A METHOD FOR CONSTRUCTING RESERVOIR AREA-STORAGE-ELEVATION CURVE USING SENTINEL-1 RADAR REMOTE SENSING IMAGE

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ABSTRACT: Reservoir elevation-area-storage (Z-F-W) curves are used for regulating discharge during the flood season and allocating water supply in the dry season. According to the latest statistics of the Directorate of Water Resources, Vietnam has about 6636 reservoirs, of which the Z-F-W curves of 474 reservoirs have been already identified and the remaining 6162 reservoirs have no information on the Z-F-W relationship. In order to regulate or allocate water in these reservoirs, operators assume a linear relationship between the area or storage and elevation, varying from the dead to normal water level. By mean of this method, calculated area and storage are subject to large errors but they are still used to operate the reservoirs. In fact, even the reservoirs attributed with the Z-F-W relationships, but the relationships may not be stationary as the reservoirs were built a long time ago with continuous sediment deposition and erosion processes that altered the reservoir bathymetry; as a result, these relationships also require corrections.

This paper introduces a method for constructing the Z-F-W curves of the reservoir with the capacity larger than one million cubic meters in Ha Tinh province of Vietnam using Synthetic Aperture Radar (SAR) Sentinel-1 remote sensing image. The scope of the paper includes such steps as (i) pre-processing Sentinel-1 image; (ii) developing image interpretation algorithms for automatic processes for determining the reservoir area using backscattering points of radar image polarization on dry, moist and wetland; (iii) eliminating noise and correcting pixel values which represent water but they are interpreted as not water and vice versa; (iv) implementing methods to validate the interpretation results of the reservoir Z-F-W relationships: conducting field survey to determine the boundary of water surface by Global Positioning System (GPS) and comparing with that determined using image interpretation, method of comparing the values of reservoir capacity which are determined based on reservoir Z-F-W curves with the values of reservoir storage which are interpreted from images, then determining interpretation errors and methods for overlaying the interpretation results with super high resolution optical images at the same time. The study results are fundamental for further completion of the method for constructing the Z-F-W curves using free satellite images and opening a new solution for such needs as flood mapping, water resource inventory and so on.

1. INTRODUCTION

Vietnam has 108 basins with about 3450 rivers and streams. In particular, nine river systems have the size greater than 10,000 km^2, including the Red, Thai Binh, Bang Giang - Ky Cung, Ma, Ca, Vu Gia - Thu Bon, Ba, Dong Nai, and Mekong river basins (Nguyen-Tien, Elliott, & Strobl, 2018). These river systems provide approximately 830-840 billion m3/year, of which more than 60% of water comes from foreign countries (Jolk, Greassidis, Jaschinski, Stolpe, & Zindler, 2010). The average per capita water volume is over 9,000 m3/year. Underground water also has a potential reserve of about 63 billion m3/year, which distributes in 26 large water storage units and concentrates mainly in the Northern and Southern Deltas, and the Central Highlands.

River basins have large reservoirs including Red River (about 30 billion m3); Dong Nai River (over 10 billion m3); Se San River (nearly 3.5 billion m3); Ma River, Ca River, Huong River, Vu Gia - Thu Bon River and Srepok River (total capacity of nearly 3 billion m3). A reservoir construction plays an important role in regulating river flow over time and space, adapting to the water demand of economic sectors, providing a basis for reasonably planning and using water resources, mitigating of floods for downstream (Herschy, 2012). However, the effective management of these reservoirs has faced difficulties because of (i) more than half of the water resources originating outside the border while water resources are unevenly distributed over space and time; (ii) increasing water demand in response to the rapid socio-economic development; (iii) increasing water pollution both in terms of level and scale; and (iv) other adverse changes such as climate change and sea-level rise, increasing saline intrusion and drought condition.

For effective reservoir operation, the elevation-area-storage (Z-F-W) curve plays a crucial role (Mohammadzadeh-Habili, Heidarpour, Mousavi, & Haghiabi, 2009). The Z-F-W curve of a reservoir is used in regulating water during the flood season and distributing water in the dry season. According to the latest statistics of the Directorate of Water Resources, Vietnam only has about 474 (among 6636) reservoirs that have information about the elevation-area-storage. The Z-F-W curve of the remaining reservoirs was established using a linear relationship between the reservoir's bed characteristics. However, a linear relationship can cause a very large error due to the non-linear-shape condition of the reservoirs' bed topography (Bayón, Grau, Ruiz, & Suárez, 2009). A Z-F-W curve can be constructed with high precision by field measurement methods but this method is expensive and time-consuming, especially for large reservoirs. Researchers have developed the Z-F-W curve based on a linear simplification, which is similar to the linear relationship. Nevertheless, linear simplification can produce large errors in optimal operation (Gao, 2015; Gao, Birkett, & Lettenmaier, 2012). This study introduces a method to determine a nonlinear Z-F-W curve of the reservoir using a free remote sensing radar image Sentinel-1. This approach shows improvement in determining reservoir Z-F-W curves.

