Allocation of water loss to individual benefits provided by the Fláje reservoir - comparison of several procedures

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Abstract. The water footprint is the sustainability indicator, which describes direct and indirect water consumption. In the case of a water reservoir, the water consumption is represented by water evaporation from the free surface water. Most reservoirs are built as multipurpose reservoirs. The water losses from the reservoirs should be allocated among individual benefits to avoid distortion of water needs throughout the life-cycle of individual benefits provided by the reservoir. Allocation procedures, i.e. splitting a specific input between multiple outputs, tend to be problematic because different strategies can be used and it is not always possible to clearly determine which strategy is the most suitable. The allocation method significantly influences the assessment of the sustainability of individual benefits provided by the reservoir. In the article, we proposed the categorization of individual allocation strategies, we tested the strategy based on the pairwise comparison of purposes of the reservoir, and carried out an assessment of the variability of results of individual allocation strategies on the pilot case of the Fláje water reservoir. It has been proposed a simplified allocation model using the Analytic Hierarchy Process which is taken as a reasonable compromise between the processing complexity and the need to differentiate between the water reservoir purposes.

1. Introduction
Ensuring sufficient water resources of suitable quality water is one of the challenges of today's world and sustainable development [1]. Therefore, methods used for quantifying the use of water in the entire life cycle and supply chains of individual processes, products, services or companies, such as the water footprint, come to the forefront of interest [2]. The water footprint quantifies the amount of directly and indirectly consumed water [3]. The water footprint is divided into three components: blue, green, and grey water footprint. The blue water footprint is the volume of freshwater that is consumed from the surface water or groundwater resources. The green water footprint is the volume of water evaporated from the rainwater stored in the soil. The grey water footprint is the rate of water pollution, which is quantified as the volume of water that is required to dilute pollutants to such an extent that the quality of the ambient water satisfies certain agreed water quality standards [4]. The availability of water resources varies over time and space. To reduce the availability inconstancy of the water resources, water reservoirs are being built, which serve to capture water at times of its abundance and allow its use at times of its scarcity. The operation of water reservoirs is associated with water losses by evaporation from the free surface and seepage. The water seepage through the subsoil is not included in the water footprint, because the leaking water can be (in the given river basin) pumped and reused [5]. The water footprint associated with the water reservoir operation is therefore usually associated only with evaporation from the free surface. Water reservoirs are built for various purposes - supplying the population with water; water for agriculture or industry; use of hydropower potential; flood protection; also improving water quality;
recreation, etc. [6]. Although some reservoirs are built for a single purpose (e.g. for the hydropower potential), they usually perform more functions, i.e. in addition to water retention, they also transform flood waves and reduce the risk of floods. Water footprint associated with the operation of the water reservoir (evaporation from the free surface), it is therefore necessary to allocate between the various purposes they provide. The literature describes several approaches to the allocation of the water footprint to individual reservoir purposes. Some authors point out that the choice of allocation method will significantly affect the water footprint values of individual reservoir functions [e.g. 7].

The paper presents a proposal of the categorization of individual approaches to allocation, based on literature analysis. Selected approaches to allocation were tested on the example of Fláje water reservoir, to verify the sensitivity of the water footprint to individual functions provided by the water reservoir.

2. Water Footprint

2.1. Water footprint calculation and allocation to individual purposes

For the reservoir water footprint calculation, only the parameter of evaporation from the water surface was considered. The water footprint values during phases of reservoir construction and liquidation have been neglected, corresponding to conclusions of published research [8], due to the water footprint of these phases is several orders of magnitude lower than the water footprint associated with the reservoir operation. The evaporation values from the reservoir water surface were adopted from the last year's study of the Fláje water reservoir [9]. Evaporation from the reservoir water surface, i.e. the reservoir water footprint is divided among the individual purposes of the water reservoir, using the allocation coefficient according to the equation:

$$WF_r = \sum_{i=1}^{n} WF_i = \sum_{i=1}^{n} \left( \eta_i \times WF_i \right)$$  \hspace{1cm} (1)

where $WF_i$ is the total water footprint of the reservoir, $WF_i$ is the water footprint of reservoirs purpose $i$, and $\eta_i$ is the allocation coefficient for reservoirs purpose $i$, and $\eta_1 + \eta_2 + \ldots \eta_n = 1$.

2.2. Literature review

The Web of Science, Scopus, and Google Scholar were used to gather scientific papers and studies containing the allocation procedures of the water footprint of water reservoirs. There is currently no generally accepted methodology for allocating impacts of water use to multiple reservoir purposes [10]. Grubert [11] used the strategy of “the first takes all”. This strategy is based on the idea that a reservoir's primary purpose is “a reasonable proxy for the primary driver of its construction and evaporative impacts” [11]. The opposite of this strategy is an equal allocation of the water footprint to all reservoirs purposes.

