Mapping the Potential for Rainwater Harvesting under Various Scenarios

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1 Relevance

Rainwater harvesting aims at reaching those people not having access to sufficient and good quality fresh water. They often live in rural areas where other means of water supply are not sufficient or feasible. Within these areas groundwater is not accessible (at technically and/or financially unreachable depths) or potable (due to water quality issues, like fluoride or arsenic contamination) and other surface water (like permanent rivers, lakes and springs) are not available or sufficient to meet basic water needs.

Identifying areas where rainwater harvesting is a feasible solution is one of the aims of the RAIN Foundation. This information on the potential of rainwater harvesting is essential to guide organizations in their implementation efforts, and is at the same time important as a strong lobby tool towards national and international governments.

Besides the current potential, a future oriented approach is required as changes in climate and socio-economic development would alter the need and the potentials for rainwater harvesting. In the years to come, temperatures will rise worldwide, but the weather will also become more extreme. Both prolonged droughts and floods, whether or not combined with sea level rise, are causing a shortage of clean drinking water.

In 2010 FutureWater and Deltares were asked by RAIN Foundation to develop maps indicating the potential for rainwater harvesting (RWH) for Mali, Senegal and Burkina Faso. FutureWater and Deltares used the same approach, but with a slightly different set of input parameters. This report describes the recommended approach to develop maps showing the potential for rainwater harvesting.

Moreover, this report builds further on these previous activities and describes a more comprehensive methodology including (i) a more advanced methodology, and (ii) including impact of climate change.

This report was written as a practical guideline to undertake rainwater harvesting mapping. A more scientific discussion on methods, assumptions and accuracy can be found in the scientific literature.

2 Conceptual Approach

2.1 Introduction

The potential for rainwater harvesting (RWH) depends on the physical conditions of an area and the socio-economic situation of people who live there. The latter depends on a broad variety of factors such as economic activities, educational level, organizational structure, institutional setting, gender issues, political choices and cultural background, amongst others. These factors are key to the success of implementing RWH and are at the same time very difficult to assess based on distant data sources and information. This report will focus on the first aspect of the potential for RWH: the conditions that can be assessed using spatial data sources.

In general two broad approaches to assess the potential for RWH can be followed. The first one, referred to as the **Parametric Approach**, is using a set of spatial data (either in vector or raster format) and developing suitability criteria for each of the datasets. By combing all the individual suitabilities a total suitability for RWH can be calculated. This method was used to create the RWH potential maps for Senegal, Mali and Burkina Faso.

A second approach, referred to as the **Dynamic Approach**, is based on a process model that captures the real processes of RWH. Based on daily rainfall and water demands the number of days when water shortage occurs can be estimated. These results can be calculated for different investment portfolios.

Both approaches have their strengths and weaknesses. The strengths and weaknesses of the Parametric Approach can be summarized as:

- Relatively easy to understand
- Depending by enlarge on expert knowledge
- Biased by setting suitability criteria
- Limited seasonal capacities
- Limited quantitative output
- No options to analyze investment portfolios

The Dynamic Approach has the following strengths and weaknesses:

- Very strong on seasonality aspects
- Very strong on climate change impact
- Unbiased output
- Based on investment portfolios (level of interventions)
- Easily adaptable to assess climate change

2.2 Parametric Approach

2.2.1 Need and potential success of rainwater harvesting

The parametric approach is based on using a set of GIS (Geographic Information System) layers, provide scoring factors to each of these maps and combine these scoring maps into the final map of the potential for RWH. Based on previous pilots the methodology described below has been proven to be not too complex and at the same time providing realistic results.

In general two types of information should be combined to assess the potential for RWH:

- **Need**: Where is the demand for additional water resources largest and most urgent?
- **Success**: Where can most water be harvested?

Each of these two factors can be divided into underlying maps. A wide range of maps can be used for the analysis, but concentrating on the most relevant ones and at the same time being practical on which data is relatively easily obtainable, the following maps are the most relevant ones:

- Need:
    - Population density
    - Land use
    - Access to other water source
    - Aridity
- Success:
    - Annual rainfall
    - Variation in rainfall
    - Soil drainage

Justification to use these seven maps can be summarized as follow:

- Population density: a higher populated area means that more people can profit from implementing RWH. If the objective of the study is to focus on remotely living people, this factor might be assigned a low weight
- Land use: more developed land use types, such as cropland and village and urban land uses, are better equipped for implementing RWH.
- Access to other water source: in locations where people have already access to clean water (piped, lakes, streams) the need for RWH is lower.
- Aridity: in dryer regions the need for RWH is obviously much higher. Aridity can be expresses as the ratio between precipitation (P) and potential evapotranspiration (PET): P/PET.
- Annual rainfall: higher amounts of rainfall means more water is available to store.
- Variation in rainfall: in cases where intermitted dry and wet periods exist, the need and success for RWH is higher.
- Soil drainage: better soil drainage means that water moves faster into the sub-subsurface, where it is less susceptible to evaporation and pollution. This is relevant for specific RWH as sand dams and underground storage.

