Characterization of Soil Depth to Coral Bedrock and Bedrock Roughness in Jozani Groundwater Forest, Zanzibar, Tanzania

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Abstract—Soils formed on coral terrain have a wide range of depths to coral bedrock and percentage of coral outcrops. Cliffs and other featuresof seawater abrasion, limited root zone, habitation and distribution of specific plant species are among the common conditions on Zanzibar coral landscapes.The current study was intended to characterize the relationship between soil depth to coral bedrock (SDCB) and bedrock roughness (BR) and determine features which are related to seawater abrasion at Jozani Groundwater Forest (JGWF). Such conditions and features have varying spatial distribution and magnitude which are likely to affect plant growth and species distribution in JGWF. The study area was divided into 320 grid points that were used as probing points for determining SDCB and BR. Global positioning system (GPS) model GARMIN ***e***trex 10 was used to locate grid points, while a long graduated stick was used to measure depths from soil surface to coral bedrock at each point. SDCB was calculated as an arithmetic mean of measured depths and BR as standard deviation of measured depths. ArcGIS 10.1 was used to map SDCB and BR of JGWF. Kichangani in Tumbatu Islet was visited to gather information related to abrasion that took place on coastal coral bedrock. Minimum values of SDCB and BR obtained from JGWF grassland were used to rank and categorize SDCB and BR in JGWF. Results from probes on the 302 grid points showed that JGWF has range of SDCB of about 0.35 - 1.4 m and above (>1.4 m) and BR of 0.1 - 0.4 m and above (>0.4 m).Trends of SDCB and BR values in JGWF were complex, decreasing towards the cliff on the West and towards North-end, but increased in the opposite direction. It was concluded from this study that there are complex relationships between SDCB and BR on coral land and that the relationships can be captured, ranked, and mapped. Such relationships affect plant growth and species distribution. Again, flat platform which was found at Kichangani and grassland of JGWF is an evidence of seawater abrasion on coral bedrocks.

Index Terms—Bedrock roughness, seawater abrasion, soil depth to coral bedrock, spatial distribution of plant species, Zanzibar

1 INTRODUCTION

ABOUT 50% of Zanzibar territory is occupied by coral terrain [1], [2]. Jozani Groundwater Forest (JGWF) which is within Jozani-Chwaka Bay National Park (JCBNP) is one of the coral forests formed less than 2 million years ago [2], [3]. The terrain of JGWF was exposed from seawater during gradual fall of sea level and the rise of corals [4]. According to [5], some parts of Tumbatu islet of Zanzibar Island is a raised Pleistocene reef platform similar to that of JGWF. Thus, the conditions in the JGWF are similar to those in some parts of Tumbatu Islet.

Coral terrains of Zanzibar are characterized by a wide range of coral outcrops and soil patches in between, and most of the soils which were developed on such terrain are shallow and polymorphic [1] (Plate 1 and 2). For decades, scholars including [1], [6], [7], [8] used the term "coral rag" to express the irregularities of the terrain. Basically, the term "coral rag" meant that the coral terrains of Zanzibar are irregular rocky (coral) surfaces, with uneven soil depths and irregular coral protrusions from un-aligned bedrock and the terrains cannot morphologically be properly characterized.

Plate1, Rocky coral terrain at Unguja Ukuu, Zanzibar, 2014. Occurrence of protrusions of various widths, heights and trends from the base of coral bedrock is referred to as bedrock roughness

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Plate 2, Coral terrain covered with polymorphic coral soilat Unguja Ukuu, Zanzibar, 2014. Soil depth variation has direct related with condition of coral protrusion underneath before the coral bedrock (bedrock roughness).

Plate 3a, *Calophyllum inophyllum* plant aged above 100 years in Jozani Groundwater Forest, 2014. Source of the plant age: Tahir Abass Haji, Botanist, Head of Jozani-Chwaka Bay Bio-sphere Reserve

Plate 3b, Wide base with radius of about 1.6 m of *Calophyllum inophyllum* plant which naturally fell before age of 50 years at JGWF, 2014. The plant was found in area almost with the same conditionsas the old plant in Plate 3a. The base of the root system had flat bottom, mixed with soil and some small (in size) stones which were protrusions from a table-like shape coral bedrock seen through a wide but shallow hole made by tree fall

Soil depth and condition of the parent materials are among morphological characteristics which are used to describe soil formation, development, and classification [9], [10]. These characteristics are among physical properties that affect plant rooting zone, plant growth and distribution [11], [12], [13]. Therefore, from these conditions it was suggested that in JGWF, plant species distribution and stability of plants of similar species depend on the depth of the coral bedrock and conditions of coral protrusions from the bedrock.

