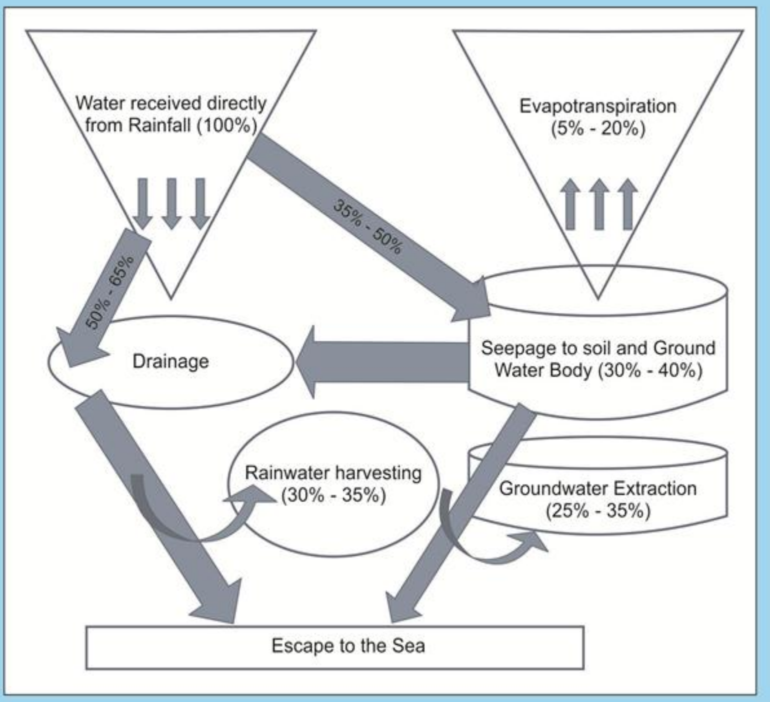
FECT Technical Report 2016-9

Developing System Dynamic Model for Estimating Water Scarcity in Maldives

Partners:

Foundation for Environment, Climate and Technology, Sri Lanka
Maldives Meteorological Services, Republic of Maldives



FOUNDATION FOR ENVIRONMENT & CLIMATE TECHNOLOGY

SYSTEM DYNAMIC MODEL FOR ESTIMATING WATER SCARCITY IN MALDIVES

DECEMBER 2016

Foundation for Environment, Climate and Technology
C/o Mahaweli Authority of Sri Lanka, Digana Village, Rajawella,
Kandy, KY 20180, Sri Lanka

Partners

Foundation for Environment, Climate and Technology, Sri Lanka

Maldives Meteorological Services, Republic of Maldives

Citation

Rathnayake Udara., Zubair Lareef., Wickramagamage, P. System Dynamic Model for Estimating Water Scarcity in Maldives, FECT Technical Report 2016-09, (Pages 22) Foundation for Environment, Climate and Technology Digana, Sri Lanka, December 2016

Abstract

Population growth, limited storage space for water, sea water intrusion and other socio-geographical factors have given rise to water scarcity in the inhabitable Islands of the Maldives. Water scarcity has been a major concern for the Maldivians for a long period of time. Limited land area restricts the freshwater quantities which increases the demand for freshwater. Therefore the availability is extremely limited. Since Maldives has a fluctuating pattern of rainfall and climate, it is important to make predictions to determine the available water from all kind of resources is sufficient to fulfill the water demand of the native Maldivians, tourists and to other industrial needs.

Water availability in a country is not constant and monthly fluctuation occurs most of the time. System dynamic models can be applied to identify the existence of water shortage in a country since it depends on time with complex interaction between variables. Vensim-software for creating system dynamic models is used to identify the water scarcity of each month in Malé, Maldives. All the variables depend on the inserted equation relevant to the island. Recharge and Runoff calculated using inserted precipitation climatology data whereas evapotranspiration is estimated in terms of two sections as potential and actual evapotranspiration.

Population and tourist data are extracted from statistical year book of Maldives 2013. Desalination water contribution is considered according to the reports and talks of MWSC. Rainwater harvesting water and water volume seepage to soil are taken as a percentage from runoff/drainage and recharge volume. The water scarcity availability is checked by the difference between water demand and water availability in Malé, Maldives. Most of the time, the shortage of water demand is fulfilled by desalination plants in the island. The nature of the freshwater, water demand, management, water availability and water scarcity availability according to the month are discussed for Malé Maldives. Results imply that the extractable freshwater availability is low during first 3-4 months relatively to last months. The rainwater harvesting water volume also estimated as a low value due to low rainfall during first few months, which leads to high water demand in Malé. Overall, the conclusion can be made that the shortage of water is high during first 7-8 months in Malé whereas it is low comparatively in other months.

List of Figures

Estimating Water Scarcity in Maldives

Shortage of freshwater in the coastal zones of many water-stressed countries is a threat mainly in small islands. By holding about 1200 small islands formed as sandy soil, coral atolls or limestone islands where surface water resources are non-existent and freshwater resources are very limited in Maldives. According to MEEW (2007), the Maldives agriculture sector is already under stress due to poor soil, limited arable land for cultivation and due to water scarcity, and changes in precipitation patterns will provide extra pressure. Rainfall deficiency over the last 18 years indicates that the Maldives islands suffer drought and flood events, drought events occurring every 9 years, while flood events occur once every 6 years. Climate change is expected to increase the severity, duration and frequency of weather related extreme events, such as droughts and floods. The Maldives water resources are vulnerable to these impacts. Since floods and drought events are the results of global, regional and local factors, they cannot be avoided. Therefore, mitigation and adaptation methods need to be identified.

