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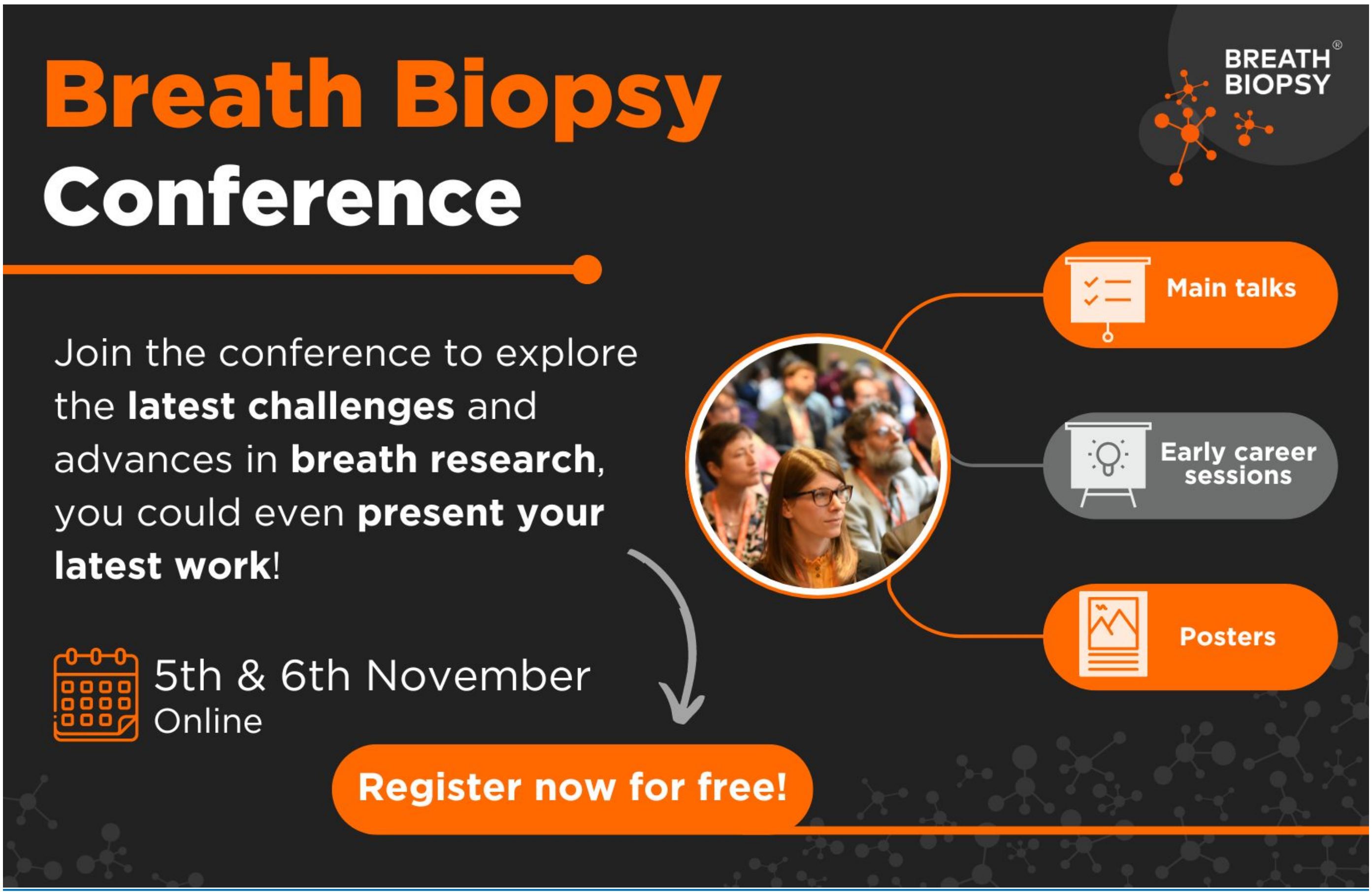

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Water circles—a tool to assess and communicate the water cycle

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Supplementary material for this article is available online

Abstract

'Water circles' are presented as flexible water cycle diagrams aggregating the flows through a system for a specific region and time period, categorized by flow type and organized by magnitude. *Water circles* for an entire system and separate storage components can be interpreted as water cycle speedometers and can help compare and communicate different climate and human impacts on different regions, time periods, and storage components. Water circles can facilitate comparisons between hydrological models and other methods for deriving water balances.

