The Forel-Ule scale converted to modern tools for participatory water quality monitoring

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Introduction

Framed within the European Project CITCLOPS (Citizens' Observatory for Coast and Ocean Optical Monitoring), the aim of this study is to present a number of tools that can be employed by citizens to estimate the color of natural waters. Firstly, a scale that accurately matches the original Forel-Ule (FU) colors was developed using accessible and affordable materials. This Modern FU scale is presented as a 'Do-It-Yourself' kit that can be prepared using high-quality illumination filters and a frame made of a white Plexiglas (or other white material). Secondly, a smartphone application (APP) prototype that could be used by anyone willing to participate in environmental monitoring is presented. This application includes a digitalized color-comparator scale, simulating the colors of the original Forel-Ule scale, to be compared to the color of water bodies, and allows the observer to take a picture of the water body to calculate the FU number using a specific algorithm. It also offers an option to include a Secchi disk depth estimate and the Forel-Ule number obtained with the Modern FU scale, if the observer is in possession of these tools. The first inputs provided by selected volunteers and researchers, offer initial comparisons between the two monitoring tools, the Modern FU scale and the digital scale included in the smartphone application. The idea is to provide a water quality index appropriate for participatory science that allows for rapid estimates and interpretation of color changes occurring in the aquatic environment, and that could be used by local or global authorities as an assessing tool.

Background

The color of natural waters has been measured globally and intensively by oceanographers and limnologists since the 19th century by means of the Forel-Ule (FU) color comparator scale (*1–3*), resulting in one of the longest oceanographic data series after the Secchi disk depth. Wernand *et al*. (*4*) used these data sets to estimate global changes occurring in the ocean in relation to the chlorophyll-a concentration, a key index of phytoplankton biomass and primary productivity studies (*5*). It was also shown that the FU scale is related to colored dissolved organic matter (CDOM) absorbance, considered as well to be one of the water quality indicators (*6*). In coastal and continental areas, the color of natural waters not only strongly affects the visual and aesthetic perception of the public and their recreational use (*7*, *8*), but has also a strong effect on aquatic ecosystems, as it has been shown to affect photosynthesis and primary productivity (*9*), predation regimes of herbivores (*10*), invertebrate behavior (*11*, *12*) and alter the availability and toxicity of heavy metals to fish (*13*, *14*). Changes in color and clarity in aquatic systems can be caused by natural phenomena, but can also be due to anthropogenic activities. Therefore, to determine if a change in color is caused by a particular anthropogenic activity, it is important to collect long-term data on the color and clarity of water bodies, making it necessary to have fast and affordable tools to cover large areas, as well as a high sampling frequency. Participatory science can be a valuable method to obtain a large amount of data extended over large areas, but it requires to provide citizens with user-friendly monitoring tools. Clarity of natural bodies can be easily and affordably estimated by means of a Secchi disk (*20*, *21*). Color, is a more difficult feature to measure as it requires the analysis of the wavelength distribution of light, which can be achieved using a spectroradiometer. However, this type of instrument is expensive and not suitable for citizen monitoring surveys nor fast interpretation. The FU scale is a simple tool that can be easily used to assess the color of water bodies by citizens. The original FU color comparator consists of 21 colored solutions, ranging between indigo blue and cola brown, going through green. These solutions, made with distilled water, ammonia, copper sulfate, potassium-chromate and cobalt-sulfate, are contained in vials. The color is determined by comparison of the color of the water observed above a Secchi disk, at half its depth, to the colored vials. Although easy to use, this scale is not simply reproduced (*22*) and the chemicals used to prepare the solutions can be toxic to humans (*23*). Therefore, the idea of reproducing a more user-friendly scale arose. Interestingly, Davies-Colley (*15*, *16*) showed that a colour-matching method using the Munsell system (*17*, *18*), one of the most widely known colour systems, is suitable for routine water resources surveys and monitoring, since humans can easily match colours observed simultaneously. This method was implemented by the National Institute of Water and Atmospheric Research (NIWA) as part of the water quality monitoring programs (*19*).