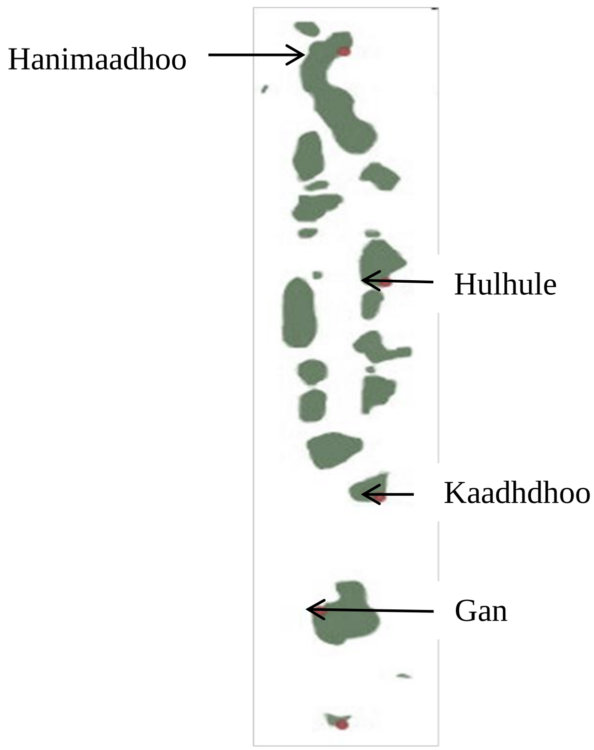


Figure 1: Weather stations of Maldives

1.1 Identify the Factors Affected to Water Balance

First, the important factors which affected to the water amount fluctuation are identified such as precipitation, evapotranspiration, infiltration, groundwater availability, runoff, water usage and escape water amount to sea.

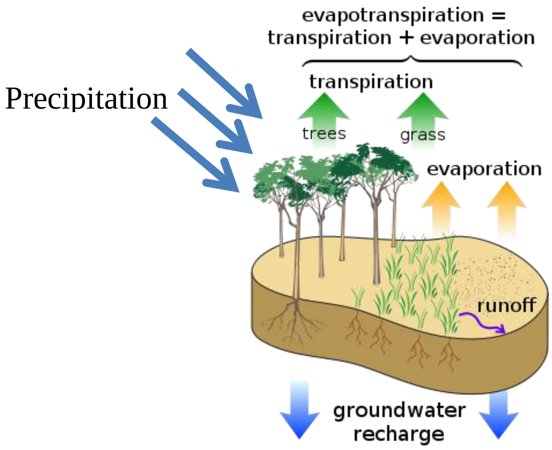


Figure 2: Simple diagram of water balance

Groundwater recharge is the balance between precipitation and evapotranspiration and the basic equation for water balance using the identified important factors can be introduced as follows (Bailey, Jenson, & Rubinstein, 2008);

Water availability for Usage= Precipitation-Evapotranspiration-Runoff

Since Maldives consists of bunch of islands, the freshwater lenses are occurred in coastal regions in many islands and essential for the local water supply. This freshwater area is used to extract groundwater in an island. The freshwater lens is depending on the width of the island (White, et al., 2007) (Bailey, Khalil, & Chatikavanij, 2014). There are no streams, lakes or any other natural water storage methods in any island of Maldives because of having limited space.

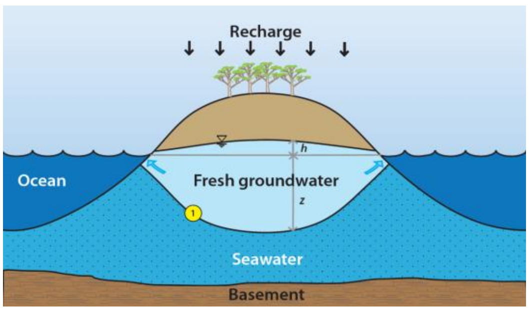


Figure 3: Diagram of Freshwater lens existence

The availability of water is limiting since most small islands depend on a single water resource, such as groundwater, rainwater, surface water or imported water.

Per capita consumption of freshwater in most small island countries is increasing. Growing expectation in larger villages suggests 100-150 L/capita per day is a more reasonable estimate (White, et al., 2007) .

The first desalination plant in Malé was installed in 1988 with a capacity of 200 m^3/day.

The water sector on Malé is operated by the Malé Water and Sewerage Company, together with Maldives government and two Danish companies. MWSC provided portable water supply to more than 80,000 residents of Malé using desalination plants (Maldives Water and Sanitation Authority , 2006). However, the desalination should only be considered when more conventional water resources are not existing, fully utilized or more expensive to implement (Falkland T. , 2002).

The population of the Maldives grows at about 1.76% annually and the government gives high priority to improve social and environmental challenges (Latheefa, Shafia, & Shafeega, 2011) With the increase in population and water consumption, the capacity has been increased steadily and is now 5 800 m^3/day (Food and Agricultural Organization , 2011). In Malé, 100 percent of the population has access to piped desalination water (Ministry of Housing, Transport & Environment, 2009).

The total municipal water withdrawal 5.6 million cu. Mtrs in Maldives whereas the industrial withdrawal was around 0.3 million cu. Mtrs in 2008. No information for water withdrawal for irrigation. All tourists' resorts have their own desalination plants (Food and Agricultural Organization , 2011). The water resources used by tourists for different purposes in Maldives can be classified as follows.

Table 2: Water resources used by the tourism industry for different purposes (Millar, 2002)

Purposes	**Type of Water**
Toilets	Salt Water
Shower	Desalination
Cooking	Desalination

Drinking (Tourist)	Bottled water
Drinking (Staff)	Rainwater (treated)
Gardening	Rainwater (tank)

1.2 Implement the Water Balance Diagram for Maldives

Following Natural Resources of Sri Lanka 2000 (Madduma Bandara, 2000), the water balance diagram is represented for Maldives. The variables and the corresponding estimations have done by taking data from various resources.

