Linear Modelling of Water Potential and Supply for Decentralized Energy-Water-Food systems – case study St. Rupert Mayer, Zimbabwe

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ABSTRACT

Limited water accessibility threatens the development of communities, especially where agriculture is the main income source. The implementation of decentralized Energy-Water-Food systems is a promising approach to improve the situation in these communities, creating synergies and improving the profitability of the system. The model urbs optimizes Energy-Water-Food systems to generate the highest revenues, considering the local conditions and sustainability limits. This work improves the hydrogeological part of urbs in order to model the water potential of a given community, establishing interrelations of the water sector with the energy and food sectors, and maximizing the long-term benefits within the sustainability limits. The proposed method was applied to the rural community of St. Rupert Mayer in Zimbabwe. In order to analyse the impact of data uncertainty on the model results, the sensitivity of the main input parameters is analysed. The results indicate that it is important to implement reliable input data for dimensioning the proper system configuration, as otherwise the whole system would not be sustainable.

KEYWORDS


INTRODUCTION

In most rural countries in Sub-Sahara Africa (SSA), their development is threatened by the challenges to supply basic resources as energy, water and food. Due to current tendencies as population growth and climate change, this situation is prone to get worse, as described by the Food and Agriculture Organisation of the United Nations (FAO) in [1] and [2]. These reports also indicate that the water availability could be enhanced with infrastructure, but most rural
communities in SSA have no economic means to install and maintain this infrastructure. Consequently, especially outside big cities, the water supply is rather a matter of luck than a controlled situation. As indicated by the FAO in [3], a reliable water supply leads to stable crop production and, therefore, also stable revenues which can payback the investment and operation cost. One promising approach is the implementation of decentralized Energy-Water-Food (EWF) systems. Nevertheless, the authors of [4] suggest that, until now, a standardized approach to plan and implement intersectoral systems does not exist.

This work focuses on the definition and improvement of the hydrogeological section of an existing linear optimization tool, the urb model, which is described below.

Other approaches to assess and plan intersectoral systems at different scales have been developed, but only a limited number of approaches address all sectors simultaneously [5]. Quantitative models for the optimization of EWF systems increase the efficiency of the resources management by modelling positive and negative interactions of every component in all sectors and optimizing the interconnections. Some works integrate scenario-based analysis for comparison of different setup combinations, as well as different economic and physical factors, as for example the works of [6] and [8]. The work of [7] implements EWF value chains analysis (to identify important linkages), analyses the effect of institutions at production processes and applies the results to different case studies where the actors' decisions depend on economic and social trends. The model proposed in [5] also includes a sensitivity analysis, which can make the approaches more robust. The work of [9] applies a multi-sectorial system analysis and combines substance flow analysis with regionalized sensitivity analysis to estimate economic benefits.

Optimization model urb

The existing model used in this work, urb, is an open-source linear optimization tool programmed in the language Python developed by the Chair of Renewable and Sustainable Energy Systems of the Technical University Munich (TUM). This model identifies the optimum economic configuration to meet the predetermined resource demand at the lowest feasible cost. The minimal total cost is a result of the techno-economic modelling of all conversion, transmission and storage processes. A detailed description of the complex mathematical processes behind this optimization tool can be found in [10].

Initially, urb was designed to optimize energy systems. Previous studies in urb focused on grid-connected and microgrid renewable energy systems, as for example the works of [12] and [11]. However, urb can be adapted to design and optimize least-cost EWF systems, interconnecting different sectors in circular processes. The works of [13] and [14] present the previous versions of the urb optimization model for EWF systems. This work adds up to the previous urb version, focussing on improving the hydrogeological sector of the model.

Figure 1 shows the flow diagram of the model. Here, it can be seen which combination of commodities can be transformed into other commodities through defined processes. Each process comprises a unit ratio for input and output commodities (e.g. m³ of groundwater for kg of tomatoes), as well as a cost per unit processed.
The approaches to develop the model are based on two conventional hydrogeological models: the Soil and Water Assessment Tool (SWAT) and the modular finite-difference flow model (MODFLOW). Hydrological and hydraulic models combined can simulate the water flow in two or three dimensions [15]. SWAT is a watershed scale model to predict the impact of land management practices on water, sediment and agricultural chemical yields. The model is physically based and requires input data from weather, soil properties, topography, vegetation and land management in the watershed. Then, it models physical processes of water and sediment movement, crop growth, nutrient cycling, etc. [16]. MODFLOW is an international standard for simulating and predicting groundwater conditions and interactions with surface water. MODFLOW simulates groundwater systems, solute transport, variable-density flow, aquifer-system compaction and land subsidence [17] [18].