Several authors used allocation strategy based on the rank of the purpose of water reservoir [12–15]. Allocation coefficient $\eta_i$ is calculated by equation:

$$\eta_i = \frac{n + 1 - \text{rank}}{\sum_{i=1}^{n} i}$$  \hspace{1cm} (2)

In the Life Cycle Assessment, there is used economic allocation [16] based on quantification of benefits provided by individual purposes of the reservoir. This strategy was used by several authors in the water footprint studies e.g. Three Gorges dam study [17], Přísečnice and Fláje reservoir study [9] or global study by Hogeboom et al. [8]. The description of benefits associated with the operation of the reservoir was described by Bakken et al. [18]; they described two other strategies for allocation. First is based on the volume used or allocated for individual purposes such as volume of water used for hydroelectricity generation, water used for irrigation, the volume of reservoir allocated for the flood protection, etc. The second strategy is suitable for the specific studies in the energy sector only, because this strategy is based on energy allocation. In that strategy, there is every water use for an individual purpose transformed to energy produced or lost.
A different approach to allocation is described by Golabi and Radmenesh [19]. These authors used Analytic Hierarchy Process (AHP) in the study of Zayanderud Dam. The AHP is a decision-making model containing a three-part process that includes i) identifying and organizing decision objectives, criteria, constraints, and alternatives into a hierarchy, ii) evaluating pairwise comparisons between the relevant elements at each level of the hierarchy, and iii) synthesis using the solution algorithm of the results of the pairwise comparisons over all the levels [20].

3. Pilot study – Fláje water reservoir
The Fláje water reservoir is situated on the Flájský stream in the Ore Mountains near the village of Český Jiřetín on the border of the Czech Republic with Germany. The catchment area is only 42.45 km$^2$ and the average long-term flow rate is 853 l/s ($Q_a$). Even though, the Fláje reservoir is a key factor in the drinking water supply system of the population in northwestern Bohemia. The dam of the water reservoir consists of a concrete heavy pillar structure of the Noetzli type with a maximum height above the ground of 49.46 m [21]. The Fláje water reservoir provides purposes listed in Table 1:

| No. | Purpose |
|-----|---------|
| P1  | drinking water supply, |
| P2  | flow rates improvement (compensation) in the Bílý stream, |
| P3  | ensuring minimum flow rates in the Flájský stream, |
| P4  | reduction of flood flows in the Flájský stream and partial protection of the area down the reservoir against floods, |
| P5  | energetic use of water supply by the peak regulation hydropower station Meziboří, |
| P6  | energetic use of minimum outflows by the small hydropower station Fláje. |

4. Results

4.1. Categorization of allocation strategies
The following categories were identified by analyzing the strategies used to allocate the water footprint in individual reservoir purposes, depending on whether:

- takes into account the importance of particular purposes,
- enables easy determination of the coefficient,
- takes into account the characteristics of the reservoir.

These categories are independent of each other and the individual allocation strategies can be included in each of these categories, i.e. they can be in several categories concurrently.

4.1.1. Importance of purposes. The category includes allocation strategies that take into account the importance of individual purposes of the reservoir. It means that the even distribution of the water footprint between all purposes or the “first takes all” strategy do not fit this category. On the other hand, the strategy based on the rank of individual purposes fits this category.

4.1.2. Easy coefficient determination. The category includes allocation strategies that does not require additional information or require only basic water management information about the reservoir to determine the allocation coefficient. This includes both, the "first takes all" strategy and the even distribution between the individual purposes, but also the strategy based on rank.

4.1.3. Characteristics of reservoir. The category includes allocation strategies that take into account the characteristics of the reservoir, such as the volume of the storage or retention space. The typical representative is the volume allocation described by Bakken et al. [18].

4.2. Design of allocation strategy based on Saaty’s pairwise comparison
There is currently no consensus on the right allocation strategy. It can be assumed that such an agreement might never be reached because each water footprint study has its different purpose and scope, and therefore imposes different requirements on procedures used in the solution. However, we hope that an appropriate strategy shall belong to each of these categories.

The volume allocation is considered to be the most robust approach for allocating water consumption between functions in multipurpose reservoirs [18].

Management of water reservoir operation is a dynamic process and - depending on people's needs and meteorological forecasts - the volume of the water reservoir intended for individual purposes can alter with high monthly and annual variability. For future status studies, the determination of individual volumes is a matter of the author's expertise. A combination of AHP and volume allocation can be proposed for these studies; due to AHP is one of the most commonly used methods for deciding on multiple criteria involving an assessor's subjective judgment based on relative measurement. It is important to note that multi-criterion assessment models do not determine the general best option, but the most optimal option for the decision-maker. Thus, by selecting appropriate criteria, the AHP model can be set optimally for the scope and objectives of the study.