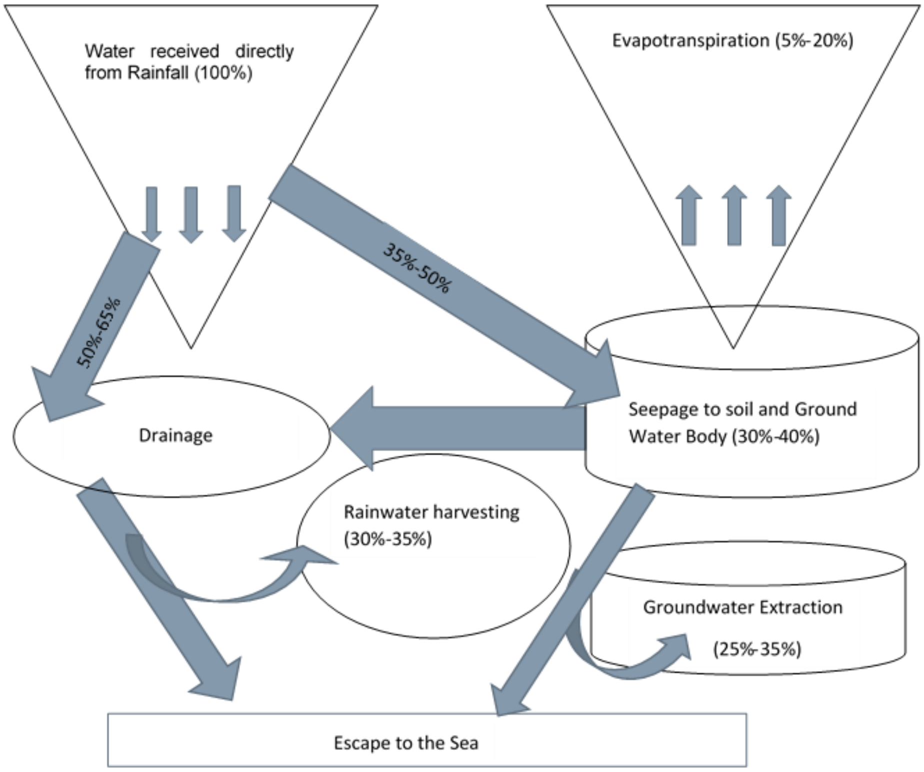


Figure 4: Schematic of water balance in Maldives

1.3 Data

Values to estimate variables using precipitation data are obtained. Only about 40% is taken from precipitation as the recharge volume whereas in typical limestone islands the recharge can vary between 25-30% (Bailey, Jenson, & Rubinstein, 2008). Also it was assumed that the recharge rate is 40% of the rainfall for high vegetation covered islands greater than the average and it is 50% for the low vegetation (citation Falkland 2001b). The vegetation coverage is roughly identified by using Google maps of Maldives. The difference between recharge volume and precipitation is taken as drainage.

The freshwater volume which can be extracted from the island aquifer is called as sustainable yield/ extractable water capacity and it is considered as 30% from average recharge volume. It represents the amount of freshwater that can be extracted without causing long term reduction (citation Falkland 2001b). From the recharge water amount, approximately 15% is lost due to the evapotranspiration and other amount seepage to soil. In the absence of filed data, 30% can be extracted as groundwater (citation Falkland 2001b). Remaining amount escapes to the sea together with the remaining drainage water. For the most part of Malé, drinking water comes from rainwater harvesting and bottled water. 30-35% of drainage water can be considered as rainwater harvesting water which use for different types of household usage. According to the duration of dry season, rainwater harvesting systems are not always well managed to ensure full capacity at the end of the rainy season (CH2M HILL, 2012). Porosity is taken as 30% (citation Falkland 2001b).

Monthly tourism data and population data in Malé is obtained from the statistics and monthly population growth is estimated using annual growth of Malé. The assumption is taken that the water usage per tourist is same as a Maldivian as 110L/day (Statistics Division of Department of National Planning, 2013).

The desalination water contribution is identified as 5000 m^3/ day in Malé according to MWSC reports (Ibrahim, Bari, & Miles, 2008).

The implementation of estimating water scarcity tool for Maldives is preliminary done without having much data. Water availability and water demand can be identify by inserting precipitation and evapotranspiration data for the relevant island and population data (Statistics Division of Department of National Planning, 2013) respectively. Using these created two variables; water scarcity availability is calculated in each month. The existence of water scarcity in each island by month can be obtained using this tool.

1.4 Methods

Since Maldives has four weather stations, comparing with the other countries a very low level, the data for each and every island cannot be obtained. Maldives has only four weather stations to represent all 1200 islands seem not easy and not accurate. Therefore interpolation techniques should be considered in Data library to identify the data in each island even without having a weather station. The interpolation functions such as Cressman and Weaver in Data library is used (International Research Institute).

Data library is used further to create output windows to identify the behavior of precipitation and temperature in each weather station.

Excel is used to identify the evapotranspiration estimations using Hargreaves equation (Hargreaves & Allen, 2003) and to obtain the behavior of precipitation, temperature and evapotranspiration together. This Hargreaves equation values have obtained using the monthly radiation values (Camerlynck, 2004) in Malé. To identify the actual evapotranspiration, the soil structure and the soil depth values considered together with potential evapotranspiration values obtained from Hargreaves equation. The soil storage capacity is estimated as 124 mm by multiplying available water capacity and soil depth (Nyvall, 2002). The available water capacity is calculated by taking the difference between field capacity and permanent wilting point whereas soil depth is considered as 1.5 m same as the low elevation above sea level of Malé ((Nyvall, 2002), (Ministry of Environment, Energy & Water, Maldives, 2007)

To calculate Freshwater lens area, following equations and methods are used (Zahid, 2011) (Falkland , 1994)

Freshwater lens Thickness (m) = (6.94*LOG(width of the island)-14.38)*Average Annual rainfall

The thickness of the freshwater lens is influenced by a number of factors such as island width, island geology, rainfall recharge rate, and evapotranspiration ((Bailey, Jenson, & Rubinstein, 2008), (Falkland , 1994), Falkand 2001b)

Freshwater lens area= (width of the island-250)*(length of the island-250)

Here the 250m is used assuming that the freshwater lens is existing 250 meters towards inner side of the island.

Groundwater availability= Freshwater lens thickness* Freshwater lens area*0.09

1.4.1 System Dynamic Modeling

System dynamics is a computer-aided approach which use to analysis and design complex models. It applies to dynamic problems arising in complex social, managerial, economic, or ecological systems. These dynamic systems characterized by interdependence, mutual interaction, information feedback, and circular interconnections between variables.

