Mapping of suitable zones for manual drilling. An overview of the method and the application as decision tools

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Abstract/Summary
Manual drilling is regarded as a potential low cost solution to increase water supply in Africa, but it can be implemented only under specific hydrogeological conditions. The identification of suitable zones for manual drilling is a condition for an effective promotion and implementation of this technique. National maps of suitable zones have been produced since 2008, with a method based on the analysis of existing data and the integration with the experience of local experts. The method has been modified and improved, in particular with a more systematic procedure for the analysis of data and the integration of indirect environmental indicators. In the mean time different institutions have used these maps and evaluate their quality and their relevance as a decision tool for the promotion of manual drilling. In this paper the method of interpretation and the results achieved in terms of utility of these maps are discussed.

Introduction

In several countries of the World the situation of access to improved water sources (supplying an adequate quantity and protected from contamination) is still critical. In this context UNICEF is promoting manual drilling as a suitable low cost technical solution to increase the use of groundwater
Manual drilling refers to several drilling methods that rely on human energy to construct a borehole and complete a water supply (Danert, 2015). These techniques use human energy or a small pump to open a hole.
Manual drilling can provide low-cost but high quality water supply. The main advantages are the possibility to be implemented with locally made tools, the cheap cost and the possibility to transport the required equipment in remote areas, where access with mechanized drilling machine is difficult.
Although different techniques for manual drilling are available, they can be applied only where shallow geological layers are relatively soft and water table is not too deep. Therefore the promotion of manual drilling to improve water supply requires a preliminary identification of those zones with suitable hydrogeological conditions.

Description of the Case Study – Approach or technology

In the framework of its program to promote manual drilling in Africa, UNICEF carried out a preliminary study to identify suitable zones at country level. This study has been completed between 2008 and 2012 in 15 countries (Benin, Central African Republic, Chad, Ivory Coast, Liberia, Madagascar, Mali, Mauritania, Niger, Senegal, Sierra Leone and Togo between 2008 and 2010; Zambia in 2010; Burundi in 2011, Guinea Conakry in 2012) with a similar approach. However, the methodology was adapted to the specific context of each country (morphology, geological environment, size of the country and scale of work, etc.) and to the available sources of information.

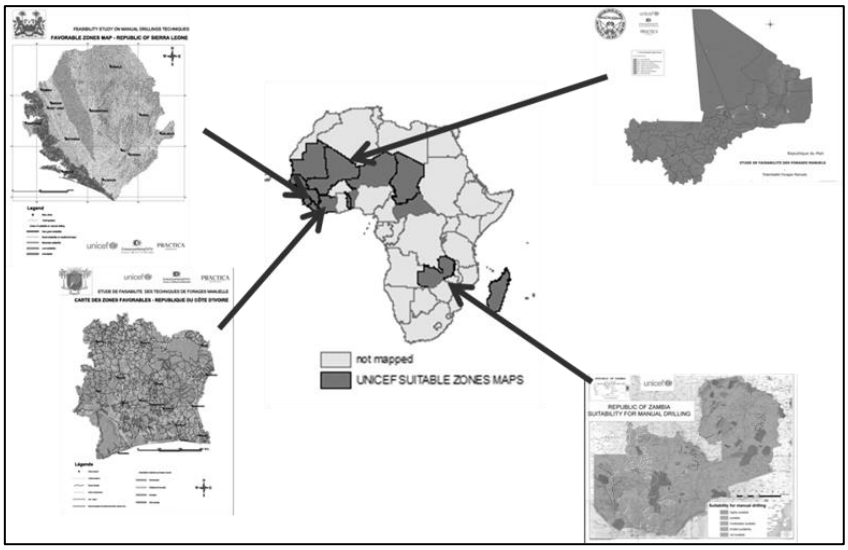

Fig.1: countries where national map of suitable zones for manual drilling has been completed and examples of maps

The goal of national mapping of suitable zones for manual drilling was the definition of regions with high potential for this technique; therefore the level of details of the study was consistent with this goal, but was not oriented to precise identification of position for drilling.