2. DATA AND METHOD

2.1 Data

To define the reservoir characteristic curve, it is necessary to have the relationship between reservoir water elevation (Z), surface area (F) and storage (W). The data of reservoir water elevation is collected from the Directorate of Water Resource (under the Ministry of Agriculture and Rural Development). The surface reservoir area is calculated from the analysis of Sentinel-1 satellite imagery freely collected from the European Space Agency (ESA). Based on the relationship between elevation and area (Z-F) in many years, the relation between elevation and storage (Z-W) is calculated by using a pyramid formula.

The reservoir surface area is determined based on the results of satellite image interpretation. The application of free satellite images to interpret the water surface area of a reservoir frequently has a significant error due to the coarse resolution of the images. Free optical satellite images are contaminated by cloud cover while using commercial remote sensing images with super high resolution is more expensive compared to traditional measurement methods. Since 2015, the ESA has begun sharing free Sentinel-1 radar images with a resolution of 10m in-ground space, unaffected by cloud cover and weather, and very sensitive to water surfaces. Therefore, Sentinel-1 images are a valuable source to identify reservoir characteristics at a low cost. For the Vietnam region, there will be a Sentinel-1 photo taken one image per 12 days in the same area and now it has been shortened to one image per 6 days.

2.2 Method

Reservoir area is usually determined by two main methods. The first method uses specialized software such as ArcGIS and ENVI to delineate the surface area of the reservoir on the image. This method is quite simple and highly accurate because it can eliminate noise like terrain shadows. However, this method is not possible in the case of a large number of reservoirs since this is a manual method that requires a great deal of manpower and time to implement. The second method is to employ algorithms to automatically identify the surface area of the reservoir. In this study, automatic image interpretation was used to determine the reservoir water area. This method is feasible for large research areas with reasonable costs and time. However, the determination of reservoir surface area through image interpretation requires optimal algorithms. To determine the optimal algorithm, it is necessary to understand the nature of the radar image as well as the big programming and data processing skills. Figure 1 and Figure 2 show the approach and workflow of constructing reservoir Z-F-W curve.