The above seven types of information (maps) can be considered as the most relevant ones for overall planning purposes to identify areas potentially suitable for RWH. Obviously, more information could be added if specific questions have to be answered. Typical examples are the need for detailed information during design phases, or specific analysis on the best type of RWH to be applied in a specific region. Data (maps) that can be included for these more tailored assessments are: groundwater quality, GDP per capita, gender issues, depth to groundwater, and slopes, amongst others.

In case impact of climate change on RWH potential should be evaluated, the Parametric Approach can be used but adjusted data, reflecting climate change, should be used as input. In practice this means that adjusted rainfall maps and aridity maps should be used as input.

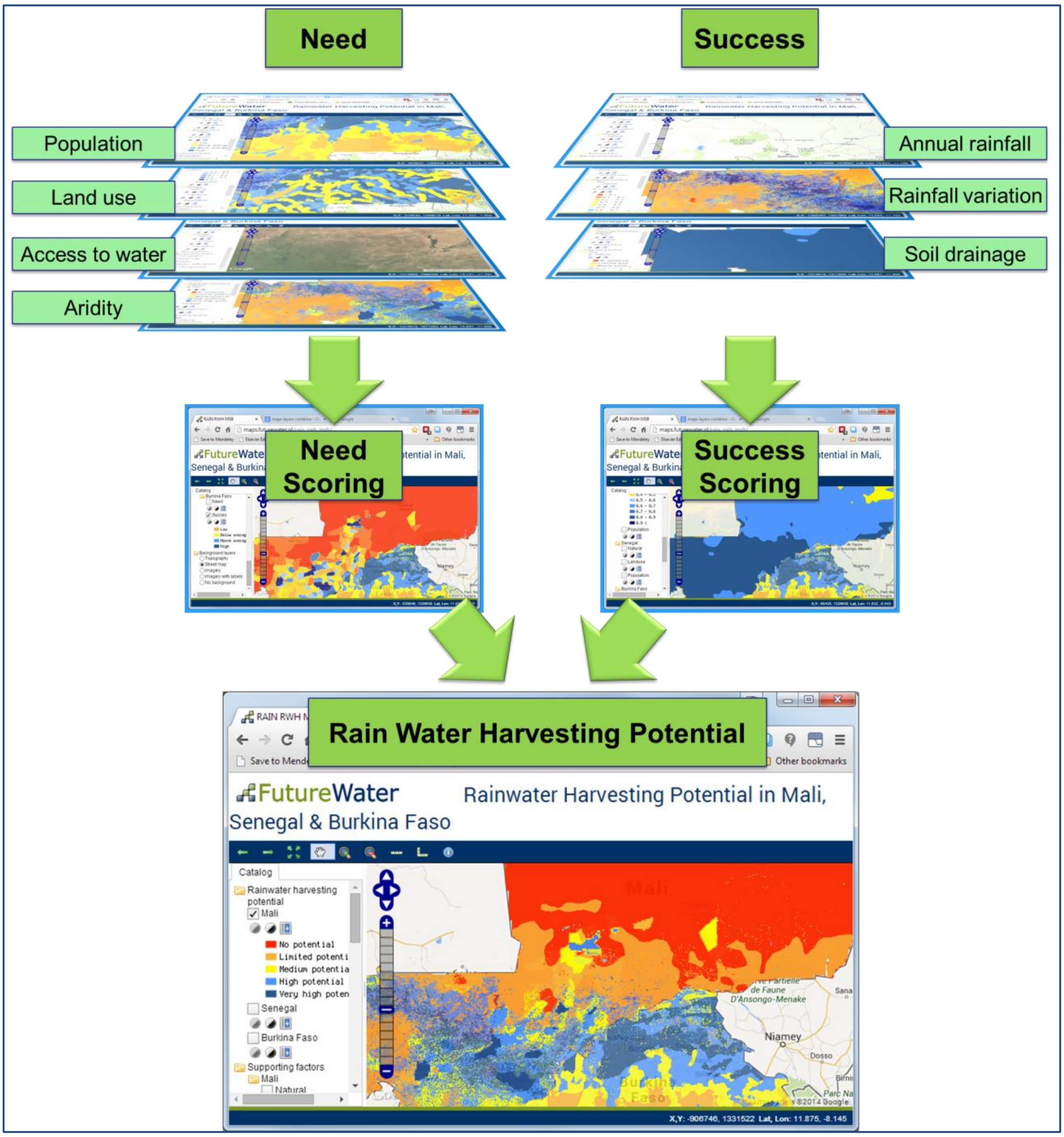


Figure 1. Flow chart to assess the potential for rain water harvesting based on the Parametric Approach using seven map layers.