Another specific research project was carried out between 2012 and 2014 to improve the method of interpretation, in the framework of the UPGRO (Unlocking the Potential of Groundwater for the Poors) program, through a joint collaboration between University Milano Bicocca (Italy), University Cheikh Anta Diop Dakar (Senegal), Service Nationale de Points d'Eau (SNAPE) in Guinea Conakry and UNICEF. This project, entitled "Use of remote sensing and terrain modelling to identify suitable zones for manual drilling in Africa and support low cost water supply" aimed to integrate indirect source of information derived from remote sensing and terrain modelling to improve the interpretation of shallow hydrogeological conditions. The proposed method was applied in two study areas in Senegal and Guinea. The results of this project contributed to the definition of an improved methodology, leading in the future to more reliable and detailed interpretation, especially in those areas with shortage of direct data.
In this section the different aspects of the methodology applied (and its modification from 2008 till now) are explained.

Source of data:
The method is based on the integration of existing organized information, obtained from numeric database or hard copy archives, together with qualitative and subjective information obtained from interviews with hydrogeologists, drillers and field technicians, having direct experience of groundwater exploitation.
The main sources of information are:

Water points data: this is the main source of systematic data used for the interpretation in the whole set of 15 countries. Database of water points were obtained from each single national water authority. Furthermore, large archives of hard copy documents with relevant details for single water points are available in each country at central level or decentralized.
Different categories of information can be obtained from water points database:

- General inventory of water points: it contains general information for each water point; in this study the following data were generally used: location, type of water point (boreholes or hand dug well), total depth and depth of static water level.
- Stratigraphic logs: they describe the characteristics of each lithological layer found during drilling. Only in few countries were they available for the study of suitable zones for manual drilling in digital format (Zambia, Guinea, Senegal and partially Ivory Coast) and they were extremely important for the estimation of shallow hydrogeological features. However large archives of hard copy reports with detailed stratigraphic logs are available; their systematic analysis required a

previous work of transforming this information to simple spreadsheet format, therefore it was possible only where more human resources and time were available for the study (Guinea and Senegal)

- Piezometers with time series of water level: since the original information concerning water level is generally recorded at the end of water point construction (therefore it can be older than 20 or 30 years), recent data obtained from piezometers would be extremely important to have un updated vision of ground water depth and identify where present conditions make manual drilling feasible. Unfortunately piezometers data are generally not systematically recorded in national database and time series of static water level are not available

Thematic maps: these are often already available in digital format and can be directly integrated in a GIS environment. The most important maps are represented by geological maps (that were available in each country). In some cases (for example Senegal and Guinea) the existence of good quality morphopedological maps provided more precise information of shallow layers (while available geological maps at national scale show the main rock formation occurring in a specific area, but often they have no specific information about the existence and characteristics of shallow weathered layer covering the main rock). Other maps related to different environmental parameters were also collected and sometimes supported the interpretation (soil maps, land cover and climatic maps). Most of the digital maps were collected directly from local institutions, while only in some cases were these data available online.
The quality of available geological maps was a big problem for different reasons: a) limited geographic details; b) low detail in classification of geological units, therefore putting together rock types having different characteristics related to shallow hydrogeology; c) limited information of shallow unconsolidated layers, the potential target for manual drilling; d) bad quality of the digital file, for example because of uncorrected topology of GIS vector layer or missing classifications of polygons; this necessitated a huge effort for data editing and correction.

Digital terrain models: Public digital terrain models available in the web have been used. In general the SRTM 90 m resolution was considered suitable for the extraction of morphological features at the scale of national maps. In case of extremely hilly morphology, the ASTER GDEM 30 m resolution was used (for example in Burundi). The extraction of morphological features through DEM analysis was not implemented everywhere, since in regions with predominant flat morphology their effect on the shallow hydrogeological context is limited (for example in Senegal, Mauritania, etc.)

Satellite images: The use of satellite images have been introduced in the study carried out in Guinea (2011-2012) for the national map of suitable zones and in the research project implemented in two smaller study areas in Senegal and Guinea (2012-2014). They have been used for visual interpretation of landscape features (as a support for rapid field survey) and for the multitemporal analysis of indirect environmental indicators. The types of images that have been used are MODIS and LANDSAT, available for free on the web (only the analysis of soil moisture required ENVISAT ASAR data that were obtained for free from European Space Agency).