Approach

The first aim of this study was to develop an affordable, 'Do-it-Yourself' color scale that matched the colors of the original Forel-Ule scale, to be used in water quality monitoring programs by citizens. This scale can be manufactured with high-quality lighting filters (LEE and Roscolux) and a white frame. To select the matching color-effect filters, both visual and instrumental comparisons were carried out between several filter combinations and the colored liquids in vials, under a diffused artificial D65 daylight simulator, in a color assessment cabinet (VeriVide) with a grey coating inside. The D65 light source has a correlated color temperature of 6500 K and was selected because it represents the average daylight, at various times throughout the day and throughout the year. The color-matching procedure was conducted following the recommendations of the American Society for Testing and Materials Standard International, commonly used in the industry to assess the color differences between objects. The liquid vial and the corresponding combination of color-effect filters were placed at the bottom part of the lighting cabinet, lying flat over a white plate. Both the visual and instrumental comparisons were carried out at a 45° degree angle, labeled as 45^0/normal geometry by the CIE and the lamp was placed above the objects at a distance of 50 cm. The visual comparison was conducted by observing simultaneously both the vials and the filters, placed side by side, 4.0 cm apart. The instrumental measurement was conducted using a Photoresearch PR-655 spectroradiometer. A detailed explanation of methods used to develop this scale and the results obtained can be found in Novoa *et al.* (*24*). The color of any object can be specified in terms of hue, saturation and brightness. Hue refers to how the color is described (e.g. 'blue' or 'green'), and it is determined by the dominant wavelength in the visible spectrum. Saturation or color purity (less saturated is more greyish than saturated, which has a more intense color) depends on the spread of energy around the dominant wavelength (*25*). Brightness refers to the amount of energy detected by the human eye, which is most sensitive around the green wavelength (555 nm). The differences between the colors of the vials and of the filter combinations were assessed by calculating the differences in dominant wavelength and saturation.

A first prototype of a digital version of the Forel-Ule scale was included in a smartphone APP developed by the Citclops consortium (www.citclops.eu). The colors of this scale were derived from the transmission spectra measured of the original FU scale solutions using a TriOS VIS-Spec Analyzer (*22*). The transmission spectra were converted to colorimetric XYZ tristimulus values (*22*), which were then converted to the standard RGB (sRGB) format, the most common format used by digital devices (smartphones, digital cameras, and computers), using formulae that can be found in the literature (*25*, *26*).

The digital images acquired by the user, are sent to the Citclops data base and used to calculate the FU number by means of a specific algorithm that converts the sRGB values extracted from the digital images, to the XYZ CIE system using the conversion matrices found in Pascale (2013):

$$[M] = \begin{bmatrix} 0.4124 & 0.3575 & 0.1804 \\ 0.2126 & 0.7151 & 0.0721 \\ 0.0193 & 0.1191 & 0.9503 \end{bmatrix} \qquad \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = [M] \begin{bmatrix} \mathrm{R} \\ \mathrm{G} \\ \mathrm{B} \end{bmatrix}$$

A programming routine does a chromatic adaptation and converts the obtained XYZ tristimulus values to chromaticity coordinates, which are then used to calculate the angle (in radians) between the vector to the chromaticity coordinates of the image and the positive x-axis. This angle is then compared to the angles of the FU solutions calculated from the transmission spectra and published in Novoa *et al.* (*22*), and the corresponding FU number is assigned. This methodology is explained in Wernand et al (2013) (*4*).

Finally, the comparisons of FU estimates provided by observers using the Modern FU scale and the digital scale on the APP, as well as some examples of images sent by the citizens are presented.