2.2.2 Suitabilities scores

For each of these seven maps suitability scores should be defined in order to combine those maps. Currently, science has not been developed sufficiently to provide fixed scoring values. Moreover, there are debates whether the scores should be added to each other or should be multiplied. The advantage of multiplying is that limiting factors are well reflected in the final suitability map. A typical example is an area with hardly any rainfall (scoring = 0) the final suitability will become zero by using the multiplying approach, while the summation approach can still show significant potential based on the other factors. It is therefore advisable to use this multiplication approach.

The scoring values as has been used during previous studies in Burkina Faso, Mali and Senegal are presented below. Based on specific characteristics of other areas, these values can be altered.

- **Need**:
    - Population density
        - Population density between 0 and 100 people km^{-2} → Suitability 0.0 – 1.0
        - Population density higher than 100 people km^{-2} → Suitability 1.0
    - Land use
        - Open water → Suitability 0.0
        - Flood-prone areas → Suitability 0.1
        - Natural vegetation → Suitability 0.2
        - Forests → Suitability 0.2
        - Bare areas → Suitability 0.2
        - Rangelands → Suitability 0.3
        - Rainfed agriculture → Suitability 0.7
        - Irrigated lands → Suitability 0.8
        - Urban areas → Suitability 1.0
    - Access to other water source
        - Distance between 0 and 5 km → Suitability 0.0 – 1.0
        - Distance > 5 km → Suitability 1.0
    - Aridity
        - Aridity above 0.65 → Suitability 0.0
        - Aridity between 0.65 – 0 → Suitability 0.0 – 1.0
- **Success**:
    - Annual rainfall
        - Rain between 0 – 200 mm/y → Suitability 0 – 0.5
        - Rain between 200 – 800 mm/y → Suitability 0.5 – 1.0
        - Rain above 800 mm/y → Suitability 1.0
    - Variation in rainfall
        - The monthly precipitation variability expressed as the coefficient of variation (CV).
        - CV below 50% → Suitability 0
        - CV between 50% - 100% → Suitability 0 – 1.0
    - Soil drainage
        - excessive → Suitability 1.0
        - well → Suitability 0.8
        - moderately well → Suitability 0.6
        - imperfectly → Suitability 0.4
        - poor → Suitability 0.2
        - very poor → Suitability 0.0

A linear interpolation between the minimum and maximum data value and the suitability classes should be applied. A typical example of this is shown in Figure 2. In equation form this linear regression is:

$$Suitability = Suit_{min} + \left[\frac{Suit_{max} - Suit_{min}}{Data_{max} - Data_{min}}\right] \cdot [Data - Data_{min}]$$

In which:

Suitability: the final suitability score between 0 and 1
$Suit_{min}$: the minimum suitability score
$Suit_{min}$: the maximum suitability score

Data: the actual pixel value
Data$_{min}$: the minimum data value
Data$_{min}$: the maximum data value

The results of this analysis are two maps: one with the need for RWH and another for the potential success of implementing RWH. These two maps should be combined again by multiplying the two scores and will result in the final map of the potential to develop RWH (Figure 1).

Weighting factors migh be added to these suitability scores to reflect study specific preferences. A typical example is that in cases were study focus is on reaching the most remote population, the suitability class for “population density” might get a lower weight. The total formula to obtain the potential for RWH is:

$$RWH_{potential} = \prod_{1}^{n} (Suitability \cdot Weight)$$

In which

Suitability: the final suitability score between 0 and 1
Weight: weighting score between 0 and 1 (might be all set to 1)
n: number of suitability maps

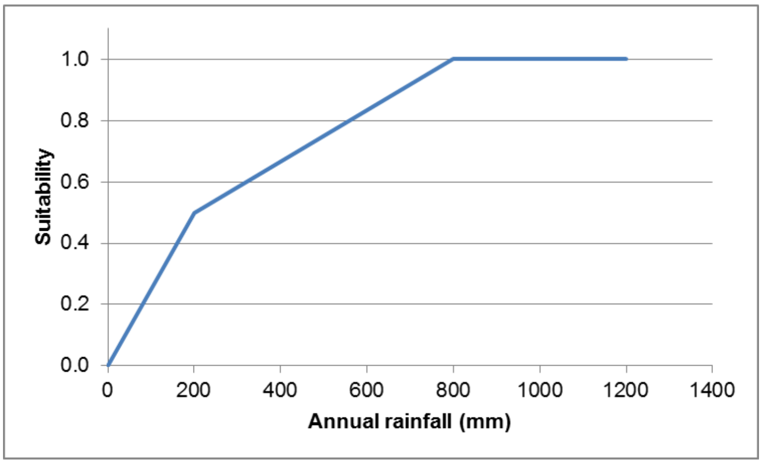


Figure 2. Example of how to transfer values into a suitability score. These analysis should be done for each pixel in the map using GIS software.