Geological and hydrogeological reports: there is a lack of hydrogeological studies in several countries. They were mainly used in those countries where more time was available for the study and a quick field survey was planned; therefore their contribution was mainly exploited in Senegal and Guinea

Direct experience of hydrogeologist, drillers and field technicians: this source of information was highly important, as existing digital database provided limited details of shallow layers (dug wells are generally not reported in water points database, or they don't have any stratigraphic information; in the meantime mechanized borehole logs provide details of deep fractured aquifers and often generic description of overlaying unconsolidated sediments). This experience was collected through continuous discussion about the procedures of analysis between the local and international team of experts in charge of the study, meeting with key informants having direct hydrogeological field experience in the country (for example staff of drilling companies, ngos, water authorities and local well constructors in the villages). The different direct experiences and perceptions of shallow hydrogeological features obtained from these informants were drawn on the map and integrated in qualitative analysis in a GIS environment, with the other available data.

Pumping tests in large diameter wells and geophysics: They were used only in a small area of Senegal during the UPGRO research project from 2012 to 2014. Pumping tests in large diameter wells provided direct measurements of hydraulic parameters referred to shallow unconsolidated aquifer, allowing a sort of validation of the indirect interpretation obtained from the analysis of geological maps and water point data; these parameters are useful to obtain an approximate estimation of the potential yield that can be extracted from hand drilled wells. Geophysics was tested in Senegal with the goal of obtaining a stratigraphic model where borehole logs were not available. However pumping tests and geophysics survey require time, therefore they cannot be considered appropriate tools for mapping suitable zones for manual drilling at national level. Still, they can be interesting methods to downscale the study to specific regions and the more precise identification of positions for drilling.

Method of interpretation

The original method of interpretation (Fussi, 2011; Fussi, 2013) used a standard schematic approach that was adapted to the hydrogeological context and the availability of data in each country. In the first round of countries (between 2008 and 2010) the procedure was based only on collection, editing, organization and analysis of existing digital data, integrated with interviews with key informants. No field survey was planned and the study was completed through remote collaboration between local experts and international consultants. This procedure has been gradually modified after 2009, mainly in the following aspects:

- A quick field survey to recognize main geological features at regional level and collect information from water technicians active far from the capital. This was introduced in Liberia, Burundi, Guinea.
- The integration of relevant data available only in hard copy (in particular stratigraphic logs) with a preliminary transformation in digital format. This was possible in those countries where more human resources and time were available (in Guinea and at regional level in NorthWestern Senegal).
- The analysis of large diameter wells (direct observation of water level, discussion with villagers concerning water level fluctuation and lithology found during excavation); this part was introduced in 2011for the map of Guinea.
- A semi quantitative approach in the characterization of shallow exploitable layer.
- The execution of pumping tests in large diameter wells.
- The integration of different sources of information and the extraction of indirect parameters.

These last three points were tested during the UPGRO research project in two test areas in Senegal and Guinea but they have not been applied for the national maps completed in the framework of UNICEF program

The original criteria to assess suitability for manual drilling derived from the combination of three aspects (Fig.2):

- *Geological suitability*, related to the hardness and permeability of the first layers of rock formations, approximately the first 30 meters. Manual drilling techniques are generally suitable for unconsolidated sediments, but not able to drill boreholes in hard rock (although some percussion techniques could break hard layers); furthermore manual drilling is not suitable in unconsolidated materials having low permeability, since in these situations the small diameter and the limited depth of the borehole can lead to low yield;
- *Suitability according to water depth*, related to the depth where exploitable water strikes can be found. It has been considered that manual drilling is generally a suitable technique when exploitable water is not deeper than 25 m (although in specific situation manual drilling has been applied up to 100 meters);
- *Geomorphological suitability,* referring to the existence of morphological features that facilitate the accumulation of unconsolidated materials, the presence of thick weathered layers and shallow water table; such features are generally associated with bottom of the valleys and sometimes with

flat areas having limited slope.