1. Article

The water cycle is the flow of water on earth. Water cycle diagrams illustrate these flows and those between storage components, influenced by physical and social conditions (Abbott *et al* 2019). Humans influence the water cycle from within (Haddeland *et al* 2014). Understanding the water cycle and our influence within it, both globally and regionally, empowers our capacity to address the challenges and opportunities on the path towards achieving sustainability and resilience (Wada *et al* 2014). 'Water circles' are visual, quantitative representations of the water cycle, illustrating the balance of flows through a region over a certain period. They are helpful graphics along with time series and maps to communicate the complexity of the terrestrial water cycle to end-users. Further, the granularity of the complexity can be adjusted for different end-users. The hope is that this fundamentally increases the accessibility and understanding of a complex system, which is essential to effectively communicating climate and global change impacts.

Hydrological models simulate the water cycle, although different models can differ in the physical representation of the system, input and output data, and spatiotemporal resolution (Wada *et al* 2017). While hydrological models have been substantially advanced with more process representations, including groundwater and human water management over the last few decades, there is a lack of tools to discuss and communicate model comparisons (Abbot *et al* 2019, Telteu *et al* 2021). Water circles are a template to visually demonstrate how models represent the water cycle and how flows and storage compare relatively through the system. Water circles are unique to the model being demonstrated and are an opportunity to compare how models are structured. Further, water circles created with different methods, such as from observations, remote sensing, data-driven methods, and expert and stakeholder opinions, can also be compared.

The water cycle is in balance—through a specific region and period, the inflows balance with the outflows and changes in storage volume (e.g. rivers, lakes, soil, groundwater, snowpack, and glaciers).

This conservation equation offers a symmetry that can be interpreted as a circle composed of three main arcs (inflows, outflows, and storage change similar to the water balance equation) subject to certain constraints. The size of each arc section represents the magnitude of the volume of the associated flow. The sum of the magnitudes of flows through the system determines the size of the circle. Water circles facilitate visual relative comparisons of the water cycle flows by presenting all flows together while emphasizing the dominant forces. Ultimately, the interest is to share information about the water cycle clearly and visually with the complexity tailored to end-users.

The partitioning of inflows, outflows, and storage components is flexible (within balance). It depends on the processes of interest, the method for determining the water balance, and the availability of information. A theoretical water circle with organizational differences is presented in Horton (1931). *Water circles* in this paper are a revival, extension, and practical application of this theoretical water cycle diagram.

Water circles are demonstrated for the Bhima basin in India. We focus this paper on describing different circle types and invite the reader to explore interactive water circles for basins worldwide at https://globalwaterbalance.herokuapp.com/. The Bhima basin is a highly managed basin with growing populations and a legacy of irrigated agriculture experiencing a monsoonal climate (Surinaidu *et al* 2013). The simulations are performed with the open-source hydrological model CWatM, the Community Water Model (Burek *et al* 2020).

2. General design

Representing a specific region/component and period, an inner circle is comprised of three main sections: total inflows, total outflows, and net storage changes (figure 1). The relative sizes of these flows are reflected in the section areas of the circle—section sizes are proportional to the volumes of the flows; for example, a flow that is twice as large as another has a circle section area that is twice as large—the methods section describes the mathematical construction of the water circle. Within this first layer, the largest of the three main flows appears on top—the three main flows are organized in decreasing order, moving counter-clockwise, opening from 3 o'clock. A second outer circle divides the main flows into further flow components—for example, storage changes partitions into the specific changes within groundwater, soil moisture, lakes & reservoirs, rivers, glaciers, snowpack, etc. Within each main compartment, partitioned flows are ordered similarly from largest to smallest, moving counter-clockwise. This hierarchy of flows is continued towards any number of outer layers. Blue represents inputs and increases in storage, while red represents outputs and decreases in storage—colours and design elements are only examples. Flow labels representing relatively small or no flows for the specific region and period dissipate from the circle. The general design is unique to the explored system, processes of interest, and the method used to make the water circle, whether modelled, observational, satellite and remote sensing, expert and stakeholder opinions, or data-driven.