The system dynamic approach involves defining problems dynamically in terms of graphs, Identifying independent stocks or levels and their inflows and outflows and formulating a behavioral model with the capability of reproducing.

There are a lot of system dynamic modeling tools which used in different fields.

1.4.1.1 Estimate water scarcity using Vensim Software

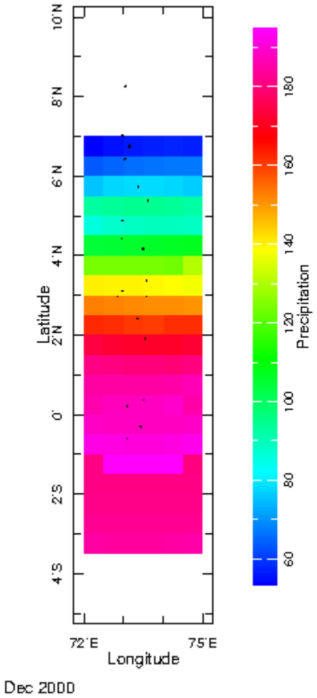
Figure 5: Logo of Vensim software

Vensim is a free software which managing large and complicated models. It provides Causal Tracing of structure and behavior and has Monte Carlo sensitivity, optimization and subscripting (Balali & Viaggi, 2015).

According to imported precipitation data, the other variables such as evapotranspiration, seepage, groundwater availability, runoff, water amount escape to the sea etc. can be estimated by changing and entering relative values in accordance. The causes for each variable separately have to be introduced carefully. Specific equation should be inserted to each variable; otherwise the model cannot be simulated. Vensim identify and modeling the variables regarding the equation which user has inserted. The equation can be inserted using imported data or manual constant values/rates.

There are lot of output windows and analyzing tools as inbuilt functions in Vensim. The tables, tree diagrams, loops, graphs can be obtain for each variable and can be displayed everything in one diagram. Software is easy in modeling complex models

1.5 Interpolate data using four weather stations in Maldives



Using Weaver function in Data Library, the interpolated data for all the islands in Maldives is obtained for precipitation for one month. The output window can be obtained for all the months separately. If time is changed as a range of years instead of a single month, the time series interpolated precipitation data can be obtained. In the same window, a running interpolated data series is obtained from the starting year to last year as monthly time steps.

Figure 6: Interpolated precipitation data for Maldives in Dec 2000.

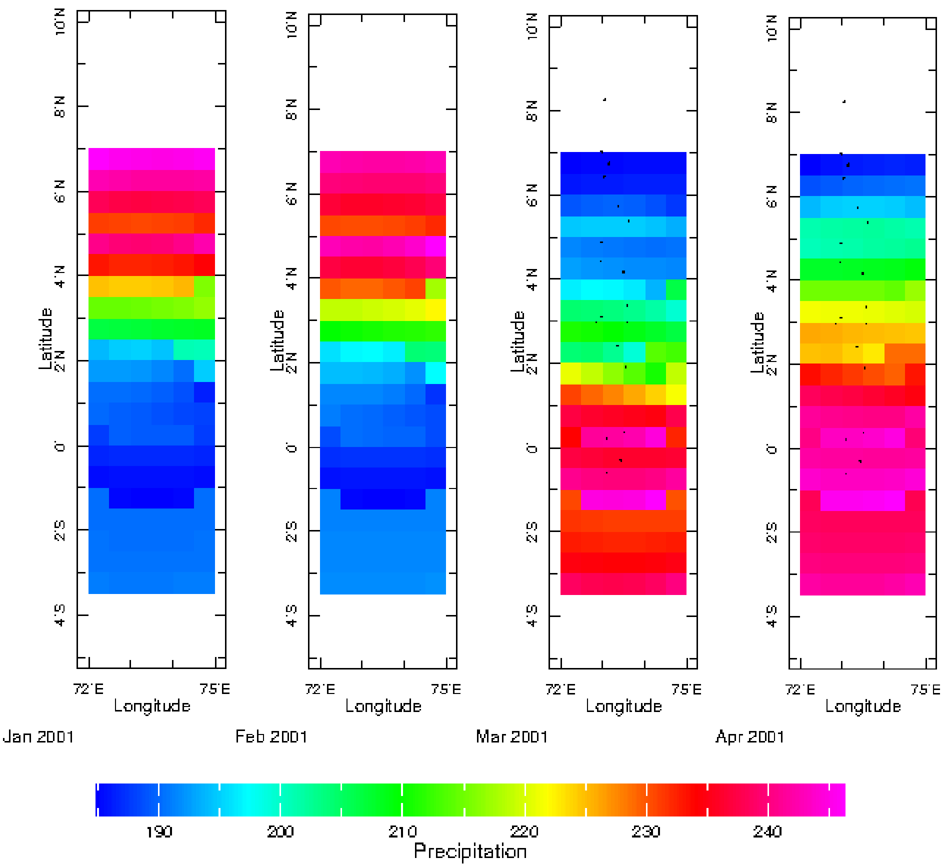


Figure 7: Time series fluctuation for interpolated precipitation data

When running from one image to another in the interpolated mapped data (as Figure 10) as months, it displays as a fluctuated data series with time.

According to the data and by applying the estimations, some outputs can be obtained for corresponding variables of water balance.

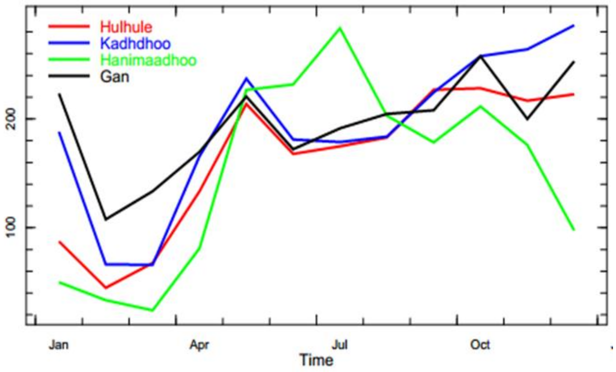


Figure 8: Yearly- climatology Precipitation data for each weather station in Maldives using Data Library 1960-2010

According to the figure 9, it can be seen that a peak of the precipitation is recorded in May in all the stations whereas October - November obtained highest precipitation.