To guarantee that the resulting system can be operated long-term, it is necessary to define the sustainable limits of the natural environment. In this version of the model, the sustainability frame indicates that only the rainwater infiltrating in the community area can be used by the system.

As the model is to be implemented in remote regions, which often do not have access to reliable data, the results of the model may be affected by uncertainty. Therefore, this work assesses the impact of data uncertainty for the most relevant hydrogeological input parameters.

The developed model is applied to the case study of the Jesuit mission St. Rupert Mayer (SRM) in Zimbabwe. SRM is located 200 km west from the capital Harare, in a rural area with a low population density. The main income sources are agriculture and farming at a small scale, producing maize and vegetables. The mission offers following services: hospital, preschool, primary school, high school and a church. Until now, the community’s water supply depends on the rainfall and electric pumps. Then again, the energy supply for the pumps depends on the centralized supply from the Zimbabwean Electricity Security Authority and on diesel (which often is complicated to obtain). Consequently, in the dry season, if there is no energy supply, there is no water supply.
METHODS

The urbs model supply the demand as efficient and with the lowest costs possible. In the hydrogeological component of urbs, complex natural processes are represented in simplified calculations: as accurate as necessary and as simple possible. In most locations, the rainfall is the only reliable natural water source, as other possible sources (e.g. rivers or lakes) may not exist in the surroundings or may be contaminated [3] – rainfall (and aquifer recharge) is also the main water source in the model. Then, if the model calculates water deficits, it is also possible to buy water at a given price per unit.

The input parameters needed to run the urbs model are divided in two main categories:

- Techno-economical parameters: All information regarding the available technologies, including the capacities and operation modes of the machines, as well as the costs for investment and maintenance. Also, the social and economic situation of the community is considered for deciding which processes can be implemented regarding acceptance of the users and capacities of the local operators.
- Environmental parameters: Physical, climatic and hydrogeological parameters (e.g. land use, rainfall, climate, soil and aquifer characteristics)

The hydrogeological part of the model is divided into two steps: the pre-calculations and the optimization. Thus, every process that does not need to be optimized is to be calculated previously and only the results will be introduced in the model.

Pre-urbs calculations

This calculations prepare the input data for the hydrogeological processes in an Excel datasheet based on the equations used in the programs SWAT and MODFLOW. The outputs of this tool are net rainfall, aquifer parameters and water demand.

Net rainfall. Calculates the losses from the total rainfall due to the following factors in a daily resolution: canopy interception and evaporation, runoff, transpiration, soil retention and soil evaporation. The “net rainfall” is the amount of rainwater that can be used in the model. The involved hydrogeological processes are presented in Figure 2.

Figure 2. Natural processes involved in the calculation of the net rainfall
One of the most important input parameters is reliable rainfall data. A fair option is the remote sensing data from the Tropical Rainfall Measuring Mission (TRMM) [19] [20].

Resembling the calculation approaches of the SWAT program, the community’s area is subdivided in “Hydrological Response Units (HRU)”. These areas are classified depending on their land use, topography (slope), soil type and vegetation [15]. This assessment and the calculation of the HRUs can be made using Geographic Information System (GIS) tools and digital elevation models. For this model setup (adapted to the case study), the HRUs are grouped in three different sectors, which have different processes for the falling rainfall:

- **A) Crop fields:** The rainfall can be used to supply the crops water demand directly and to recharge the aquifer. The net rainfall is the sum of the groundwater recharge plus the retention in the top soil and unsaturated zone (UZ), minus the soil evaporation.
- **B) Area outside the crop fields minus the area of buildings:** This sector can be subdivided in different land uses (HRUs), as fallow land (B.1) and forest (B.2). The rainwater falling on this sector can only be utilized if it reaches the aquifer.
- **C) Building roofs:** The rainwater falling on this sector can be harvested to supply the domestic water demand.