Users see the flows organized according to category and size and can quickly evaluate and compare flows within and between water cycles. This unfolding handles complexity by allowing the observer to interact with simpler versions, adding elements not presented in the first place (Harold *et al* 2016). *Water circles* are most appropriately played with in their interactive forms, allowing users to hover over sections and collapse the circle into subcomponents (figure S1). The circles are non-static, expandable, and interactive.

3. General water circle for two example months

The water cycle for the Bhima basin in March 2002 is a giving system (figure 2(a)) with outputs greater than inputs (inputs are near negligible); in July 2002, it is a gaining system (figure 2(b)), with inputs greater than outputs. Evapotranspiration is the main outflow in both, followed by relatively less downstream discharge, lake evaporation, consumption (here referring to domestic, industrial, and livestock consumption) and channel evaporation. Rainfall is the only input to the system and is the dominant flow in July and the smallest flow in March. In March, all storage components show a net decrease in the order of soil moisture, Lakes & reservoirs, groundwater, and rivers. There are no glaciers or snowpack in Bhima. In July, all storage components show a net increase. There is three times less flow through the system in March (10 cm) than in July (30 cm), visualized in figure 2, with the March circle presented as three times smaller than the July circle (figure 2). Although illustrative, it can be generally impractical to visualize water circles using their relative sizes. For this reason, to compare between circles, the size of the circles, determined as the sum of all inputs, outputs, and storage change magnitudes (here, divided by the basin area), is presented inside the circle. This allows the user to compare the relative size of different circles and estimate the values of partitions within each circle; for example, rainfall in July 2002 is around 15 cm across the basin and evapotranspiration in March 2002 is about 4 cm over the basin. The tiny sections representing 'Rain' in March and 'Consumption' and 'Channel evaporation' in July might be too small to read, but highlighting the more significant flows allows the user to

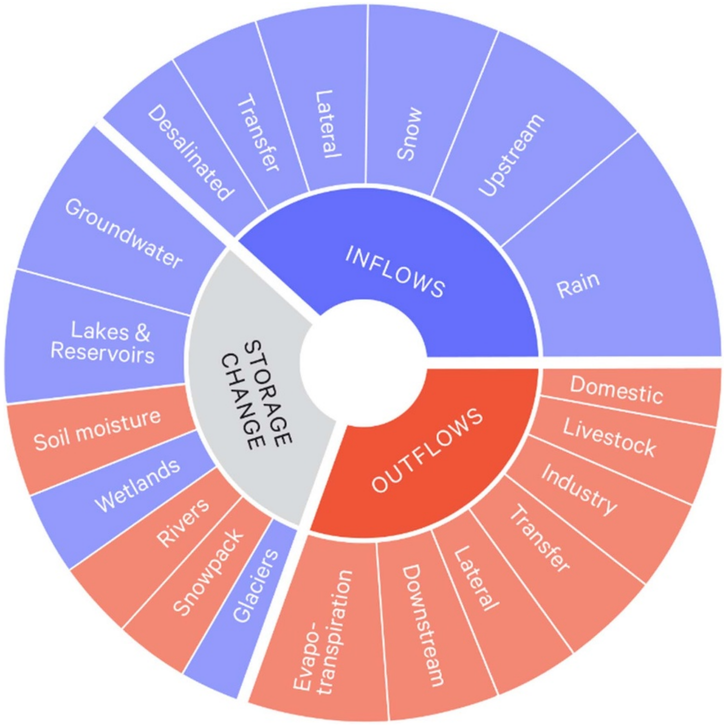

Figure 1. General water circle example. Inflows include the water that entered a specific region/component over a specified period. Storage changes highlight how the different storage components increased (blue) or decreased (red) over the period. Outflows include water that leaves the region/component over the period.