Since no weather station is available in Malé- the capital of Maldives and Hulhule is very close to Malé (about 3km), most climate data in Hulhule weather station can be applied to Malé. For the study, Hulhule data are used as Malé island data such as precipitation, and temperature.

Table1: Rainfall and potential evapotranspiration values in Malé Maldives

Malé	**Rainfall**	**ET**
January	84	36
February	44	44
March	66	45
April	129	41
May	222	35
June	164	31
July	175	34
August	188	33

September	223	36
October	230	38
November	214	36
December	219	33

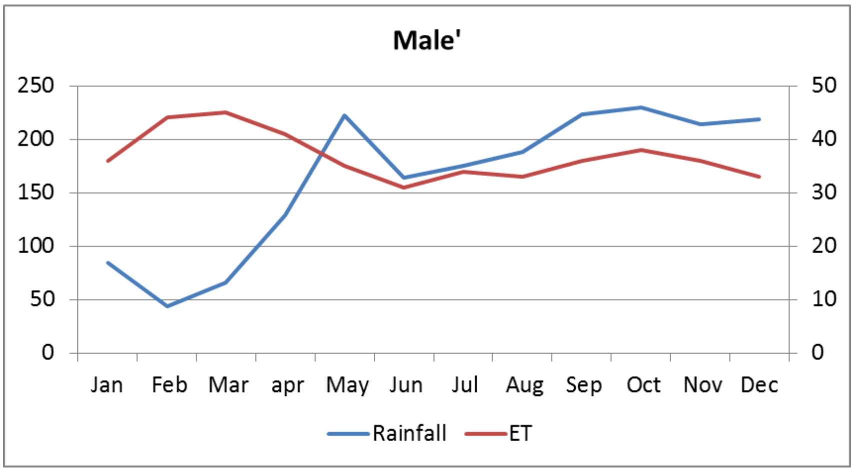


Figure 9: Precipitation and ET fluctuation according to the months in Malé

When the rainfall is high, the ET is low and vice-versa. But there are some other factors such as humidity and wind speed effected for Evapotranspiration.

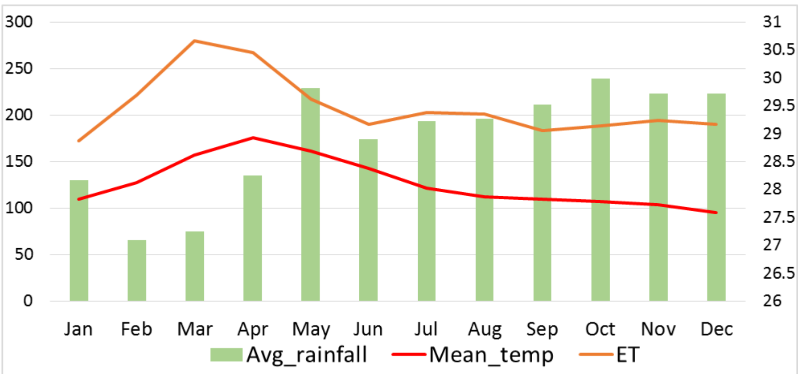


Figure 10: Monthly seasonality of mean temperature, mean precipitation and evapotranspiration for Maldives (based on the average of all the stations).

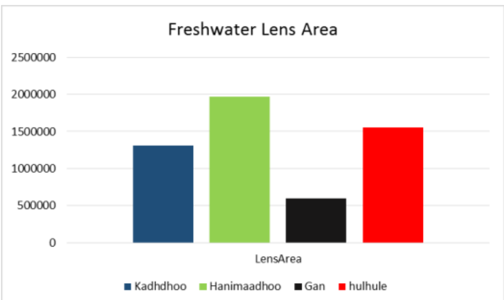


Figure 12: Freshwater lens area in each island using island width

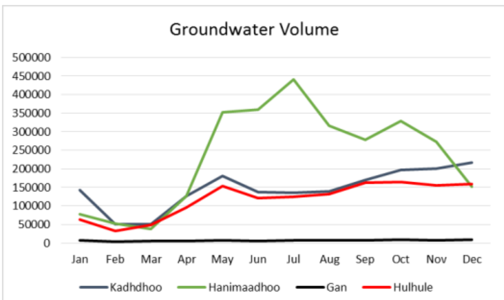


Figure 11: Groundwater availability in each island using Freshwater lens

Since the width of the island is small in Gan island, the groundwater availability is also low. The freshwater lens is much more huge in large islands than on small islands (Woodroffe, 1989)

Vensim PLE (Personal Learning Edition) is software used to build the models for Water resource that gets started in system dynamics modeling and inexpensive for commercial use. This is ideal for classroom learning of system dynamics.

For precipitation, data were imported using Data library data and simulation has done for 12 months Jan-Dec.

All the details regarding each variable can be grabbed quickly by a single graph contributing all the variables with each other relatively.