Following hydrogeological processes are calculated daily in the urbs tool:

- **Evapotranspiration:** depending on the potential evapotranspiration and water available.
- **Interception:** The rainfall volume intercepted by the vegetation, which can evaporate, depending on the Leaf Area Index (LAI) and climatological aspects [21] [22]. The tool calculates the daily amount of rainfall stored and evaporated, as well as exceeding the retention capacity.
- **Runoff:** this value depends on: slope, soil type, vegetation and dryness or saturation of the ground, as well as on the rainfall intensity [23] implementing the Soil Conservation Service runoff equation [24] and considering the previous rain events.
- **Transpiration:** the amount of water that plants consume depending on their morphology and growth phase, as well as on available water. For the areas in the B sector (forest and fallow land), this process is a “water loss”.
- **Soil evaporation:** If the daily potential evaporation has not been met after canopy evaporation and transpiration, a certain volume would evaporate from soil’s water retention. Depending on the climatic and geological circumstances, the water can be extracted from the top soil or from deeper layers. This amount is influenced by the degree of shading and the extent of biomass above the ground (vegetation) [22].

Soil and Aquifer data. The urbs model conceives three ground layers: the Top Soil layer (TS), the Unsaturated Zone (UZ) and the aquifer (Aq), as can be seen in Figure 3.

![Figure 3. Ground storage units in urbs](image_url)
The soil evaporation and the amount water exceeding the retention capacity is calculated for a daily basis, indication the volume percolating to the lower ground layer. The groundwater flow is described by Darcy’s Law [22], whereas the rate at which the infiltrated water reaches the water table depends on the thickness of the UZ [25]. The relation between rainfall and percolation is directly related to annual rainfall pattern (intensities) [26] [27]. The aquifer’s water-storage capacities may vary greatly among short distances [28], thus, extensive measurements should be done onsite to define the aquifers structure. General geological data is an option for a roughly estimations of the aquifers structure, as for example the Quantitative Maps of Groundwater Resources of [29].

**Water demand data**  two kinds of demands are set in an hourly rate as the drivers of the optimization processes:

- Domestic water demand: To be measured for the given community, considering the minimum water demand per person (50 litres per day) [30].
- Crop water demand: the crop evapotranspiration [31] is calculated depending on local climatic and geographic characteristics, as well as on the crop type and its growth phase. The program CropWat 8.0 from the FAO is a useful tool [32] [33]. As crops can resist a couple of days without irrigation [31] [34], this supply is flexible in time and volume.

**Water component of the urbs model**

The urbs model operates with a complex python optimization code, which gathers its input data from a structured excel document. It includes all hydrogeological processes that directly affect the water availability per time step and the systems costs. The models flow diagram can be seen in Figure 4. The model input data is classified in:

- Demand: defined as m³/h of each water type
- Commodities: resources including its price per unit (m³)
- Fluctuation supply: availability of natural resources at each time step
- Processes: specification of costs and efficiencies involved (e.g. transport capacities [m³/h], annual fix costs [€/y per m³/h], etc.)
- Process-Commodities: ratio between input and output commodities for every process
- Storage: storage units for a specific commodity, including a percentage loss per hour (represents tank leakages or evapotranspiration)
As can be seen in Figure 4, the domestic water demand is supplied from the pumped groundwater and from the harvested rainwater, whereas the crop water demand is supplied by:

- **Rainwater:** calculated multiplying the net rainfall by the crops area and used in three ways: 1) to supply the demand directly; 2) if its volume is greater than the demand, the rest is stored in the top soil for a later use; 3) percolation to deeper layer if the top soil is saturated.

- **Irrigation:** If the usable rainwater does not cover the demand, the missing volume is supplied through irrigation. The total Irrigation Delivery Requirement (IDR) includes the plant watering requirement and the water losses for distribution.

If the local water resources are not enough to cover the demand, the system will buy water. This also indicates that the system is not self-sustainable and it should be improved (e.g. to change the crop types for ones consuming less water).

The net rainfall is introduced into the model as an intermittent supply input. It is modelled as a change in capacity (a capacity of 100% represents a rainfall of 10 mm/h) multiplied with the area of each HRU.