Tropical forests on coral terrains of Zanzibar are usually covered by plant communities of dry bushland thickets that constitute biomass of about 10 $tonha^{-1}$ [1], [3], [14], [15]. Although JGWF is among the coral terrains and/or surrounded by coral terrains, it has a wide diversity of plant species and biomass exceeding 50 $tonha^{-1}$, [3], [15]. Presence and stability of forest tree species are influenced by biotic and abiotic factors [16]. Vigorous growth of plant species (Plate3a) and natural tree falls of the same species (Plate 3b) are occurring in JGWF, something that has never been reported in other coral terrains. The assumptions for this anomaly include: (1) plant species growth trend and distribution are likely associated with conditions of coral outcrops, soil depth, and coral protrusions from the base of the coral bedrock, and (2) the conditions resulted from specific geological and biological processes (habitation of plant species) that happened before the emergence and during the early stages of JGWF development.

This study was therefore intended to characterize the soil depth to coral bedrock and roughness of the coral bedrock that influence plant roots' zoning and species distribution and, to some extent, give a clue on geological processes that occurred on the coral bedrock of JGWF.

2 Materials and Methods

2.1 Description of the Study Area

The study was conducted in Jozani Groundwater Forest (JGWF), an area which is located between Chwaka and Uzi bays (Fig. 1). The study area occupies the central part enclosed by coral forests and bush-land within Jozani-Chwaka National Park (JCBNP) [2]. The forest is found on the lowest part of Zanzibar Island that mainly comprises of Quaternary geologic formations predominantly limestone {3], [4]. According to [4], [17], JGWF is on a stream-like terrain running between Chwaka and Uzi bays. The forest has close to the ground surface water table which often emerges above the surface forming temporary marshes [18].Tumbatu Islet of Zanzibar Island is located about two kilometres off the Mkokotoni area [8], [19], [20]. Tumbatu-Kichangani has E524 550 and N 9 354 860 coordinates in UTM Zone 37S.

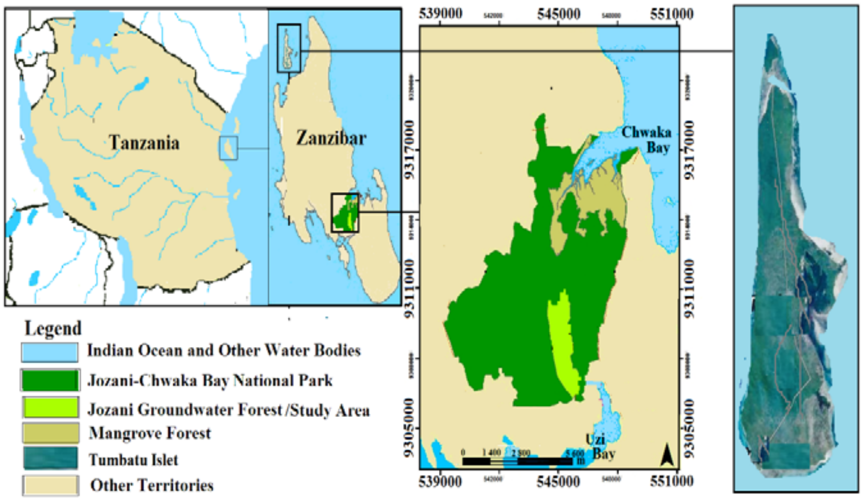

Fig. 1, Location map of Jozani Groundwater Forest and Tumbatu Islet. The map is based on AbassMzee of Department of Forest Non-renewable Natural Resources, Zanzibar, 2014

2.2 Long Stick Probing for Soil Depth to Coral Bedrock

Spatial patterns and geo-statistical studies use transect and grid designs [21], [22]. From table work, the study area was divided into 32 northern and 10 eastern grid lines making a system of 320 grid points. Global positioning system (GPS) GARMIN *e*trex 10 was set into UTM 37S coordinates system and was used to direct the study teams to the grid points for probing. The probe teams measured the depths from the soil surface to the coral bedrock. On the grid points along the northern grid lines, five long stick probes were done at one-metrelong interval between probes. The collected data were recorded in a field book with their respective grid points.