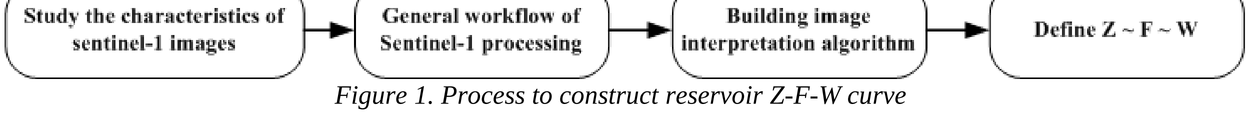

Figure 1. Process to construct reservoir Z-F-W curve

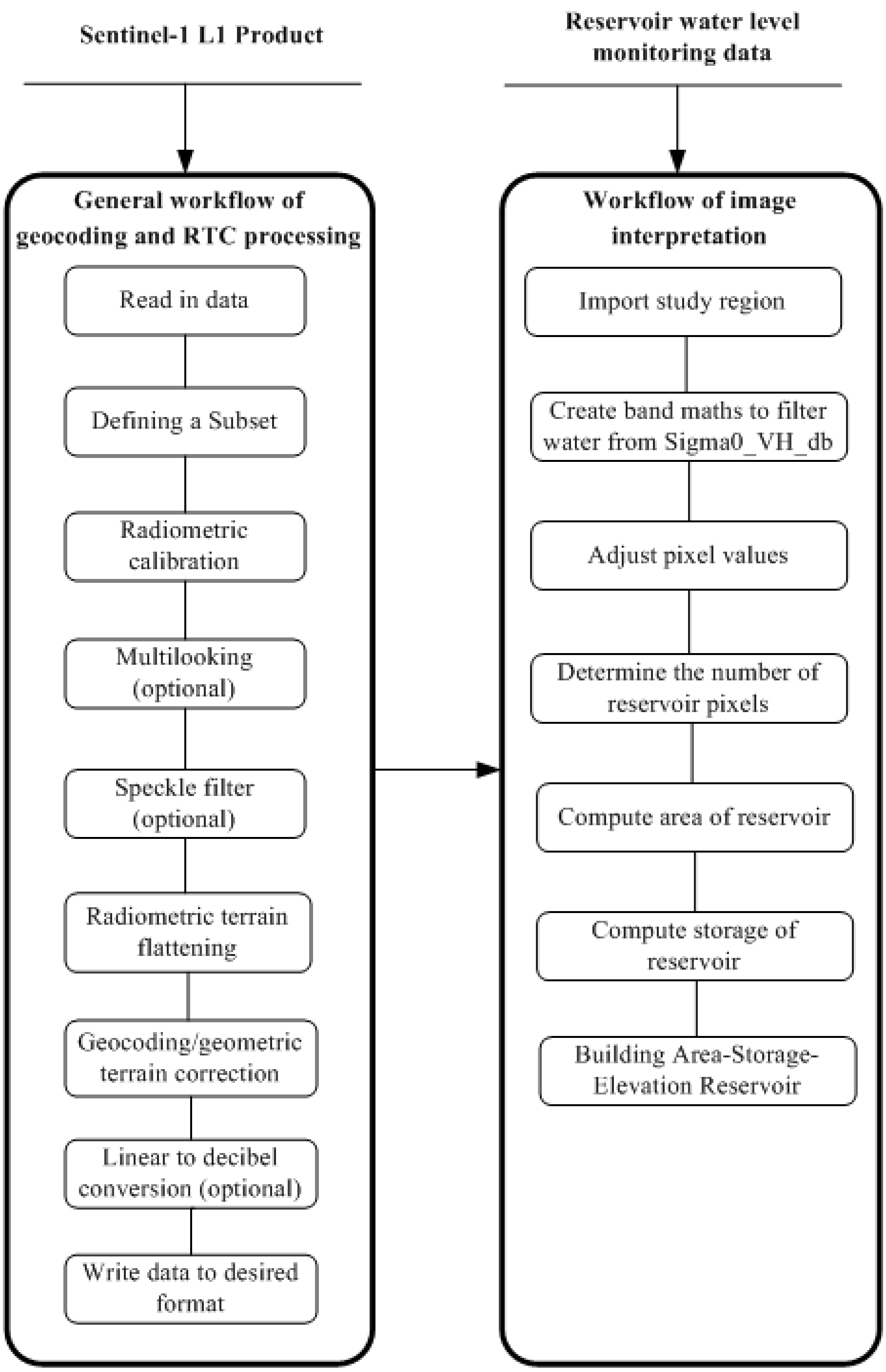

Figure 2. Workflow of constructing reservoir Z-F-W curve

2.3 Constructing reservoir Z-F-W

Sentinel-1 image processing

SNAP Desktop software is used to clip the study area and load satellite image data into the file management window. The image data is radiometrically and geometrically calibrated. Radiometric calibration creates images whose values of each pixel corresponds to the backscatter of the surface. This correction is necessary for quantitative image analysis. Geometric calibration fixes deformations (Slant Range), layover, shadows, and foreshortening. To correct geometry, 30m DEM data is used in this study.

For reservoirs with smooth and uncomplicated water edge, Multilooking is used to transfer the 10-m image resolution to the 20 m to reduce processing demand. Also, the linear Sigma0_VH image data band is transferred to decibel and saved as Sigma0_VH_db.

Working area

A buffer zone is used to define the interpretation area of a reservoir and pixels outside the buffer zone are considered. Using the buffer zone not only reduces the number of pixels processed but also localizes the reservoir area. For example, for reservoirs built on large rivers, the buffer zone is determined from the upstream boundary of the river to the dam which was constructed to store water.

Defining the reflection threshold of water

Based on the yearly-series Sentinel-1 images corresponding to the water levels measured in the working area, the lowest water level and the highest water level are known. Sentinel-1 backscattering values taken at the time of the lowest water level and the highest water level are calculated using SNAP Desktop software. The backscattering value at the time of the lowest water level is lower than the backscattering value at the time of the highest water level. The elevation of the reservoir water level is directly proportional to the threshold of backscatter value. It means that the thresholds are first set for the lowest and highest water levels, then backscattering values corresponding to other water levels are interpolated using a linear relationship.