The ground layers are represented as storage units with specific urbs properties: storage capacity, input-output capacity (representing infiltration) and hourly discharge (representing soil evaporation). For simplification, it is assumed that the ground is homogenous in all directions and completely interconnected. The infiltration rate is modelled as an adaption of the methods of the program MODFLOW, which calculates the groundwater flow in three-dimensional ground units [18]:

- **Top soil storage (TS):** the storage capacity is calculated as the crops area multiplied by the root depth and by the water percentage available for the plants (soil’s porosity minus the wilting point). The commodity stored is Crop Water and is affected by soil evaporation.
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- Unsaturated Zone: modelled analogous to the top soil, it buffers the water path from the top soil to the aquifer, which is modelled as a transfer from the TS unit into the UZ at a given (percolation) rate. The water stored cannot be used.
- Aquifer: For simplification represented as a shallow unconstrained aquifer. The total volume is the area of the community multiplied by the aquifer depth and by the usable storage capacity.

The model’s infrastructure system is composed of a solar pump, photovoltaic panels and a storage tank, which are dimensioned to optimize all costs. To generate electricity, the process “PV” converts the fluctuating resource solar irradiation into electricity, where the efficiency is determined by the solar capacity factor per time step. In the solar pump’s process, electricity and groundwater are the inputs with specific ratios, and “pumped water” is the output. This commodity is stored in tanks and can be transformed into “crop water” or “domestic water” to supply the respective demands. The pump size is limited by the aquifer’s extraction capacities. The pump rate should be obtained performing pump tests onsite. The hydraulic sizing of the submersible pump represents the electrical power needed to pump one cubic meter of groundwater to the storage tank, considering the dynamic groundwater level and the system efficiency.

Sensitivity analysis

Because of the uncertainty of the data available, it is necessary to identify which input parameters have a greater impact on the model’s result, as some parameters may need exact input data in order to obtain reliable results.

The base scenario consists of one solar pump to cover the water demand of 15 ha of Maize with three harvests per year and of a community of 600 people. For this analysis, following parameters are to be tested:

- Maximum pumping rate (max. Q): the limit of the pumping rate must be based on aquifer characteristics. The values used are 0.1, 0.5, 1.0, 1.5 and 2.5 l/s
- Aquifer hydraulic conductivity (K): affecting the infiltration rate and storage capacity. The values used are K=8E-07 m/s for the base scenario, 3E-04 m/s for the best-case scenario and 8E-09 m/s for worst-case scenario (fractured metamorphic rock) [35].
- Aquifer storage capacity: In the basis scenario, the aquifers area is the area of the whole community and it is assumed completely interconnected (every water drop percolating anywhere could be extracted by the pump. For the worst-case scenario, the aquifers area is 0.75 % of the community area and has a hydraulic conductivity of K=8E-09 m/s.
- Land use: two scenarios are analysed: 1) deforestation scenario, 73.7 % of the forest area is converted into fallow land; 2) afforestation scenario, the forest area increases 66.5 %
- Rainfall pattern: Different scenarios are analysed, representing changes due to climate change and local environmental changes. Two artificial rainfall patterns with the same total rainfall amount (864 mm/year) are considered. In the first scenario, the daily rainfall intensities are reduced and the total rain volume is distributed within more days in the wet season (mid-November to mid-March). In the second scenario, the daily rainfall intensity is increased and the number of rainy days reduced, concentrating the water volumes in fewer days. This rainfall patterns can be seen in Figure 5.

![Rainfall Pattern](image-url)
RESULTS and DISCUSSION

Following, the results of the pre-calculations and of the urbs model are presented and discussed.

Pre-calculation results

For the case study in SRM, four HRUs are defined (crop fields, fallow land, forest and buildings), and their respective net rainfall is calculated. The calculated yearly water balance for the year 2017 can be seen in Figure 6. This figure shows which amount of the total rainfall is available for the model (groundwater), and which is lost due to the different factors (runoff, canopy interception, soil evaporation and transpiration). The forest HRU supplies the highest amount of available water for the model with 233.5 mm, whereas the fallow land only supplies 4.3 mm. For the crop area, the useful water amount comprises the groundwater (83.9 mm) and the plants transpiration (287.1 mm), which reduces the demand for irrigation.