2.3 Estimating Soil Depth to Coral Bedrock and Bedrock Roughness

The data from five deep stick probes at a grid point were used to estimate the soil depth to coral bedrock (SDCB) and the mean height of protrusion from the bedrock (bedrock roughness (BR)). From the data, SDCB and BR were computed as an arithmetic mean and standard deviation of measured depths by Formulae (1) and (2), respectively.

$$\mathrm{MDB} = \frac{1}{n}\sum_{i=1}^{n} Xi \quad (1)$$

$$\mathrm{RB} = \sqrt{v}, \text{where } v = \frac{1}{n}\sum X_i^2 - \left(\bar{X}\right)^2 \quad (2)$$

Where, Xi; is measured depths (m) from the soils surface to the bedrock, n; is number of probes.

2.4 Ranking of Soil Depth to Coral Bedrock and Bedrock Roughness

Minimum values of SDCB and BR in the study area were used as the units for SDCB and BR ranking. The SDCB and BR values were ranked in two sets of five ranks with corresponding attributes for SDCB as: too shallow (1), shallow (2), moderately deep(3), deep (4), and too deep (5); while BR attributes were: smooth (1), a bit smooth (2), moderately rough (3), rough (4), too rough (5).

2.5 Visit to Tumbatu Islet for Study of Seawater Abrasion on Coral Bedrock

During reconnaissance in the study area, the effects of seawater abrasion were clearly observed on the Western border and the Northern end of JGWF. The main indicators of seawater abrasion were the presence of a cliff on the Western border and a flat platform and the remaining protruded coral rocks on the North-end. Therefore, a visit to Tumbatu Islet was made to capture detailed information on the effect of seawater abrasion from which the condition that occurred on the JGWF could be properly inferred and described.

Data Analysis

Excel spread sheets were used to compute mean soil depth to bedrock (SDCB) as an arithmetic mean of measured depths. Standard deviations of measured depths were used to estimate the length of protrusions from the base of the coral bedrock (bedrock roughness (BR)). Regression analysis was used to characterize the general existence and trends of percentage of counts of soil depth to bedrock (SDCB) and roughness of the bedrock (BR) of Jozani Ground Water Forest (JGWF). ArcGIS 10.1 was used to map SDCB and BR of JGWF. Descriptive analysis was used to relate SDCB and BR characteristics and condition of JGWF trough.

3 Results and Discussion

A total of 302 (94%) grid points were probed, soil depth to coral bedrock (SDCB) and bedrock roughness (BR) were captured. The rest 18 (6%) grid points were not accessible and hence omitted. Lowest values for SDCB (0.35 m) and BR (0.1 m) were recorded from the grassland which occupied the space between North-end of JGWF and Mangroveforest at

Chwaka bay. These values represented the shallowest depth and the least roughness. Hence, 0.35 m (SDCB) and 0.1 m (BR) were used as the unit values for ranking SDCB and BR (Table 1) in Jozani Groundwater Forest (JGWF). Table 2 shows the data collected from gridline N9 309 800 probing and the computed ranks of SDCB and BR. Arithmetic analysis of SDCB and BR ranks of data collected from 302 grid points is presented in Table 3.

TABLE 1
RANKS OF SOIL DEPTH TO CORAL BEDROCK (SDCB) AND BEDROCK ROUGHNESS (BR)

	Ranks				
	1	**2**	**3**	**4**	**5**
Soil depth to coral bedrock (SDCB) (m)	0.0 - 0.35	0.35 - 0.7	0.70 - 1.05	1.05 - 1.4	>1.4
SDCB Rank	Too shallow	Shallow	Moderately deep	Deep	Too deep
Bedrock Roughness (m)	0.0 - 0.1	0.1 - 0.2	0.2 - 0.3	0.3 - 0.4	>0.4
BR Rank	Smooth	A bit smooth	Moderately rough	Rough	Too rough

TABLE 2
RANKS OF SOIL DEPTH TO CORAL BEDROCK (SDCB) AND BEDROCK ROUGHNESS (BR)