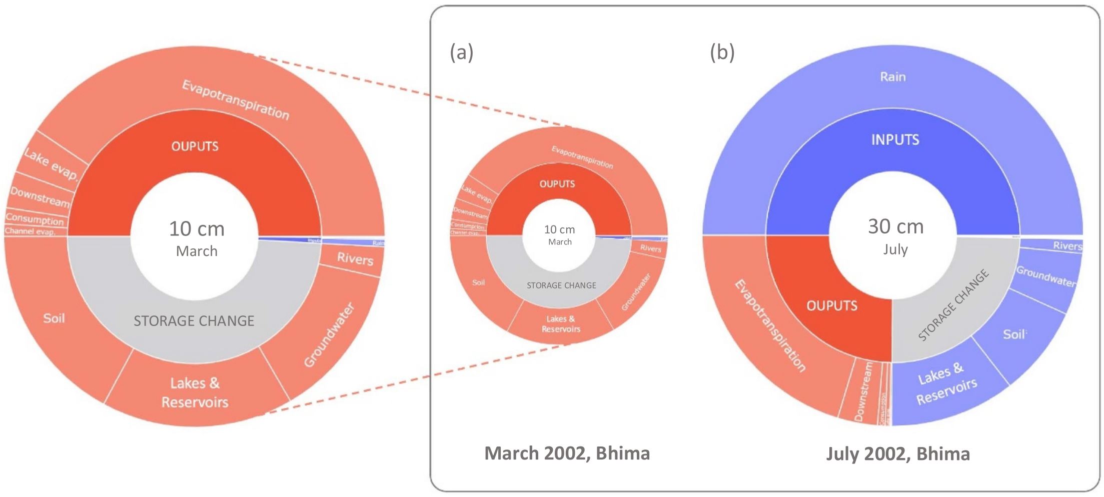

Figure 2. Water circles for the Bhima basin in (a) March 2002 and (b) July 2002. The size of the circle, namely the sum of inputs, outputs, and storage change magnitudes over the time period and basin, is presented inside the circle. Water flow labels are described in table S1.

focus on those driving the specific example, reducing noise and complexity; sections can be hovered over and expanded in the interactive version. Further, the absence of a flow label is itself informative, indicating that this flow in this context is relatively negligible. Water circle flow labels are collected and described in table S1.

4. General water circle with four levels

Figure 3 shows that the Bhima was a giving system in 2002 with outputs greater than inputs (outputs appear on top). Evapotranspiration is the largest output, followed by Downstream discharge, lake evaporation, non-irrigation consumption, and channel

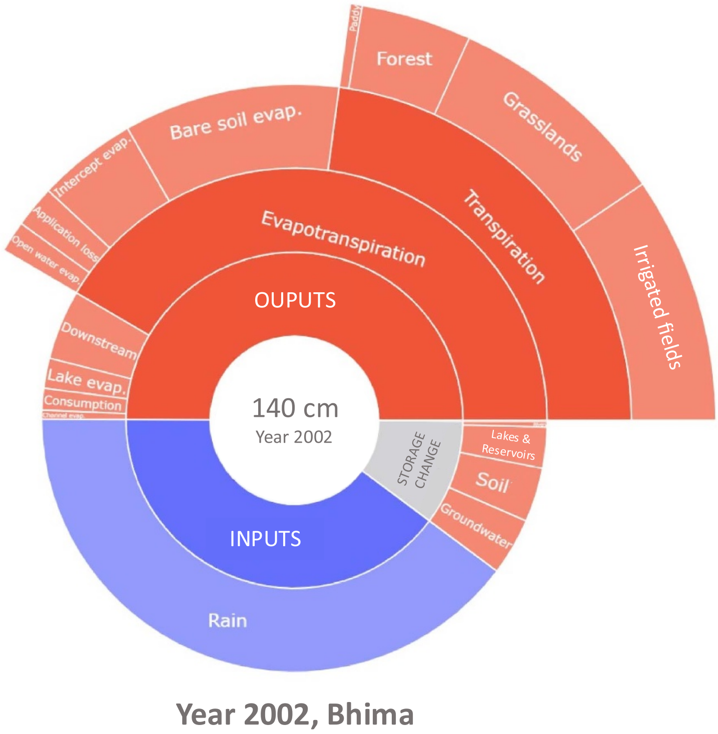

Figure 3. General water circle for the Bhima basin 2002 with four levels. The size of the circle, namely the sum of inputs, outputs, and storage change magnitudes over the time period and basin, is presented in the middle. Water circle flow labels are described in table S1.