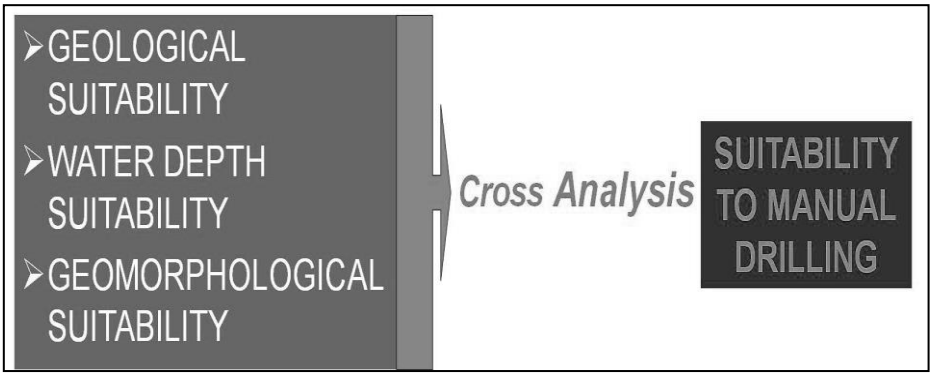

Fig.2: Schematic procedure for the estimation of suitability for manual drilling

The aspect of water quality was partially considered in the assessment of suitability because the main problem for shallow hand drilled wells is related to organic contamination, from bad hygienic condition. Concerning specific problems of chemical water quality due to hydrogeological context (like high salinity, arsenic, fluoride, etc) there is no generally sufficient data to characterize the different regions (water quality information is almost absent from groundwater database) and those data available refer to deep borehole (exploiting different aquifers, with different water chemistry). However in the map of suitable zones for each country there was specific indication of those regions where local experts agreed that problems of water quality could arise.

An assessment of the expected degree of "reliability" of the interpretation was sometimes indicated in the final maps. In those areas with lack of previously existing data and limited direct experience of exploiting shallow aquifer the class of suitability for manual drilling was assigned but it was suggested that a revision be carried out once more data were available. In this sense the feedback obtained from the future construction of manual drilled wells (and consequently a precise collection of information during this activity) is considered of great importance.

This method of assessing the suitability for manual drilling was conceived between 2008 and 2010 (with adjustments from the first attempt in Madagascar to the last country in the initial sample of 12 maps). Limited previous models could be taken as reference (in particular because of the geographic extent of mapping at country level). The main limitations of this method could be considered:

- The interpretation is based on a qualitative estimation, mainly based on subjective perception of experts and visual observation of water point data; a systematic and quantitative procedure to elaborate existing data is limited
- The assessment of shallow hydrogeological conditions cannot be considered reliable in case of shortage of previously existing data (water point data, direct field experience).

The UPGRO research project tried to find some possible solution and proposed an innovative approach under different aspects: a) a systematic and semi quantitative elaboration of stratigraphic logs and the extraction of a set of textural and hydraulic parameters, leading to an evaluation of the potential for exploitation of shallow aquifer; b) direct measurements of hydraulic conductivity of shallow aquifer through pumping test in large diameter well; c) the use of remote sensing to extract indirect environmental parameters (like vegetation, soil moisture, thermal inertia) that can be put in relation with shallow hydrogeological conditions through a multivariate statistical approach (fig.3) or visual interpretation of satellite images. A full explanation of this method is available in Fussi(2015)

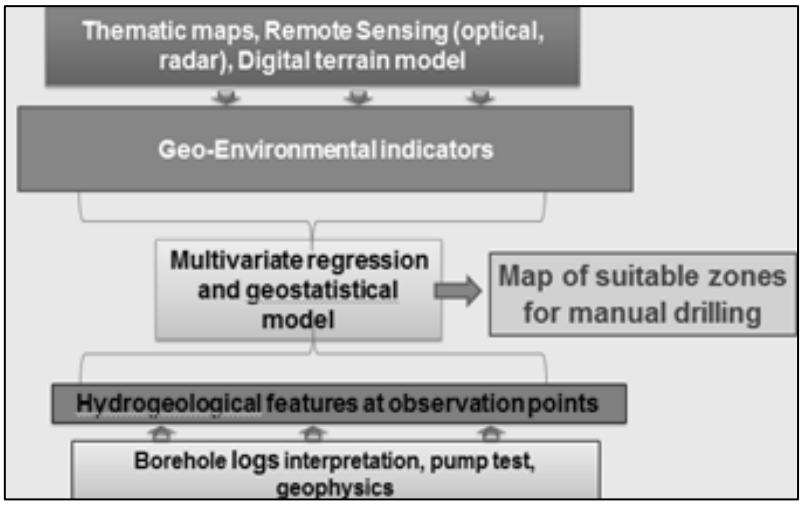

Fig.3: relation between environmental indicators and shallow hydrogeological condition

Main results and lessons learnt

The main outputs of this work are a series of maps and report specific for each country (most of them are available on the UNICEF website at http://www.unicef.org/wash/index_54332.html). The maps and reports have been validated by national institutions and used for the definition of national strategy for the promotion of manual drilling.