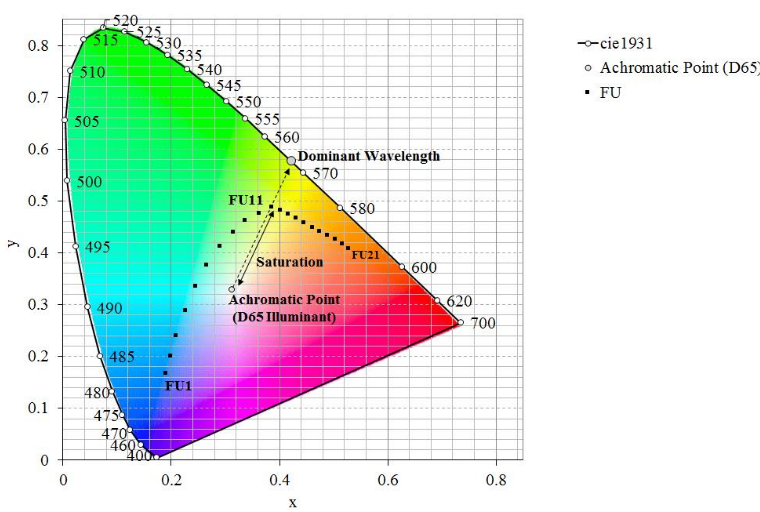

Figure 1. The CIE1931 chromaticity coordinates, based upon transmission measurements, of the *FU*-scale colours 1 to 21 (Novoa et al. 2013 (*22*)) including the achromatic point of a D65 illuminant. The outer curved boundary is the spectral locus, with wavelengths shown in nanometers.

Results

The resulting Modern FU scale is shown in Figure 2*a)*. The format can be different, but it is important that the frame is around an A4 size and that the filters are cut with a rectangular shape of dimensions 85 x 10 mm. There should be a distance between the filters and the white background of 4 mm. A total of 30 color effect filters (27 LEE and 3 Roscolux) were necessary to match the colors of all 21 vials. The colors measured (Dominant Wavelength, *DW* and saturation, *S*) of the filters deviated a maximum of 20.83 % and 12.18 %, respectively, from the colors of the vials. Figure 5 shows the comparison of the dominant wavelength and saturation estimated for the FU vials and filters. There is a strong match in *DW* and *S* between the vials and the filters, so the selected filters were considered to be appropriate for the scale. This scale should be used to estimate the color of the water together with a Secchi disk in the same way as the original scale developed by Forel and Ule is used.

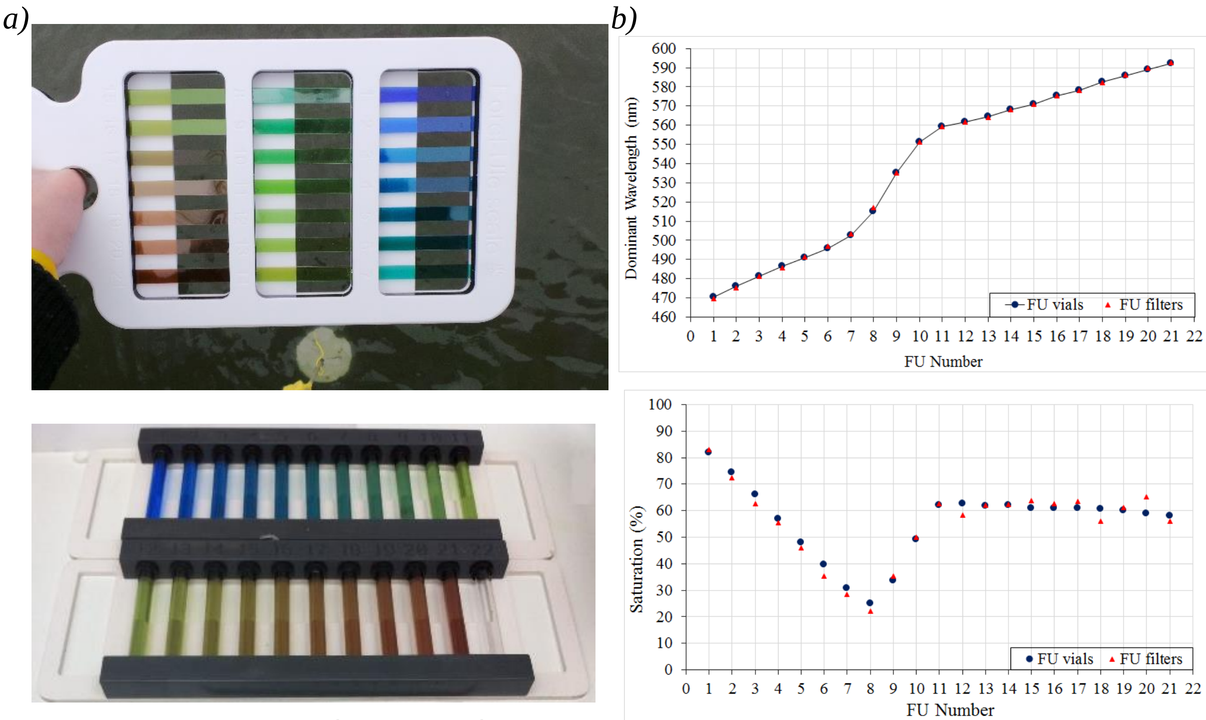

Figure 2 *a)* Picture of the resulting Modern FU scale, made of lighting filters, and the original FU liquid scale (bottom right). 2 *b)* Dominant wavelength and Saturation percentage, respectively, of the instrumentally measured vials and filter combinations.

