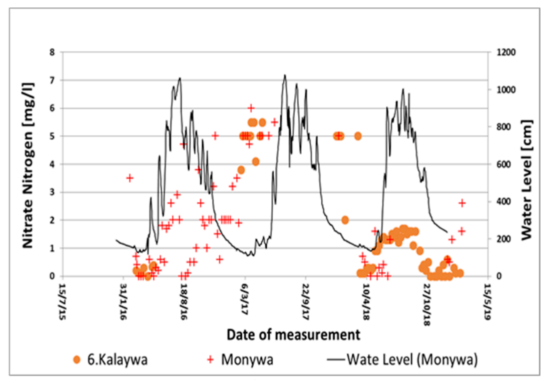
Supplementary Materials III

Time series of the strip-based measurements of nitrate nitrogen, pH, phosphate and iron comparing to the relative water level are shown in the following figure 1 to 4. The water quality results do not show a clear relation with water level.



a



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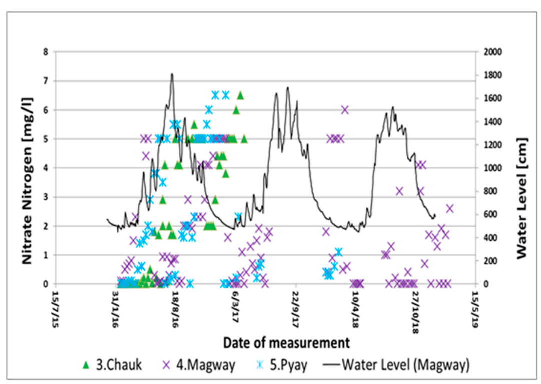

c

Figure S14. Trends of nitrate nitrogen a) Upper Ayeyarwady, b) Chindwin and c) Ayeyarwady (after confluence with Chindwin).

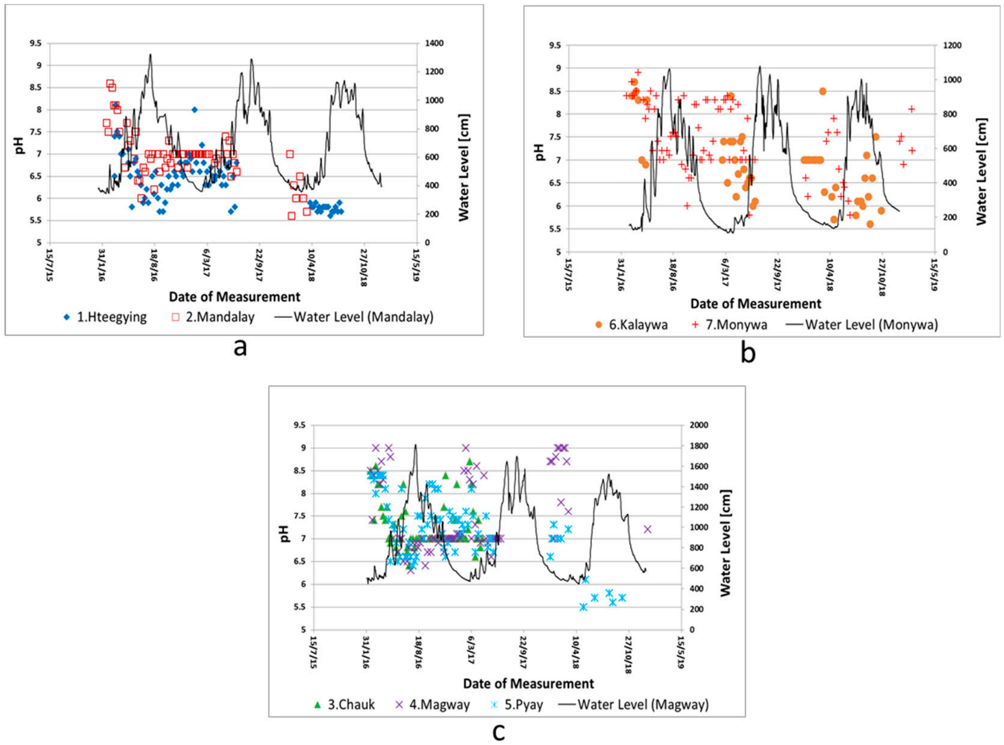

Figure S15. Trends of pH a) Upper Ayeyawardy, b) Chindwin and c) Ayeyarwady (after confluence with Chindwin).

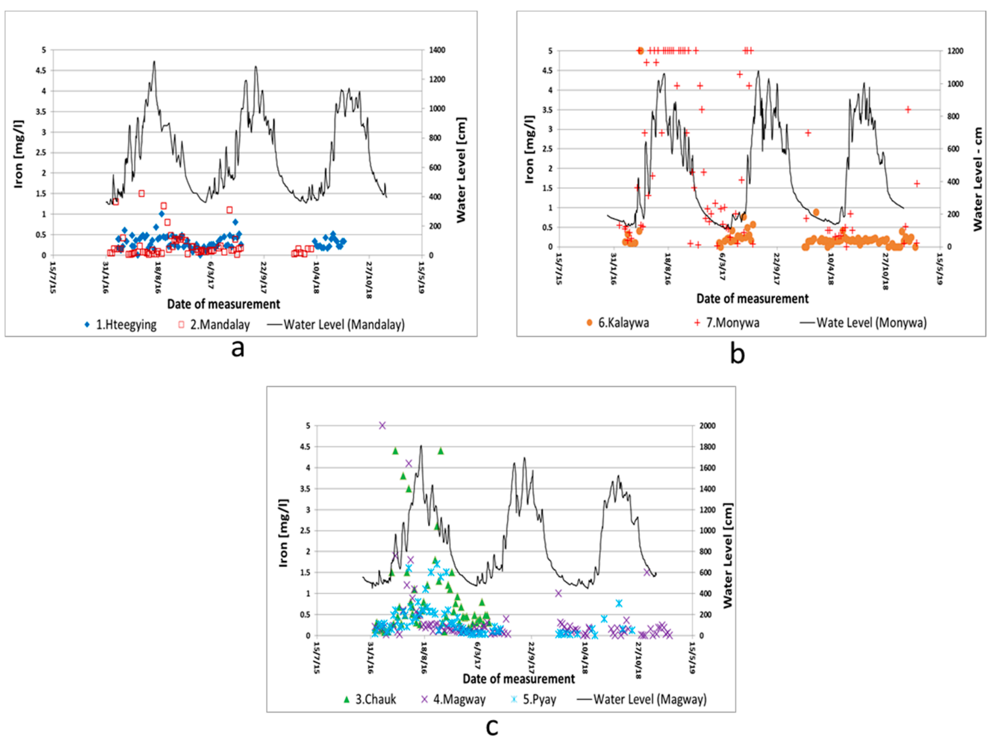

Figure S16. Trends of iron a) Upper Ayeyarwady, b) Chindwin and c) Ayeyarwady (after confluence with Chindwin).