Eastern (E) coordinates	**Outcrops %**	**Measured soil depths from soil surface to coral bedrock, m**					**Ranks**	
		Probes	**Min**	**Max**	**SDCB**	**RB**	**SDCB**	**BR**
544 400	10	0.86, 1.48, 1.04, 0.98, 1.60	0.86	1.60	1.19	0.23	4	3
544 600	0	1.26, 1.35, 1.50, 1.22, 1.63	1.22	1.63	1.39	0.15	4	2
544 800	0	1.40, 1.00, 1.60, 1.23, 1.42	1.00	1.60	1.33	0.20	4	2
545 000	0	1.85, 2.38, 2.02, 1.95, 2.30	1.85	2.38	2.10	0.20	5	2
545 200	0	2.40, 2.02, 1.98, 2.54, 2.42	1.98	2.54	2.27	0.23	5	3
545 400	0	1.92, 2.24, 1.76, 1.69, 2.33	1.69	2.33	1.99	0.26	5	3
545 600	0	1.53, 1.02, 1.73, 1.30, 1.36	1.02	1.53	1.39	0.24	4	3
545 800	0	1.22, 1.06, 0.98, 0.63, 1.02	0.63	1.22	0.98	0.19	3	3
546 000	20	0.44, 1.15, 1.42, 0.93, 1.32	0.44	1.32	1.05	0.35	3	4
546 200	>20	1.34, 0.65, 0.92, 0.68, 1.42	0,65	1.42	1.00	0.32	3	4

TABLE 3
PROBES AND CORRESPONDENCE PERCENTAGES OF SOIL DEPTH TO CORAL BEDROCK (SDCB) AND BEDROCK ROUGHNESS (BR)

	Number of Probes and Percentages of SDCB and BR											
SDCB/BR	**Smooth**	**%**	**A bit smooth**	**%**	**Moderately rough**	**%**	**Rough**	**%**	**Too rough**	**%**	**Total**	**%**
Too shallow	26		3		0		0		0		29	
%		8.6		1.0		0		0		0		**9.6**
Shallow	8		8		5		0		0		21	
%		2.6		2.6		1.7		0		0		**7.0**
Moderately deep	6		35		34		25		0		100	
%		2.0		11.6		11.3		8.3		0		**33.1**
Deep	4		45		22		16		13		100	
%		1.3		14.9		7.3		5.3		4.3		**33.1**
Too deep	0		23		20		4		5		52	
%		0		7.6		6.6		1.3		1.6		**17.1**
Total	44		114		81		45		18		302	
%		**14.5**		**37.7**		**26.9**		**14.9**		**5.9**		**100**

3.1 Rational of Soil Depth to Coral Bedrock and Bedrock Roughness

Figure 2 shows that JGWF terrain has complex trend of SDCB and BR. The terrain mainly consists of moderately deep to deep SDCB and smooth to moderate BR.

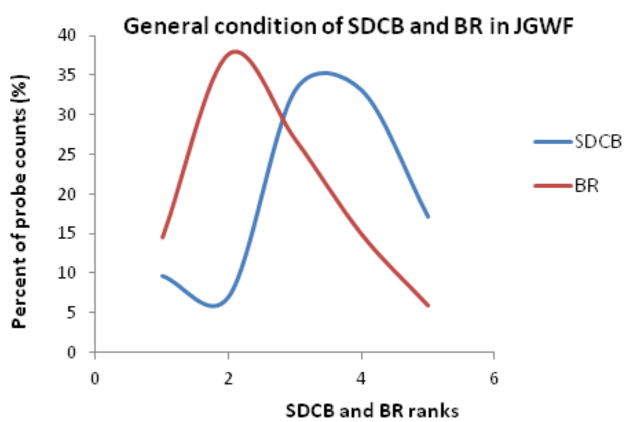

Fig. 2, General existence and trends of percentages of counts of soil depth to coral bedrock (SDCB) and bedrock roughness (BR) of Jozani Groundwater Forest, 2015

3.2 Spatial Distribution of Soil Depth to Coral Bedrock and Bedrock Roughness

Figure 3 shows that the North-end of JGWF is dominated with shallow and smooth SDCB and BR ranks, respectively. Such spatial distribution of the ranks implies that the area favors grasses and small plant speciesonly. The rest of the areas with complex distribution of a mixture of SDCB and BR towards the South-end and East of JGWF favour more plant species including bigger plants. The protrusions that were above the soil surface (outcrops) were found mainly in the Eastern borderline of JGWF and the outcropping increased as the area approached the coral forest East of JGWF. However, this study did not relate values and ranks of SDCB and BR to coral outcropping. Shallow soil depths were also found in areas where the outcrops exceeded 20%. Patches which were too deep were not recorded during the probing but were observed in some areas close to the Southern end of JGWF. Shallow depth to coral bedrock (SDCB) and smooth (BR) were also found as patches in several points especially where bigger plants fell down before reaching climax/old age. This condition implies that such combination of SDCB and BR tended to destabilize bigger plants when they grow beyond the stable-height or when the branches incline beyond stability-zone. However, the extent of the incidents and conditions that led to the falling of trees need further studies.