2.2.3 Data sources and data handling

A wide range of data can be used to undertake the analysis. In general, local data is often more accurate but more difficult to obtain. Below an overview of global public domain datasets that might be used in cases where local data is missing:

- Population density
  - CIESIN/FAO/CIAT gridded population of the world
- Land use
  - GLOBCOVER developed by European Space Agency
- Access to other water source
  - SRTM drainage networks

    - GLOBCOVER for lakes
- Aridity
    - Climate Explorer from CGIAR
    - CRU from University of East Anglia
- Annual rainfall
    - TRMM satellite from NASA, or
    - CRU from University of East Anglia
- Variation in rainfall
    - TRMM satellite from NASA, or
    - CRU from University of East Anglia
- Soil drainage
    - Harmonized World Soil Data Base (HWSD) from IIASA

All analysis should be done using a Geographic Information System (GIS). GIS allows the combination and visualization of spatial data into maps and can give advanced insight in spatial relations and help to answer spatial questions. The most applied GIS systems these days are ESRI-ArcGis and QGis. The first one is a commercial software package with very strong capacities but rather expensive. QGis is a very popular and widely used public domain package with similar capacities as ESRI. Some other GIS packages exist such as ILWIS, MapWindow, SAGA.

Finally, one should decide which spatial resolution and time resolution should be used to undertake the analysis. This depends on the objective of the RWH analysis: e.g. scoping, project preparation, and/or detailed design. For scoping studies a spatial resolution of 10 x 10 km^2 is recommended as this provides sufficient detail while at the same time data sets are widely available at this scale.

2.3 Dynamic Approach

2.3.1 Concepts

The Parametric Approach as described in the previous section works fine for most applications. However to include a higher level of accuracy and to cope with changing situations (climate, socio-economic) this approach might be somewhat to simplified. In those cases a Dynamic Approach can be followed.

The Dynamic Approach to analyse the RWH suitability is based on modelling the actual processes involved in capturing, storing and consuming rainwater. The analysis is undertaken at a daily (or monthly) time scale and at a raster cell resolution. For each day and for each raster cell the daily rainfall will be used as input. This rainfall will be captured and stored. From this stored water abstractions can be used for consumption. Also water might be lost by evaporation and/or leakage. A schematic overview is shown in Figure 3. Note that this capture can be of any form: roofs, soils, surfaces. Also storage can vary: tanks, ponds, soil water, sand dams. For this Dynamic Approach the following input is required:

- Daily rainfall in mm/d
- Water requirement per person per day
- Storage type: open or covered
- Storage type: leakage losses

- Investment portfolio:
  - Capture surface per person
  - Storage capacity per person

The latter two inputs can be seen as an investment scenario and can be altered to explore the impact of a certain investment portfolio.

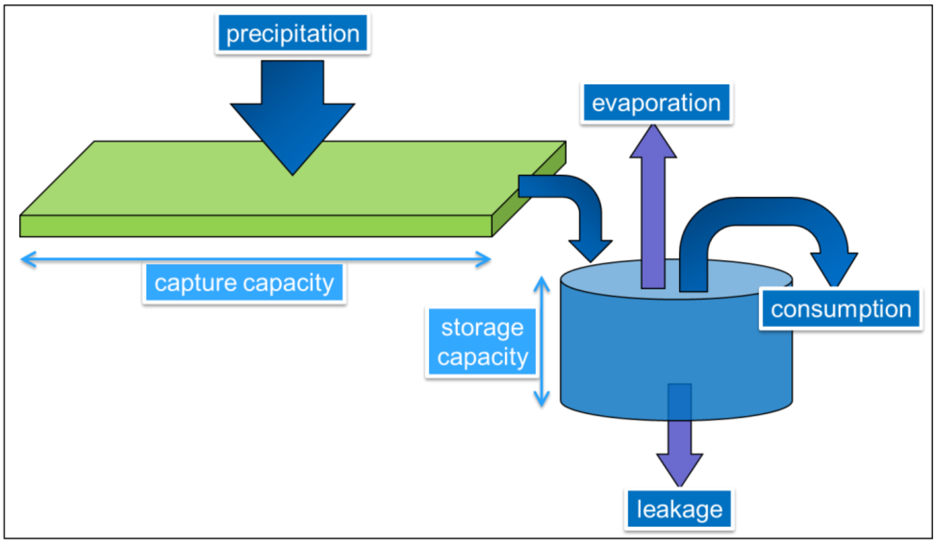


Figure 3. Schematic representation of the Dynamic Approach to assess RWH potentials.