evaporation. All storage components show a net decrease. Evapotranspiration is partitioned into transpiration across different land categories (model-specific and within CWatM as grasslands, forest, paddy, and irrigated), as well as bare soil evaporation, interception evaporation, application loss from irrigation, and open water evaporation. Figure S1 shows an unfolding of and interacting with figure 3. Water circles require only model outputs and can thus be used to compare between models with different configurations (e.g. land categories and evapotranspiration partitioning) and resolutions and other methods for composing the water balance.

Bar charts, regular and stacked, are conventionally used for time-aggregated water balance diagrams. Compared with bar charts, water circles offer the following advantages: different hierarchies appear naturally on different levels, separate flows can be compared more easily against each other as all flow sections are based at the centre, the three main flows are separated onto their own 'axes,' and a system that is not in balance (for troubleshooting model development) is readily apparent (figure M1). Further, circular charts may be easier to understand and read more accurately than the same information presented as bar charts (Briggs 1978).

5. Water circles for lakes & reservoirs, soil moisture, and groundwater

Flows through specific storage components are demonstrated for (a) lakes & reservoirs, (b) soils, and (c) groundwater in figure 4. Water can cycle through these systems multiple times compared to the general water circle. For example, rain and irrigation percolating through the soil into groundwater and then pumped and applied as irrigation is counted twice in the soil circle. If this again percolates to groundwater, it is counted twice in the groundwater circle. Interestingly, in our example year and basin, there is about 20% more movement through the soil component than in the general water cycle (figure 3), and there is over five times more movement over and through soil than through groundwater.

6. Water circles for communicating human influence within the water cycle

Human influence is a significant driver of the water cycle through consumption, affecting quality (chemical, biological, and temperature), diverting, and storing water. While many people are conscious of domestic water use, many are surprised

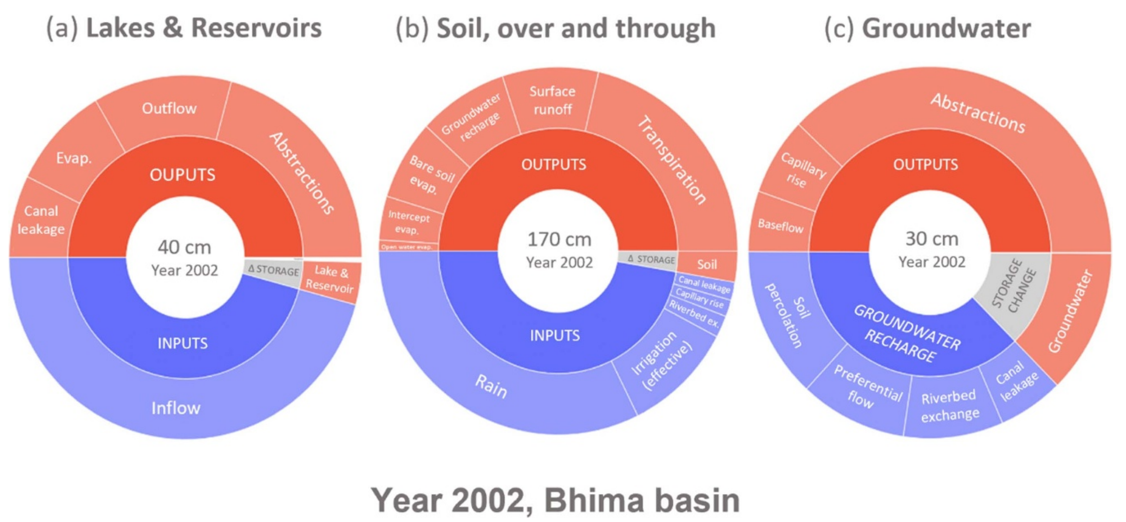

Figure 4. Water circles related to (a) lakes & reservoirs, (b) soil, and (c) groundwater, representing the Bhima basin in 2002. The size of the circle, namely the sum of inputs, outputs, and storage change magnitudes over the time period and basin, is presented in the middle. Water circle flow labels are described in table S1.