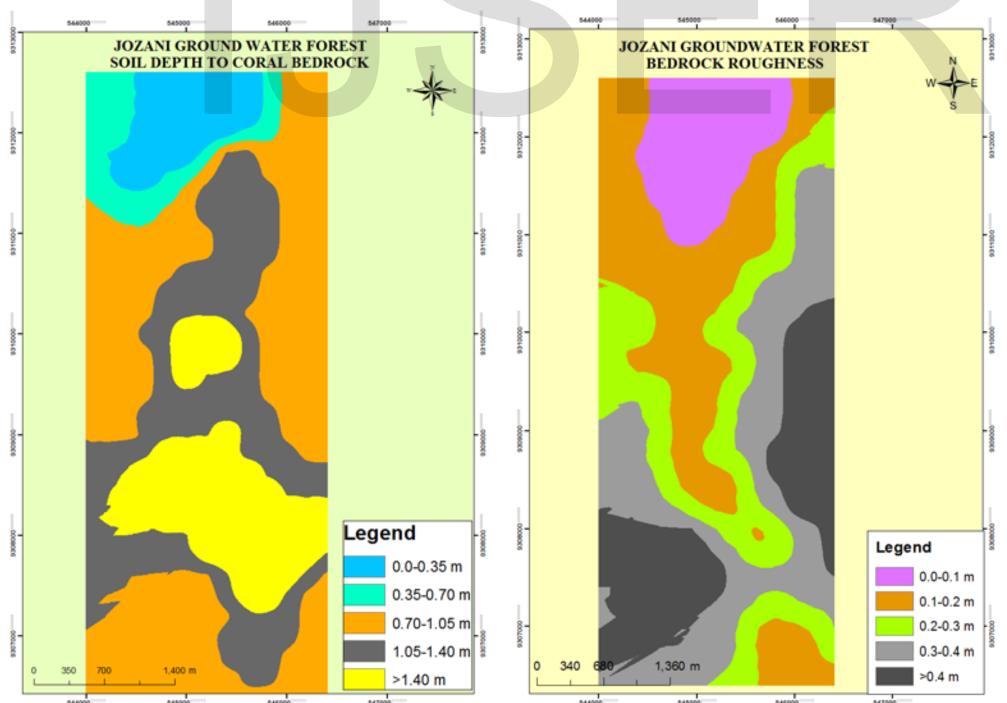

Fig. 3, General trends of soil depth to coral bedrock (SDCB) and bedrock roughness (BR) of Jozani Groundwater Forest, 2015

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3.3Seawater Abrasion on Protrusions off the Coral Bedrock

Marine terraces of Zanzibar consist of coral limestone and are indicative of marine and tectonic origin [5]. The conditions of SDCB and BR in JGWF were found to be related to seawater abrasion before the emergence of JGWF.Information from the study site (Jozani Groundwater Forest (JGWF)) and the study visit to Tumbatu Islet revealed evidence of seawater on the protrusions of coral bedrock in JGWF. This study found that during the early stages of sea water level fall, and rise of coral terrain, the western part (before the cliff) of JGWF lay along the coastal line and was affected by seawater movements from the east, north (Chwaka), and south (Uzi). The coral bedrock had more protrusions of different sizes and conditions, and the protrusions were subjected to strong sea water abrasion. Abrasion in JGWF terrain occurred in several stages, but the magnitude of abrasion declined with time. Such abrasion resulted into cliff formation which currently acts as west borderline running in North-South direction and separating the JGWF from the higher elevated coral terrain above it. As the fall of sea water level and the rise of coral land continued periodic abrasion processes ledto the formation of Jozani trough with small irregular terraces on the east of JGWF (Fig. 4).

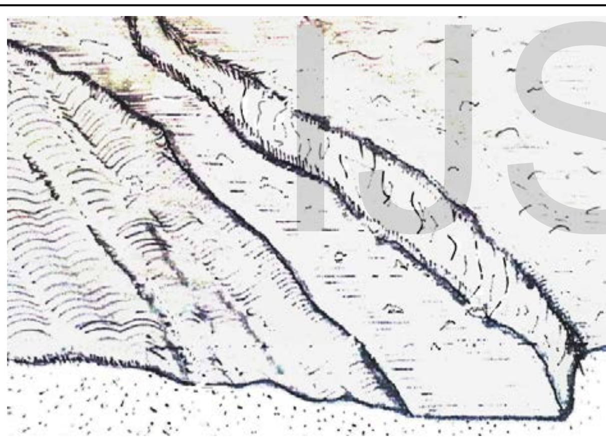

Fig. 4, Sketch of coral bedrock of Jozani Groundwater Forest in North-South (bottom-up) direction. This sketch of JGWF shows a trough-like terrain of JGWF in relation to elevation map of JGWF [24]

According to [23], a sort of cliff adjacent to the sea shore platform limits the movement of sea water across the cliff. Similarly, seawater abrasion forces remained active and abraded the coral protrusions between the cliff on the West and terraces on the East.