In Figure 4 two examples are shown of this Dynamic Approach using data from Rubya (Tanzania) meteorological station. Depending on the capture surface per person and the storage capacity per person the number of days when RWH can be supplied is calculated. For the example when the capture area is 10 m^2 per person and the storage capacity is 2 m^3 a total of 12,000 liter per year (= on average 33 liter per day) can be supplied. More relevant is to calculate the number of days when the demand can be met. With this investment scenario 101 days per year sufficient water can be delivered.

For the second example (Figure 4, bottom) investments are bigger (capture surface of 20 m^2 and a storage capacity of 5 m^3). The resulting RWH delivery is also bigger: on average 346 days a year. Only at the end of the dry period water is short.

Other investment scenarios can be analysed as well and a typical example of results is provided in Table 1.

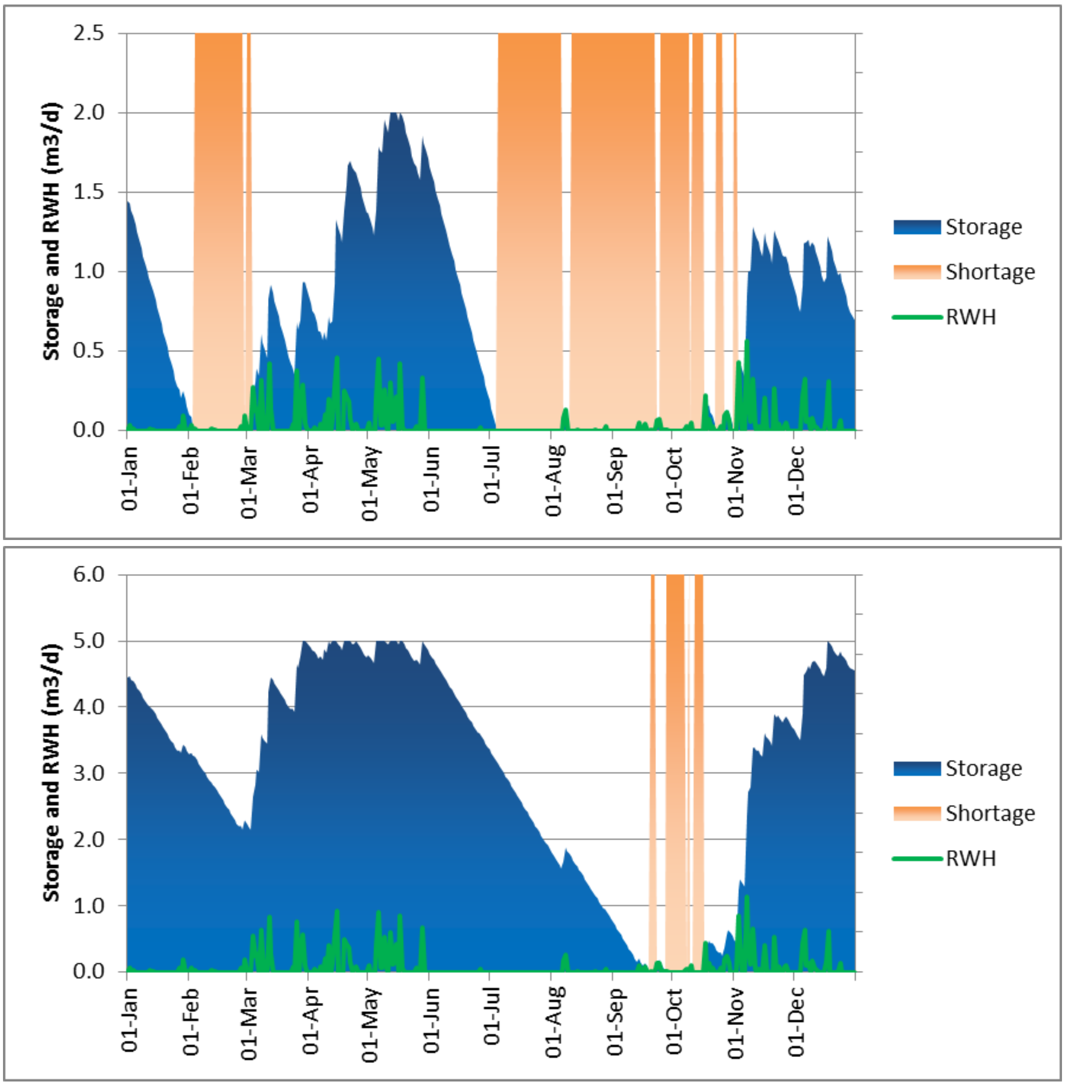


Figure 4. Example of Dynamic Approch to assess RWH potential using data from Tanzania (Rubya). Assuming a capture surface of 10 m^2 and a storage capacity of 2 m^3 (top) and 20 m^2 and 5 m^3 (bottom).