Concerning the UPGRO research project carried out between 2012 and 2014, the final results have been presented in Dakar in April 2014 and are available at http://www.rural-water-supply.net/en/resources/details/663

The analysis of the results of this process has considered two main aspects: a) the utility of these maps and reports as a decision and planning tool for the implementation of manual drilling; b) the quality of the maps in terms of reliability of the interpretation. For this analysis the feedback received from the countries that participated in this activity and the technical analysis from a group of experts who collaborated in the study have been considered.

In order to obtain a feedback from each country concerning their perception of quality of the national map and how this map has been used as a decision tool for the definition of national strategy for the promotion of manual drilling, the WASH section of WCARO regional UNICEF office in Dakar sent a questionnaire (table 2) to all those countries that were interested in manual drilling (some of them had already completed the national map of suitable zone while others have not implemented this activity). The countries that filled the questionnaire are: Benin, Burkina Faso, Ivory Coast, Guinea, Madagascar, Mali, Mauritania, Niger, RCA, RDC, Senegal, Chad, Togo, and Zambia. Furthermore two webinar conferences were held (for French and English speaking countries) on 9 April 2015, with participation of more than 10 countries. A final input was obtained from key informants consulted in August 2015.

Table 1: Questionnaire concerning mapping of suitable zones for manual drilling

COUNTRIES WHERE NATIONAL MAPPING HAS BEEN COMPLETED
Have you (in UNICEF) used the report, map or data collated, and if so, for what?
Have other stakeholders in the country used the map or data collated, and if so, for what?
Have the report and maps been useful for the planning of manual drilling program implementation, and if so how?
Did you find the information of the maps and report generally correct?
What would you improve about the reports, maps or data collated?
What would you improve about the mapping process?

COUNTRIES WHERE NATIONAL MAPPING HAS NOT BEEN DONE
Do you think that such reports, maps and data would be useful?
What would you like to know about the reports, maps or data collated?
What would you like to know about the mapping process

The main relevant aspects obtained from the analysis of the answers are:

Use of the map as decision tool for manual drilling strategy

The national maps of suitable zones for manual drilling have been used in several countries where this activity was completed by UNICEF; their main application has been the definition of national strategy in agreement with the Government and the implementation of manual drilling programs in selected regions. Other stakeholders have used these maps (for example the Spanish Cooperation in Mauritania, World Bank in Togo).

The selection of zones for the promotion of manual drilling and the definition of strategy for the implementation have partially taken into consideration the results of the mapping depending on the country:

- In Madagascar the coherence between manual drilling strategy and results of the map could be improved. The programme PEAR (Programme d'Alimentation en Eau et Assainissement en milieu Rural) completed 384 positive mechanized boreholes at shallow depth (less than 35 m) and 64% of them are in areas considered partially or fully suitable to manual drilling; but this cheaper technical solution was not included as an option in PEAR strategy; in the meantime 75% of manual drilled wells have been constructed in regions with high priority for water needs, but with low suitability for manual drilling. Furthermore some organizations that could have played an important role in the implementation of manual drilling in the country were not fully informed about the results of the mapping study.
- In Niger manual drilling was promoted and applied initially in a pilot area (region of Zinder) but later it was expanded in other regions (Maradi, Tahoua, Diffa) on the basis of the map, obtaining good results.
- In Mali the results of the map were taken into consideration for the implementation of a pilot manual drilling program in suitable zones of Mopti region (43 boreholes drilled between 2013 and 2015); after this first positive experience the Ministry of Water and UNICEF launched an extended program to increase manual drilling in suitable areas (88 wells in Mopti region) and test medium and low suitable zones (30 wells in the regions of Kayes, Koulikoro and Sikasso)

Reliability of the map

The perception is that the information is generally correct and allowed a correct identification of zones with good potential for manual drilling. Some partial discrepancy have been reported in Ivory Coast (where the interpretation is evaluated correct for 60-70%) and Guinea (where it has been remarked that the high geological complexity of the country made it difficult to be precise in the national map, suggesting the implementation of more detailed maps). Results in Mali confirmed the zonification of the map: 100% positive results in suitable areas, 50% in moderalety suitable, 0% in low suitable.