Twenty-one colored bars formed the digital color scale that was implemented in the Citclops application, just like the original FU scale. However, each color bar was then divided in three tones to mimic how the same FU color would be observed under different sky and light conditions (See Figure 3), and facilitate the comparison to natural water bodies. This was achieved by increasing and decreasing the saturation of each FU color. This prototype is still being tested by selected groups of volunteers, and improvements are being implemented taking into account the observers' suggestions. This first prototype, requests observers to take a picture with the camera placed on top of the water with a maximum incline of 40^0 with respect to the water surface and the sun on their back in case of sunny weather, to avoid sunglint. Observers are then asked to select the color on the digital scale that matches best the color of the water body observed (See Figure 2), using either the image just taken or by looking directly at the water surface. They are finally requested to answer several questions on the meteorological and location conditions.

Since the publication of the APP in April 2014, the database received approximately 150 images, where 30 of them were not pictures of the water surface, so they were removed manually. Only metadata including Modern FU estimates are compared to the FU estimates using the Digital scale. More estimates were conducted in water bodies of colors comprised between FU 9 and 14 (Figure 4), compared to the 'bluer' (FU1-FU8) or 'browner' (FU16-21) colors of the scale, so the relationship is weighted towards the first range.

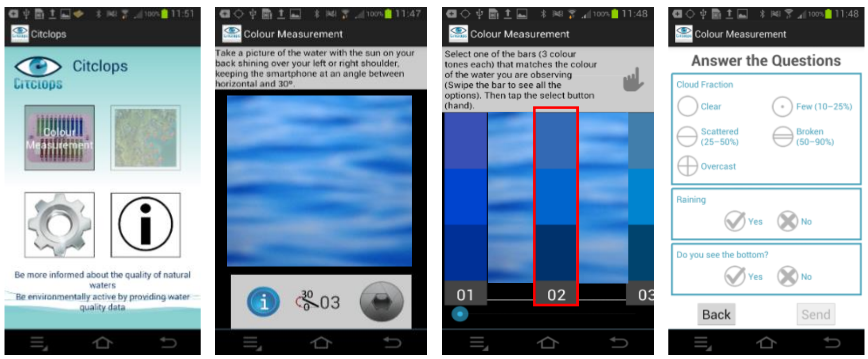

Figure 3. Smartphone application for the water color comparison. The observer takes a picture following the specified protocol, compares it to the FU digital scale, and then answers questions on the meteorological and location conditions.

a) *b)*

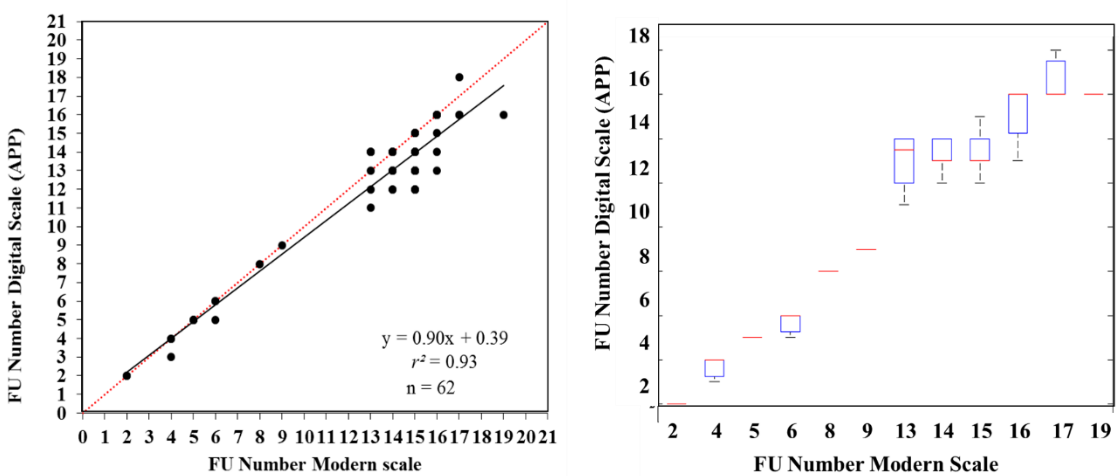

Figure 4. a) FU index estimates comparison conducted with the Digital Scale included in the APP and the FU modern Plastic Scale. b) Boxplot-whisker graph of the same comparison.