Table 1. Number of days in a year when RWH can be provided giver a certain capture surface and a storage capacity.

Storage (m3)	Surface (m2) 5	10	20
2	101	215	262
5	101	228	346
10	101	228	365

2.3.2 Implementation

The Dynamic Approach analysis should be undertaken on a spatial scale using raster grids. For each raster grid these calculations will be repeated, resulting in maps showing spatially for each grid what the RWH potential is. This potential is not shown as one map, but is a function of the selected investment scenario (=average capture surface per person and average storage capacity per person).

Since the Dynamic Approach is based on mimicking real-world processes, no weighting factors are required as in the Dynamic Approach. The previous mentioned investment scenarios can be seen as a decision making factor: what will happen if a certain capture surface and a certain storage capacity will be installed.

To undertake those analyses a standard GIS approach is not sufficient. Dynamic spatial analysis software is currently available. A typical example is the SPHY model that has been applied widely in Africa and Asia. SPHY is a raster based hydrological model built in Python and running in the PCRaster meta-language. SPHY is in the public domain. To use SPHY for these analysis changes in the code are required to include these RWH processes.

2.3.3 Climate change

To assess the RWH potential using the Dynamic Approach is relatively straight forward. By altering the precipitation and evaporation data to reflect the impact of climate change, the same analysis can be undertaken.

Climate change projections can be obtained from various sources preliminary based on the IPCC 5th assessment report and the associated CMIP5 database covering output of the major GCMs. Note that during the previous RHW potential mapping (in 2010 for Mali and Senegal) the A1B - IPCC 4th Assessment Report projections were used. Important is to note that instead of having one climate projection the IPCC defined a set of most likely scenarios (pathways) based on expected changes in greenhouse gas emission. The four Representative Concentration Pathways (RCPs) are RCP2.6, RCP4.5, RCP6, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m2, respectively).

These climate data should be downscaled to the resolution required for the RWH analysis (e.g. 10 x 10 km). Various downscaled procedures are available.

2.3.4 Data requirements

The data requirements of the Dynamic Approach are relatively low. The most relevant are daily precipitation and daily evaporation. The ranges of the investment portfolio (=average capture surface per person and average storage capacity per person) should be defined.

Obtaining observed daily rainfall records used to be a difficult process. However, the global science community has developed standardized historic climate data (gridded products) that can be used. Those data, often referred to as reanalysis data, can be obtained free of charge, but require some expertise to use. Previous analysis by comparing various reanalysis products revealed that the so-called Princeton data set is performing best.

2.3.5 Integration

The Dynamic Approach as discussed above generates the overall potential for RWH. Obviously, many areas do not require RWH as these might be connected to pipe systems, have access to surface water and/or groundwater. The results from the Dynamic Approach should therefore be overlayed by results from the simplified Parametric Approach that shows the need of RWH.

In other words, the Dynamic Approach assesses the potential for RWH for everyone, while the simplified Parametric Approach can be used to exclude areas that have no or limited need for RWH.

Finally, and as an extension, the daily/seasonal component can be strengthened to integrate the analysis above with a water availability assessment. Using a full hydrological model it is possible to identify areas where during certain time of the year sufficient water is available from streams, groundwater and/or lakes. Such an analysis will require substantial resources, but will provide an additional accuracy level. A typical example of such an analysis is the study on the irrigation potential of the Southern Nile countries using the SPHY model.

3 Planning and Resources

To undertake the RWH potential mapping as described in the previous chapters, time and resources are required. In order to assess planning and resources the following issues should be known:

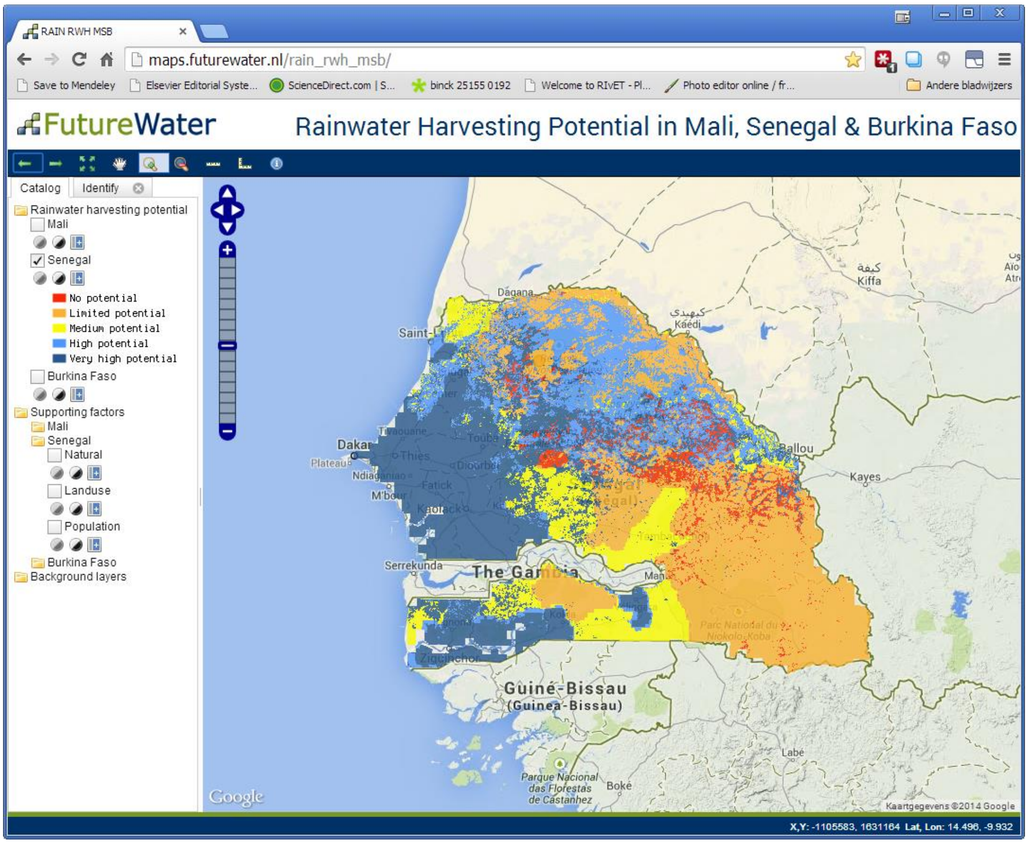
The following planning/activities are needed:

- Obtain the following boundary conditions information
  - Objective of analysis
  - Area/countrie(s)
  - Required spatial resolution
- Obtain spatial data:
  - Population density
  - Land use
  - Access to other water source
  - Aridity
  - Annual rainfall
  - Variation in rainfall
  - Soil drainage
- Define scoring factors for each data set
- GIS analysis
- Validation output and if necessary refine scoring factors and redo GIS analysis
- Communication, outreach, reporting
- Conversion to WebMapping tool

For the Dynamic Approach the following steps need to be added:

- Integrate RWH processes in SPHY
- Convert existing data into SPHY format
- Run SPHY for various:
  - Investment portfolios
  - Climate change scenarios.
- Overlay with maps showing need for RWH
- Output analysis