3.4 Effects of Abrasion on Jozani Groundwater Forest Coral Bedrock

According to [25], the rate and mode of abrasion are highly dependent upon the position of the rock and the forces that worked on it. In the case of JGWF terrain, the abrasion process led to the formation of various BR values which increased towards the South-East and decreased towards the North-West of JGWF.

Terrain conditionsas shown in Fig. 3 (Section 3.2) indicate that abrasion took place much longer and were stronger in JGWF areas with a minimum RB. Such abrasion on coral bedrocks results into a formation of flat coral platform [23], [26]. As an evidence of the effects of abrasion on JGWF coral bedrock, Plate 4 shows flattened coral bedrock at Kichangani seashore in Tumbatu Islet. Plate 5 confirms that similar magnitude of abrasion took place at JGWF grassland.

Plate 4, Flat area with coral bedrock used as football play ground during low tides at Kichangani, Tumbatu Islet, 2015

Plate 5, Flatland covered by *Paspalum vaginatum* at North-end of Jozani Groundwater Forest, 2015. Remain (whitish) almost flat corals is the evidence of coral bedrock underneath and sea water abrasion

3.5Relation betweenSoil Depth, Bedrock Roughness and Vegetation

From the above conditions of SDCB, BR and the trend and magnitude of abrasion on coral bedrock, this study found that abrasion in JGWF area stopped when sea water run between terraces (on the east) and cliff (on the west) attained its minimum velocity. Meanwhile, pioneer plants which were dominated by *Paspalum vaginatum* [12], [27] by then were regenerating from seashore edges (Plate 6a). Furthermore, Plate 6b upholds the fact that JGWF areas with moderate and above ranges of RB are exposed to either less force or shorter periods of abrasion. Plant inhabitation was accelerating from the South-Eastern area of JGWF towards the North-West. The accumulation of plant residues filled pot-like spaces between several partially abraded protrusions that rose from the coral bedrocks. Thereafter, other plant species including salt-tolerant and non-salt tolerant higher plants were growing, following a similar trend of pioneer species. These conditions on one hand have a direct relation on soil depth that affects root growth, plant stability and species distribution; and on the other hand contributing to the elevation trend of JGWF.

Plate 6a

Plate 6b

Plate 6a, Grassland at North-end of Jozani Groundwater Forest (JGWF) covered by *Paspalum vaginatum* and few erected coral remains (stand still as coral outcrops) beside strong abration on the surrounding area. Plate 6b, shows a gradual increase of coral outcropping with a gradual change of plant species towards inner parts (the South) of JGWF

4. Conclusions and Recommendations

The study concluded that flat platform with grassland had minimum values of soil depth to coral bedrock (SDCB) and minimum protrusions from coral bedrock (bedrock roughness (BR)). As there were no abrupt falls in sea water level and/or rise of corals, for a long time seawater movement was thus limited towards the West and the East, but moved freely between the North and the South (Chwaka and Uzi) bays. A continued seawater abrasion led into the formation of Jozani trough between the East and the West cliffs. When seawater velocity on the trough was at its minimum, this condition was conducive for pioneer plant species habitation, from which organic sediments were the basic soil components. The process led to soil formation with various ranges of SDCB and BR values. These ranges of SDCB and BR are the ones which make JGWF terrain to have polymorphic soils, with wide range of outcrops and rough surfaces of coral bedrock. Thus, it is concluded from this study that the condition of SDCB and BR affects root growth, stability of bigger plants and plant species distribution in the JGWF. Furthermore, it is concluded that the flatland which is found at Kichangani in Tumbatu Islet and that on the grassland between JGWF North-end and mangroves are the evidence of the prevalence of severe seawater abrasion on coral bedrocks in the sites.

From this study it was recommended that the values of soil depth to bedrock (SDCB) and bedrock roughness (RB) can be used in soil volume calculations, in the characterization of plant root zone conditions and for describing the productive capacity of coral lands. The values are good indicators and/or inputs for planning and implementing agronomic, engineering and environmental projects and related works or studies.

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