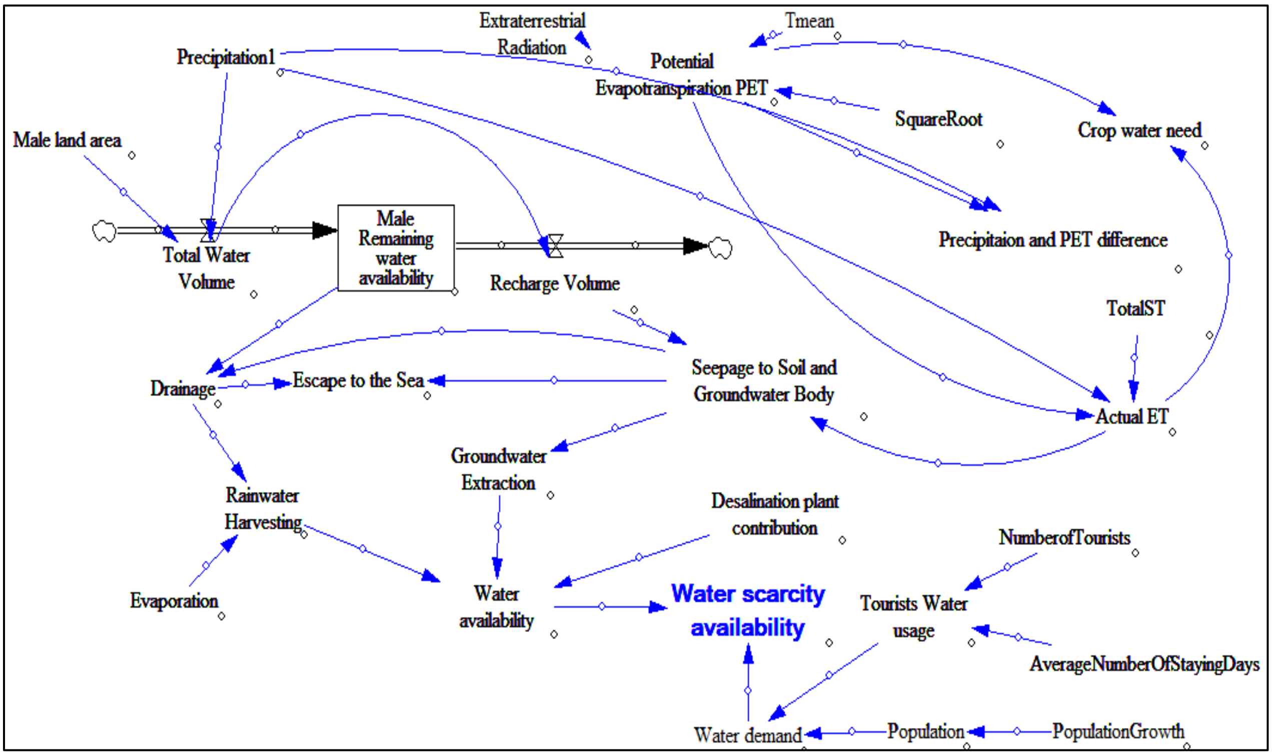


Figure 13:Vensim Diagram for water balance in Malé island.

The figure 15 shows the related variables, causes and other factors which affected to Malé water availability with imported precipitation data for 'Precipitaion1'. Water demand is calculated using the population size multiplying the average water usage for a Maldivian as 110L/day. The estimated "water availability" using precipitation data and calculated water demand is compared to check the water scarcity in Malé island. Water availability is estimated in terms of groundwater extraction, Rainwater harvesting, and desalination water contribution whereas water demand is accounted using tourist water usage and population in Malé island. The general travellers who travel from on island (in Maldives) to Malé is also estimated according to the statistics. (Statistics Division of Department of National Planning, 2013). The industrial and agricultural water usage should also be considered.

Evapotranspiration is calculated using potential and actual evapotranspiration with a long process of soil moisture calculations in terms of soil depth, Hargreaves equation (for potential ET), permanent wilting point, and field capacity and soil storage capacity.

The ‘test21’ is the latest simulated version of the created model. In each editing or changing, it is needed to simulate the model to obtain accurate outputs.

Output windows for some variables are as follows. By clicking the relevant variable and using analyzing tabs, the graphs, tables and other output windows can be obtained.

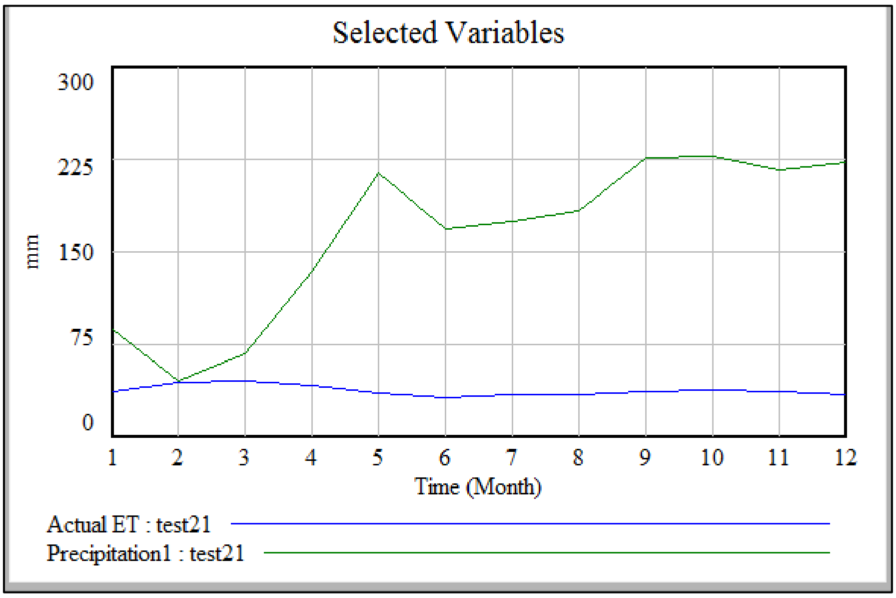


Figure 14: Output windows of Precipitation and ET in Malé island.