4 Appendix: Some example of output



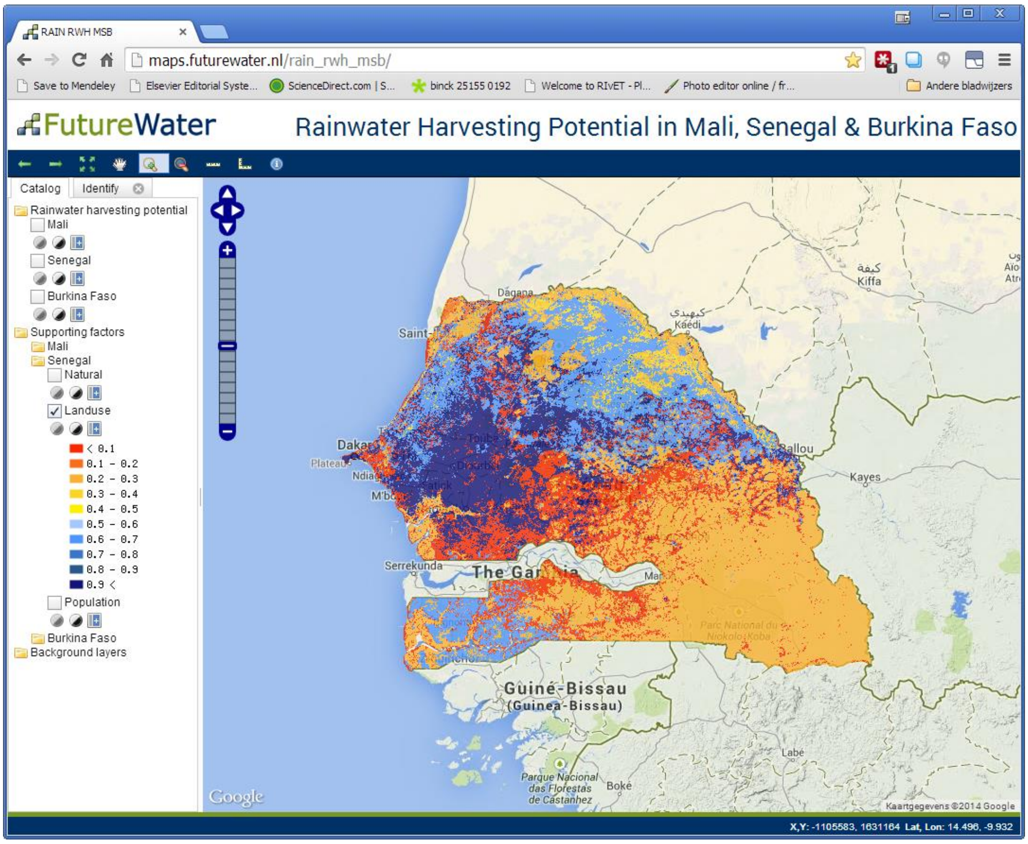


FIGURE: Potential for rainwater harvesting in Senegal (top) and example of one suitability factor on landuse (bottom) as displaid in the RWH Mapping Tool.

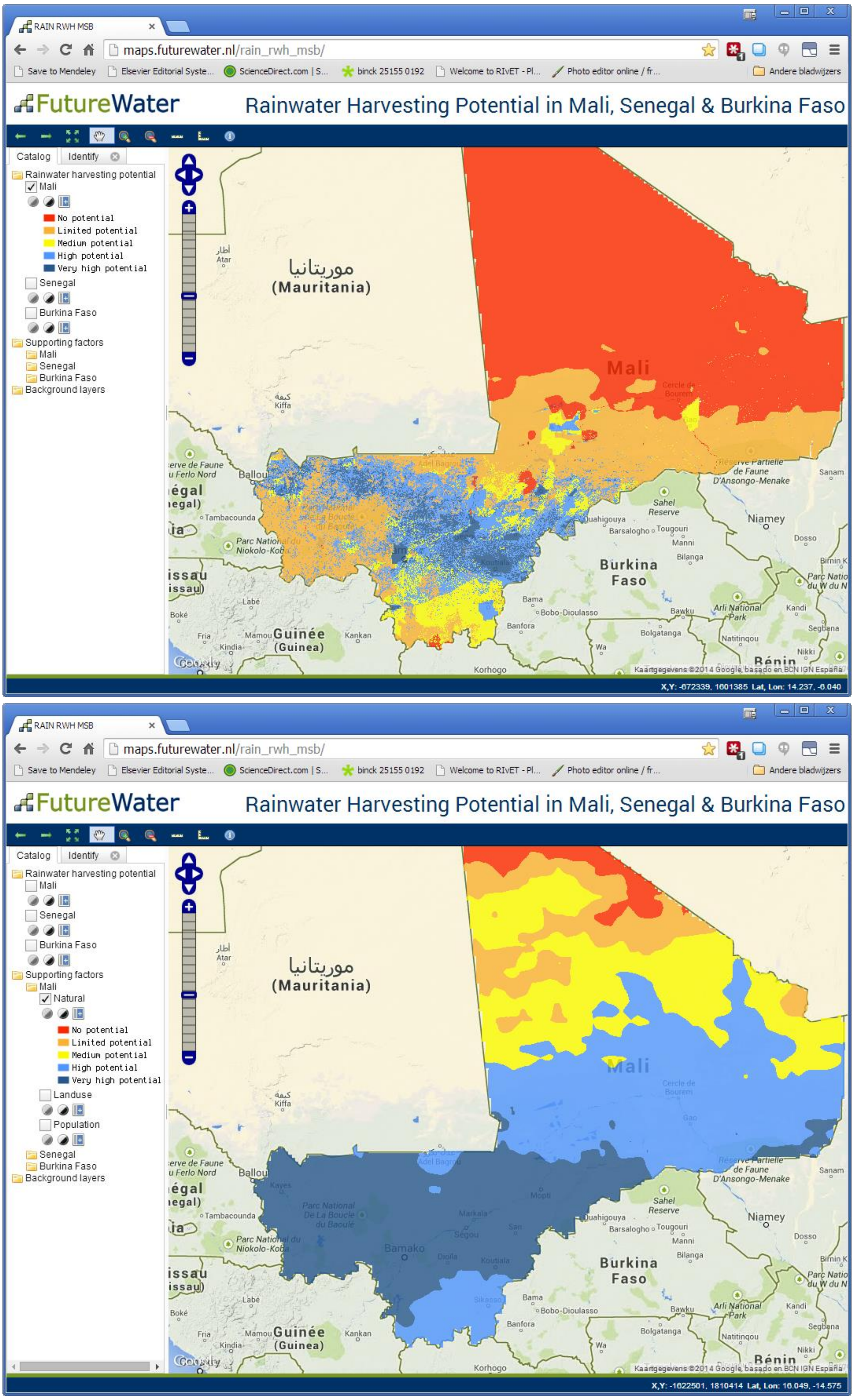


FIGURE: Potential for rainwater harvesting in Mali (top) and example of one suitability factor on physical suitability (bottom) as displaid in the RWH Mapping Tool.