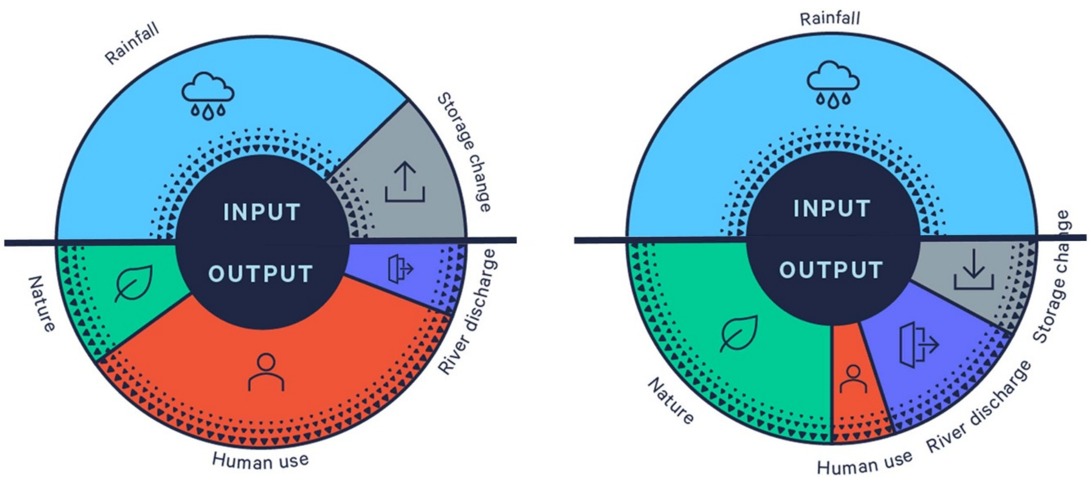

Figure 5. Water circles for communication, showing rainfall, storage change, river discharge, human-related consumption, and nature. The left figure shows a system where outputs are dominated by human use, while nature use and river discharge are at their lower limits, and storage is being depleted. The right figure shows a system where storage is increasing, with nature use and river discharge being larger than human-related consumption.

to learn that their water footprint is actually dominated by the water consumed for growing crops, including from both rainfed and irrigated agriculture. To facilitate communication with stakeholders, school groups, and the interested public, figure 5 demonstrates a condensed, reorganised, and redesigned version of the overall general water circle from figure 3: condensed components include human use (evapotranspiration from rainfed and irrigated agriculture and consumption from industry, domestic, and livestock) and nature (all other evapotranspiration); the water circles in figure 4 can be similarly redesigned highlighting the human influence. Highlighting human-driven water cycling is embracing the concept of a hydro-social cycle (Linton and Budds 2014). Figure 5 shows two systems, one where outputs are dominated by human use and the other by nature and river discharge. As an exercise, groups can be asked to draw what they think the water circle looks like for different regions and periods and then compare these with ‘actual’ water circles. Further, groups can be asked to draw what the water circle could look like under different future scenarios and explore opportunities to move towards realities where human water use finds balance and synergy with nature. Integrating water quality into the circles is a next step; for example, the vibrancy of the colour used for river discharge in figure 5 can indicate water quality status.

Water circles are a template to visually compare flows within and between regions, periods, and storage components under different climate and human impacts. Water circles are model-specific and can facilitate visual model comparisons independent of resolution, inputs, and physical representation, as well as with other methods for determining the water balance. Water circles offer simplicity, comprehensiveness (i.e. including all relevant components), a unique interactive element unfolding complexity, visual appeal, and benefitting from the symmetry of a balanced system. Water circles can help, along with other tools, to communicate the human influence within the water cycle and the effect of specific actions on it, historically and in the future.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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