A simple AHP model was designed for the study of the Fláje water reservoir, where only one criterion was determined: How much more or less important is the purpose of \( A_i \) than the purpose of \( A_j \)? The significance of the relationship between the individual criteria is expressed by a nine-point scale. The basic scale uses odd values supplemented by verbal evaluation, see Table 2:

| Scale | Explanation |
|-------|-------------|
| 1     | Two activities contribute equally to the objective. |
| 3     | Experience and judgment slightly favour one activity over another. |
| 5     | Experience and judgment strongly favour one activity over another. |
| 7     | An activity is favoured very strongly over another; its dominance demonstrated in practice |
| 9     | The evidence favouring one activity over another is of the highest possible order of affirmation. |

Mean levels of 2, 4, 6, 8 can be used for more sensitive expression of preferences.

The results of the pairwise comparison are put into a matrix of relative importance called Saaty’s matrix (Table 3). The vector priority was determined using the geometric mean method [23]. Due to only one decision criterion was used, the vector priority values represent the values of the allocation coefficients of the individual purposes of the Fláje water reservoir.

| Number of purpose | P1 | P2 | P3 | P4 | P5 | P6 | Geometry mean | Priority vector |
|-------------------|----|----|----|----|----|----|---------------|----------------|
| P1                | 1  | 5  | 2  | 7  | 9  | 9  | 4.22277       | 0.437           |
| P2                | 1/5| 1  | 1/3| 1  | 3  | 5  | 1.00000       | 0.103           |
| P3                | 1/2| 3  | 1  | 5  | 9  | 9  | 2.91021       | 0.301           |
| P4                | 1/7| 1  | 0.2| 1  | 3  | 7  | 0.91839       | 0.095           |
| P5                | 1/9| 1/3| 1/9| 1/3| 1  | 3  | 0.40031       | 0.041           |
| P6                | 1/9| 1/5| 1/9| 1/7| 1/3| 1  | 0.22134       | 0.023           |

Description of purposes is presented in Table.

4.3. Allocation coefficients for the Fláje water reservoir

To compare the results of individual allocation strategies, those strategies were chosen that allow easy determination of the coefficient without the need for additional data or additional studies, which means the „First takes all” strategy, Evenly distribution, and Rank of purpose. The coefficients for the economic allocation strategy were taken from an earlier study [9], however, it should be mentioned that only the
water supply and energy production were taken into account for the calculation of the allocation coefficients. The results are shown in Table 4.

Table 4. Allocation coefficients for different allocation strategies in the Fláje water reservoir

| Number of purpose | First takes all | Evenly distribution | Rank of purpose | Saaty’s pairwise comparison | Economic allocation |
|------------------|----------------|---------------------|----------------|----------------------------|---------------------|
| P1               | 1.000          | 0.167               | 0.286          | 0.437                      | 0.994               |
| P2               | --             | 0.167               | 0.238          | 0.103                      | --                  |
| P3               | --             | 0.167               | 0.190          | 0.301                      | --                  |
| P4               | --             | 0.167               | 0.143          | 0.095                      | --                  |
| P5               | --             | 0.167               | 0.095          | 0.041                      | --                  |
| P6               | --             | 0.167               | 0.048          | 0.023                      | 0.006               |

\(^a\) Description of purposes is presented in Table 1.  
\(^b\) Average values taken from [9] – only water supply and energy production were considered.

5. Discussion and Conclusion

By comparing the results of individual strategies for the calculation of the allocation coefficient (Table 4), it is clear that the choice of allocation strategy will influence the results of the water footprint of the individual purposes of the reservoir. A basic categorization of the allocation strategies was proposed based on the expression of three basic characteristics, such as i) consideration of the importance of individual purposes of the reservoir, ii) complexity of the allocation coefficient determination, and iii) consideration of the reservoir's characteristics. In this study, only the status "meets" or "does not meet" was considered for each criterion. Even a more detailed classification can be suggested; it is a matter of further discussion of the scientific community whether it is needed. However, it can be concluded that allocation strategies that do not consider the importance of individual purposes or the reservoir characteristics can significantly affect the final results. The use of such allocation strategies for the water footprint studies or the specific selection of reservoirs (e.g. reservoirs with one predominant purpose) must be carefully considered to avoid influencing the results.

In the study, the determination of allocation coefficients was performed by a simple AHP model based on a simple comparison of the significance of the water reservoir's individual purposes. This procedure seems to be also applicable to studies involving many reservoirs. In these studies, a detailed solution concerning each reservoir is in many cases impracticable and the proposed simple AHP model is a suitable compromise between the data requirements and time required for processing and the need to distinguish among the importance of water reservoir purposes. However, it needs to be noted that this approach includes subjective preferences and therefore requires higher expertise of the assessor as well as adequate water management data for each reservoir.

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