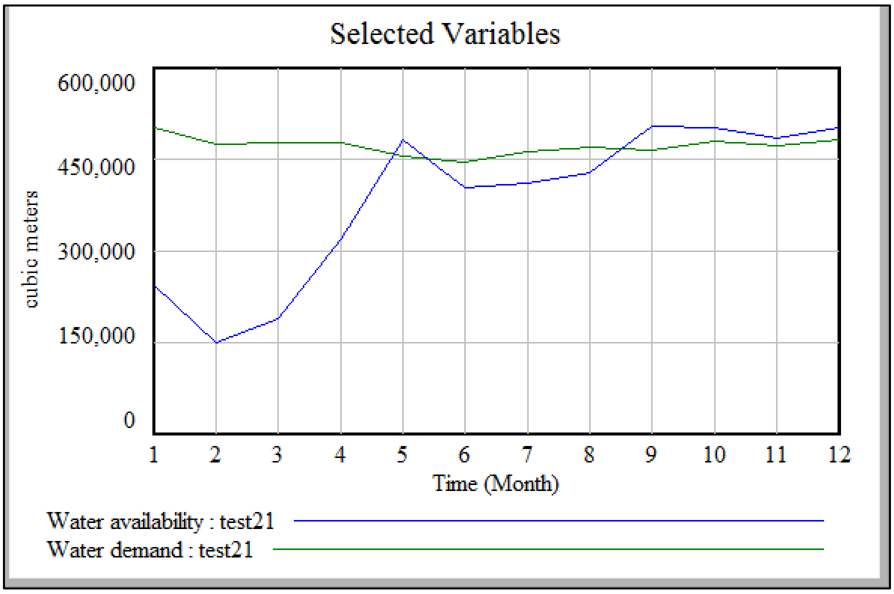


Figure 15: Output windows in Water availability and water demand in Malé island.

The related variables and its' behavior can be displayed as follows in one window.

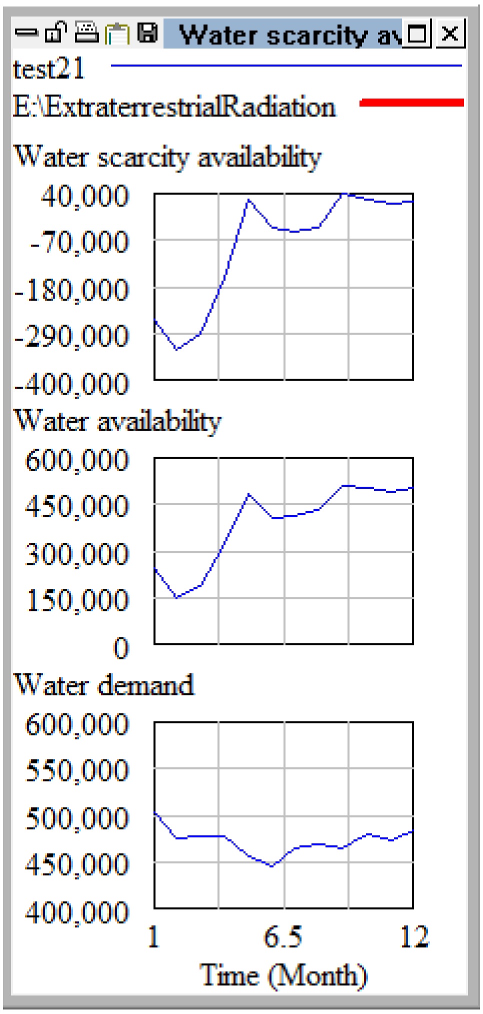


Figure 16: example of behavior of the water scarcity availability and its related variables in Malé island.

By selecting the "water scarcity availability" variable, the figure 18 is obtained.

The tree diagrams can also be obtained to see the relationship between the variables. One can easily identify what are the factors effected to a specific model variable and what are not.

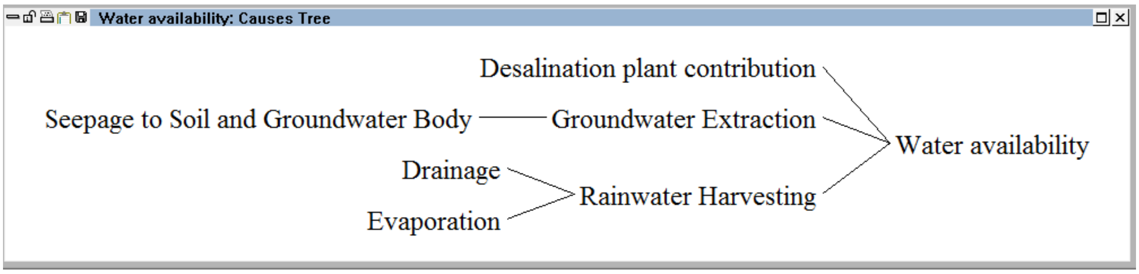


Figure 17: example of a tree diagram of water availability in Malé Island

The table of the values can also be obtained for each variable and the output gives the estimations automatically according the imported data and the created equation for the relevant variable.

Time (Month	"Water	Water scarcity a	--
1	scarcity	-259545	
2	availability"	-327451	
3	Runs:	-287704	
4	test21	-156971	
5	E:\Extraterrest	25626.3	
6	rialRadiation	-41851.7	
7		-52145.3	
8		-41868.8	
9		39277.1	
10		24048.6	
11		12626.4	
12		18049	

Figure 18: example of table with estimated values for water scarcity in Malé – cubic meters per month.

By modeling different types of simulations, the model comparison can also be done**.** All the simulated models can be displayed in one graph for further use and to make comparisons.

DISCUSSION

According to the preliminary outputs, the water scarcity availability can be displayed in negative and positive values indicating the existence of deficit of water in each month.

During first 4 months, negatives values can be identified for this variable whereas positive for other months. The water availability is increasing from 5th month to last month but somewhat low during first 4 months because of having low precipitation. The water demand is also high in first for months comparing with other months. Since water scarcity availability is calculated using the difference between water availability and water demand, the water scarcity availability differ accordingly.

Because of having few numbers of weather stations, the obtained data is also less. Interpolation techniques may not be that much accurate for all the islands since Maldives is located on the equator along north to south with varying climate from one
island to another.

CONCLUSION

According to the results, a preliminary conclusion can be made that there is a water deficit during first few months in Malé Maldives and during last months, there is no water scarcity according to the outputs. This might be because of the precipitation pattern in Malé, low in first months and quite high in last 6-8 months.

The storage capacity is identified as 124 mm and the actual evapotranspiration is estimated using this storage capacity and precipitation. The actual evapotranspiration is high in January-April and somewhat low in other months because of the behavior of precipitation and total soil moisture. The precipitation is also low during the particular first 3-4 months in Malé.