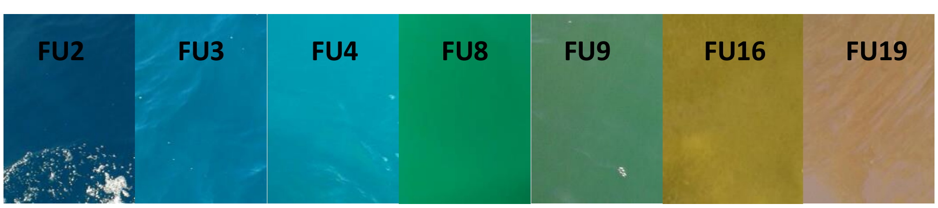

Figure 5. Example of images sent by the public, where FU index selected by the public in the digital scale matched the FU calculated by the algorithm.

Discussion and conclusions

The industrial production of standardized plastic filters has provided the means to construct a simple color comparator scale to estimate the color of natural waters to be employed in participatory science. After extensive experimentation in the laboratory, the authors are confident that the colors represented by the Modern FU scale match with appropriate accuracy the colors of the solutions of the original FU scale. The plastic filters have the advantage that the color is identical for all positions, while the thickness of the vial and the glass itself of the original FU scale, have an effect on the color perception (*22*). This Modern scale is an improvement with respect to the original scale, as it is light-weighted, inexpensive and easy to produce, as well as safer for the observer since there is no risk of glass breakage.

The APP will make it easier for users to estimate the color of natural waters and provide more data to the consortium, as it could be distributed easily and at no cost. Due to the different smartphone screen displays and camera characteristics, the plastic FU scale could be used as a way of validating the colors selected by the users via the application. The APP includes an option where the user can introduce the FU number measured with the Modern FU scale, the comparison of both estimates (FU from the APP, and FU from the scale) would give information on the accuracy of the digital colors. Results show a good correspondence of the water color estimated using both methods, but more comparisons are necessary. The aim is to allow observers to use the digital scale with and without a Secchi disk, for that reason different tones created by altering the saturation were introduced in each bar. Discrepancies have been observed in some cases in the selection of the FU index, with and without the disk. This occurred mostly during very cloudy and dark days, when not enough light is coming from the water column. In this circumstances, the use of the Secchi disk increases the signal coming from the water, competing like this with the sky reflection when the disk is at half its depth.

The algorithm to extract the FU from the digital images is still been optimized, so concluding results cannot be presented at this point. However, work has been carried out on images acquired by the consortium during two field campaigns, one undertaken in the North Sea and the other in coastal and continental water bodies across the Netherlands. During these two field campaigns images of the water surface were acquired, along with spectroradiometric TriOS sensors and water quality indicators, such as suspended matter, chlorophyll-a concentration and colored dissolved organic material. The results of these campaigns are very promising regarding the use of digital images to estimate the color of natural waters, based on the FU index, and will soon be published in a more detailed document. The main problem with the extraction of the FU index from images relies on the way the image is acquired by the observer and the type of camera used. Research is still ongoing on this subject, trying to find a way to minimize the users work, but also acquire all the information necessary to calculate the FU correctly.

The authors would like to emphasize that these tools are tested as part of the Citclops project, whose final objective is a proof of concept. The project needs to show that, in terms of color, an observer should be able to capture images, select the corresponding color of the water body and send the metadata collected to a database, where it is analyzed and displayed, together with additional data provided by the consortium, on an easy–to-access interface. For example, the data collected via participatory science is displayed in combination with FU layers based on satellite images (*4*).

To achieve this final objective, the tools that are presented here are ideal, due to their affordability and usability. In the future, the authors would like to establish more connections between the FU index and established water quality parameters. Meanwhile, the project also aims at collecting transparency and fluorescence data, which complemented with the color, will make the entire system become a remarkable water quality monitoring tool, and help raise awareness among citizens.

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