The main improvements in the mapping process suggested by UNICEF country offices are:

- the consideration of the aspect of water quality in the classification of suitable zones (Mauritania, Chad, Niger), with specific attention for the identification of areas with high salinity in the water
- The production of more detailed maps in the most potentially suitable regions
- In some areas with hilly or mountainous topography classified as "not suitable" it is possible to find specific locations at the bottom of the valleys where manual drilling can give positive results (for example this was suggested for Western and Northern regions of Ivory Coast and in the Eastern sector of Madagascar). The identification of these zones require maps with more detailed scale, an improvement in the analysis of morphology in the interpretation and in some cases a quick field survey
- In some cases it has been suggested that the GIS files of the map could be accessible for the National Water Authority for an easy overlay on existing topographic maps. Furthermore in Mali

They suggested that the data of manual drilled wells constructed could be organized in a database and be used to improve the original delimitation of suitable zones.

The technical group who was in charge of the elaboration of all these maps and the implementation of the research project underlined a series of points concerning the pertinence and validity of the methods of interpretation, taking into consideration both the experience of country maps completed between 2008 and 2012, as well as the results of the UPGRO research project carried out between 2012 and 2014. The following aspects of the technical evaluation are underlined:

- The analysis of stratigraphic logs is crucial for the interpretation of shallow aquifers and the validation of the perception of hydrogeologists and drillers. But this information is still limited in numeric format; therefore the availability of human resources to input the huge amount of hard copy logs in the computer and the elaboration of systematic procedures of codification and analysis of stratigraphic data allow the exploitation of these important data. An example of this tool and a systematic procedure of analysis were developed during the research project (Fussi, 2014)
- Considering the large effort in data input and correction of existing information (the most time consuming task of the whole process), it would be important that the revised database obtained be properly organized, with complete metadata to facilitate the correct use of the information and made available for potential users.
- The information of hand dug wells can provide better information on shallow aquifers and avoid possible bad interpretation based on national water point inventory containing data only from deep mechanized boreholes. This is extremely important in countries where the presence of confining layers (for example Northwestern Senegal, Central Ivory Coast) made it difficult to the determine the depth of the water level in the shallow water table. However the information of hand dug wells is generally limited in the database; for this reason it is considered important a quick field survey to check selected large diameter wells and those interviews with persons involved in digging wells in rural areas.

Conclusions and Recommendations

Since 2008 specific studies to identify suitable zones for manual drilling at national level have been carried out in 15 countries in Africa, and the study in the 16th country (Guinea Bissau) is almost completed. The method of interpretation is based on existing information and limited field survey, in order to make it applicable for maps at national scale obtained in a relatively short time (from 2 to 6 months, according to the extent of the country, its complexity and the available information). Several modifications have been introduced, allowing an improvement in the results in those countries mapped in the last years. The results achieved have been in general appreciated in those countries where this study was carried out and have provided valid decision tools for planning the development of manual drilling. However it seems evident that different aspects contributed to the improvement of the mapping process: the integration of different sources of information, the definition of a more systematic method for data processing and an increase in the human and logistic resources to carry out the study.

Considering the limited previous experience in the characterization of shallow aquifers in Africa at regional level, it would be important to share the new future experience that will be done in other countries and exploit the new data that can be obtained from manual drilled wells to improve the maps already completed.

It is also important (as was indicated by some countries where the national map have been used) to consider the production of more detailed maps in those regions considered suitable for manual drilling and having high priority for improving water supply. Downscaling the scale of interpretation and delivering more detailed maps can be more useful for direct implementation of manual drilling in the field. For this purpose the integration of other sources of information is crucial (like satellite images, selective field survey, etc), it can fill the gap of existing data and provide information with higher spatial resolution compared with existing thematic maps.

It is also important that the large effort to create well organized database and revising the available information (generally having high level of errors) could be used not only for the production of these maps, but also could provide relevant data for further hydrogeological studies.

This work can be considered still in a highly experimental phase and the joint contribution of researchers,

decision makers, and drillers to improve the methodology is considered important.

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