The forest HRU has greater canopy interception and transpiration losses than the fallow land, but in the fallow land the losses through runoff and soil evaporation are significantly higher, which affects the percentage of groundwater recharge. This is a clear example of the value of trees and vegetation, which also increase the roughness of the ground, decreasing the surface runoff [23]. Considering the small water cycle and its long-term effects, by increasing the vegetation, it is possible to preserve and increase the local water availability [36].
The water sources to cover the domestic demand are shown in Figure 7. In the rain season, the domestic water demand is supplied mainly through rainwater harvesting (purple) and the stored water (yellow) — there is no need to use the pump. In the dry season, the demand is covered by a combination of water pump (blue) and storage.

![Figure 7. Domestic water demand: rainy season (top) and dry season (bottom).](image)

The water sources to cover the crop water demand can be seen in Figure 8. For the crop water demand, during the rainy season, a great amount is covered directly by the rainwater (purple) stored in top soil (yellow). When the incoming rainfall exceeds the demand and the soils retention capacity, this amount percolates into the lower ground layer, reaching the aquifer at some point. The stored water volume in the top soil layer can be seen in Figure 9. As the operation costs for the solar pump (blue) are set to be near zero, it runs for some hours every day, even though it is not necessary.

In the dry season, the only local water source available is the solar pump (blue), which is not enough to cover the demand. Therefore, the model indicates that it is necessary to buy water (orange) to cover the deficits.
Figure 8. Crop demand: rainy season (top) and dry season (bottom).

Figure 9. Top Soil storage

Sensitivity analysis

The maximum pumping rate has a significant impact on the model optimization. Figure 10 shows the water sources to cover the demand and its percentage for each scenario with different pump rates. The water deficit (buy) increases for lower pumping rates, being 99.224 mm for a rate of 0.1 l/s and 0 mm for a rate of 2.5 l/s.
Figure 10. Effects of max. pumping rate on the coverage of the yearly water demand.

As can be seen in Figure 11 and Figure 12, the max. pumping rate impacts the water deficit significantly, especially in the dry season. With a max. pumping rate of 0.1 l/s, in the dry season, the available water (blue) is critically lower than the demand (the orange area represents the water deficit to cover the demand). A max. pumping rate of 1 l/s improves the water supply significantly, but it is still not enough to cover the demand in the dry season. For a pumping rate of 1.5 l/s, the water deficit represents 0.08 % of the demand. Figure 13 shows the amount of water deficit presented for each scenario.

Figure 11. Max. Q = 0.1 l/s – Crop Water supply in the rainy season (top) and dry season (bottom)
Figure 12. Max. Q = 1.0 l/s – Crop Water supply in the rainy season (top) and dry season (bottom).

Figure 13. Water deficit for different max. Q values and K=8E-09 m/s

The aquifers hydraulic conductivity has an impact on the water deficit. Even in scenarios where great max. pumping rates are allowed, this rate is limited by the aquifers properties. Therefore, the hydraulic conductivity has a greater importance for the optimization. This impact can be seen in Figure 14.
The parameter aquifer storage capacity has a significant impact on the optimization results. The percolation rate into the aquifer is 28.8 m³/h/ha in the base scenario, compared to 0.3 m³/h/ha in the worst-case scenario (decreased aquifer area and hydraulic conductivity), increasing the total water deficit. These results can be seen in Figure 15.

Figure 14. Water deficit for different K values and max. Q = 54 m³/h

In the base scenario, the pumping rate is the limiting factor. In the worst-case scenario, the limiting factor is the groundwater storage volume. Thus, urbs administrate the available resources implementing lower pumping rates. Whereas in the base scenario the aquifer is frequently full (storage volume of 80,000 m³), in the worst-case scenario the maximum volume stored is 697 m³ (right after the rainy season). The stored volume decreases constantly, to get empty by the end of the dry season. In the “perfect” scenario for this case, the aquifer storage capacity must be big enough to store the groundwater needed in the dry season, and the pumping rate should be 2 l/s or higher.

Regarding the land use, in SRM, from the 864 mm of total rainfall in the year 2017, the fallow land has a calculated yearly runoff of 520.5 mm (60.3 %) and the forest 173.7 mm (20.1 %). Whereas, the forest area contributes to the yearly groundwater recharge a calculated volume of 213.5 mm (27.0 %), the fallow land contributes only 4.3 mm (0.5 %). In the deforestation scenario (forest area decreases 73.7 %), the runoff volume increases 50 % and the groundwater recharge decreases 67.2 %. In the afforestation scenario (forest area increases 66.5 %), the runoff volume decreases 44.2 % and the groundwater recharge increases 60.6 %.