Since the seepage water amount to soil is calculated by taking the difference between recharge and actual evapotranspiration, in the months which the actual evapotranspiration is high, the seepage water is low. Negative values are there for February and March for seepage water amount due to the high volume of evapotranspiration in these months- which leads to negative groundwater extractable amount in February-March too. The rainwater harvesting water volume is very low during the first 3 months because of having low precipitation. The total water availability is also obtained as lowest for January-March relative to the other months since the low estimations of rainwater harvesting and extractable groundwater. In September, the available water amount is obtained as highest. The only monthly varying variables effected for the water availability are rainwater harvesting and extractable groundwater amount where the desalination plant water contribution is assumed as fix for the year. All together the rainwater harvesting water volume and extracted groundwater are controlling the monthly water availability in Malé, Maldives. The conclusion can be made that the water scarcity is exist in first 7-8 months in Malé because of giving negative values in those months whereas the problem does not exist in last few months since Maldives has high rainfall.

Due to having no data for streams or lakes and having sandy soil, escape water amount to sea is high which is estimated about 60% from both seepage water and drainage. This drainage is considered as the residual water amount in the island. This escape water amount to sea is very low in February and the values are considerably low in January and March also. The highest escape is recorded in September as 723734 m^3/month.

Considering the water demand section, the highest tourist water usage is as 123784 due to the highest recorded number of tourist in January whereas it is lowest in July.

Therefore, the water demand is very high in January comparing with the other months, in terms of tourists and Malé population water demand.

FUTURE DIRECTION

The water demand should be identified in terms of industrial water usage and agricultural water usage also. Furthermore, the general travellers should be included to the model from other island in Maldives to Malé to identify the water demand correctly. The data regarding groundwater wells should be considered separately and rainwater harvesting tank area should be included instead of assuming evaporation in these tanks. There are some errands to complete with soil structure issues and soil depths in Malé. Some other factors will also be considered not only the precipitation, soil characteristics and temperature but other factors such as wind speed, water availability etc. to identify the fluctuation of evapotranspiration.

The model can be implemented for other islands also in Maldives with relevant data.

In this tool, water scarcity is calculated in terms of water availability and water demand, but there may be some factors which water can be wasted and used in various ways, which does not accounted here.

Since there are no data for rainwater harvesting area, accurate data for agricultural land usage in each island and industrial water usage, the plans should be made to identify those statistics in Maldives or extract those data using shape files in GIS. The soil structure should be checked and soil depth should be identified in each island because of having special sandy soil structure in Maldives.

Although this tool is implemented only for one island, according to the inputs and data availability, relevant island statistics can be extracted.

REFERENCES

Bailey, R., Jenson, J., & Rubinstein, D. (2008). Groundwater Resources of Atoll islands: Observations, Modeling and Management . *ResearchGate* .

Bailey, R., Khalil, A., & Chatikavanij, V. (2014). Estimating transient freshwater lens dynamics for all islands of the Maldives. *Journal of Hydrology*, 247-256.

Balali, H., & Viaggi, D. (2015). Applying a System Dynamic Approach for Modeling Groundwater Dynamics to Depletion under diffrent Economical and Climate Change Scenarios. *Water*.

Camerlynck, J. (2004). *Modelling of Renewable Energy Systems in the Maldives.*

CH2M HILL. (2012). *Climate Vulnerability Assessment- islands of Dhidhdhoo and Hinnavaru, The Maldives.*

Falkland , A. (1994). *Climate, Hydrology and water resources of the Cocos (Keeling) islands.* Washington: National Museum of Natural History.

Falkland, T. (2002). *Overview report on Water Resoure Management.* Canberra: Pacific Regional Consultation on Water in Small Island Countries.

Food and Agricultural Organization . (2011). Maldives. *AquaStat*.

Hargreaves, G., & Allen, R. (2003). History and Evaluation of Hargreaves Evapotranspiration Equation. *Journal of Irrigation and Drainage Engineering*, 53-63.

Ibrahim, S., Bari, M., & Miles, L. (2008). *Water Resource Management in Maldives with an emphasis on desalination.* Malé: Maldives water and sanitatoin authority.

International Research Institute . (n.d.). *IRI/LDEO Climate Data Library*. Retrieved September 2015, from Interpolation Techniques: http://iridl.ldeo.columbia.edu/

Latheefa, A., Shafia, A., & Shafeega, F. (2011). *State of the Environment Maldives 2011*. Malé: Ministry of Environment and Energy .

Madduma Bandara, C. (2000). Water resources of Sri Lanka. In T. N. Foundation, *Natural Resources of Sri Lanka 2000* (pp. 75-109). Colombo: The National Science Foundation.

Maldives Water and Sanitation Authority . (2006). *Maldives water and sanitaion authority five year active plan 2006-2010.* GWP consultants.

Millar, J. (2002). *The Ability of the Maldives to Cope with Freshwater Scarcity via the Adaptive Capacity of its Political Economy.* London.

Ministry of Environment, Energy & Water, Maldives. (2007). *National Adaptation Program of Action(NAPA), Republic of Maldives.* Malé: Ministry of Environment, Energy and Water.

Ministry of Housing, Transport & Environment. (2009, March). National Adaptation to Climate Change. Malé, Maldives.

Nyvall, J. (2002, February). Soil Water Storage Capacity and Available Soil Moisture. Abbotsford, British Columbia, Canada.

Statistics Division of Department of National Planning, M. o. (2013). *National Bureau of Statistics Maldives*. Retrieved November 2015, from Statistical Year book 2013: http://planning.gov.mv/yearbook2013/yearbook.html

White, I., Falkland, T., Perez, P., Dray, A., Metutera, T., Metai, E., et al. (2007). Challenges in Freshwater Management in low coral atolls. *Jornal of Cleaner Production* , 1522-1528.

Woodroffe, C. (1989). Salt Water Intrusion into Groundwater: an Assesment of Effects on Small Island States. *Small States Conference on Sea Level Rise.* Malé: Ministry of Planning and Environment.

Zahid. (2011). *The influence of Asian monsoon variability on precipitation patterns over the Maldives.* (Doctoral Dissertation).