Nevertheless, the land use has little impact on the results of the model optimization. This may be due to the local rainfall patterns (intense rainfall events and long dry periods) with high runoff and evapotranspiration rates. In the rainy season, the available rainwater exceeds the demand and storage capacities, but at the end of the long dry season, all available water (from storage) is consumed. Considering the local natural conditions, is clear that the rainwater storage capacities should be increased in order be able to cover the demand of the whole year.

With the rainfall intensity and pattern of SRM (short events of high intensity in the rainy season), even receiving a greater volume of rainwater would not decrease the water deficit significantly, because the water availability in the dry period would not increase. Instead, a rainfall pattern with lower intensities and more rainy days would improve the local water
availability, especially if the dry season is shortened. These effects of different rainfall intensities on the yearly water balance can be seen in Figure 16.

![Figure 16. Effect of rainfall intensity (52 mm, 32 mm and 11 mm) and distribution patterns on the yearly water balance for the different HRUs.](image)

The rainfall intensity and pattern have a significant impact in the calculation of the net rainfall. In all HRUs, the runoff percentage rises with increasing rain intensities. Concerning the losses through canopy interception, in the crop fields and the forest areas, these losses increase with more rainy days of lower intensities. The same applies to the losses through soil evaporation in the fallow land. In contrast, the groundwater recharge in the fallow land decreases for rain patterns of high intensities in less rainy days, because losses through surface runoff are greater. Further on, in the rainy season, whereas a rain pattern of low intensities is enough to cover the whole demand, the rain pattern of high intensities and les rainy days presents water shortages. This deficit occurs because the rainfall volume at each rain event is greater than the volume that can be used or retained, thus, a smaller amount can be utilized.

**CONCLUSION**

This work develops the water component of the urbs model, with the aim of representing hydrogeological processes – as accurately as necessary and as simple as possible – in the frame of a decentralized EWF system. A pre-urbs calculation tool is created to estimate all model input parameters that do not need to be optimized. The urbs model is improved based on the approaches used in conventional hydrogeological models. In order to assess the performance of the model, it is implemented in the rural community of St. Rupert Mayer, Zimbabwe.

The available input data is examined in the Sensitivity Analysis to assess the impacts of some parameters on the results. This analysis indicated the aquifer characteristics are the most sensible parameters. However, these input data is the most difficult to obtain in remote rural areas, especially if it is not possible to do measurements onsite.

Having reliable input data, the urbs model is a valuable tool to optimize the elements of an EWF systems, as well as to assess if the planned dimensioning is sustainable or not. The final results must be corroborated in detail, as the uncertainty in the input data may have an impact. Further on, the model optimizes the costs of the system within the physical and sustainability
limits, but it is not able to describe the accurate allocation of water resources; this must be defined by experts. Also, the allocation and installation of the systems components requires professional expertise.

The water component of urbs could be improved using GIS methods to define and calculate the HRUs. Another possible improvement is to consider additional water sources, as for example rivers or the reuse of treated wastewater. Further on, the whole model could be developed to model urban systems, including further infrastructure elements, as for example biogas (energy) generated from wastewater in treatment plants. Additionally, extra measures to increase the local water availability could be implemented in the community, as for example reducing the runoff, collecting rainwater for agricultural use, increasing the aquifer recharge and adapting the crop fields to reduce water losses.

The limited water availability is one significant factor threatening the development of rural communities in Sub-Sahara-Africa, especially if the main source of income is agriculture. This situation will get worse due to climate change, where the available water would decrease due to extremer seasons [1] [2]. Guaranteeing a water supply reduces the dependency on rainfall events and minimizes the impacts of climate variability. Moreover, the farmers can increase their revenues as the agricultural activities are not limited to the rainy season.

Decentralized Energy-Water-Food Systems are a promising approach to prompt development, in remote rural communities, supplying the community’s needs with low environmental impacts and generating revenues [3]. The program “urbs” can be used for the dimensioning of decentralized EWF systems for a given location and to optimize each of the system’s components within the sustainability frame, securing the food and water supply.

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