Handling of misclassified pixels

Based on the above-established threshold values of water, the pixels that are mistakenly identified as water from residential areas, mountains, and roads are fixed. Pixels are terrain shadows that are corrected based on the incident angle and 30 m DEM digital elevation map, using SNAP Desktop software (Figure 3).

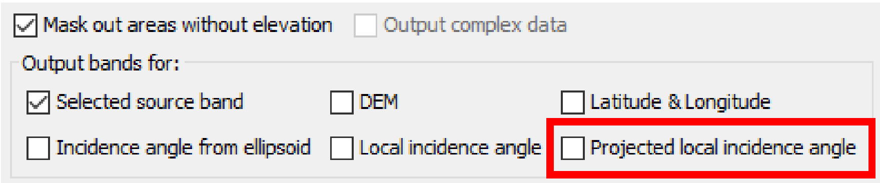

Figure 3. Using projected local incidence angle band to remove terrain shadow

Correcting pixel values which represent water

Basically, the threshold of backscatter value to separate the water is smaller in the dry season when the water level in the reservoir is often low in comparison with other periods of the year. When using the Band Maths function of the SNAP Desktop software to separate water based on the threshold of backscatter value of the VH image, for example, Sigma0_VH_db equal or less than -24 will detect some pixels representing water but they are eliminated because the VH_db value is greater than -24. Figure 4 below illustrates the pixels that represent water but they are excluded because of the small threshold value.

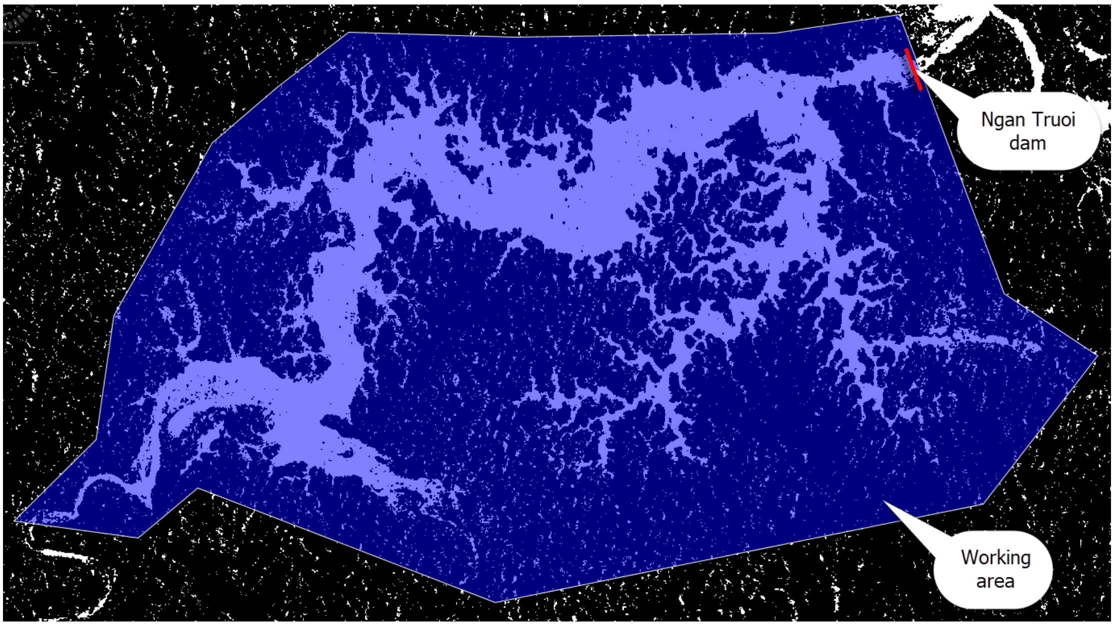

Figure 4. An example showing eliminated water pixels when the threshold value is small

In this case, a propagation algorithm is developed to determine a series of pixels that are not water. From the list of non-water pixels, only those equal or less than 20 or 5 (corresponding to the image resolutions of 10 m and 20 m, respectively) are considered; then the pixel values are converted from zero (non-water) to one (water).

In Figure 4, it can be seen that although the terrain shading has been removed, there still exist pixels that are terrain shading but they are interpreted as water and need to be eliminated. The above propagation algorithm is also used to determine a series of water pixels. Similarly, only those equal or less than 20 or 5 (corresponding to the image resolutions of 10 m and 20 m, respectively) are considered; then the pixel values are converted from one (water) to zero (non-water).

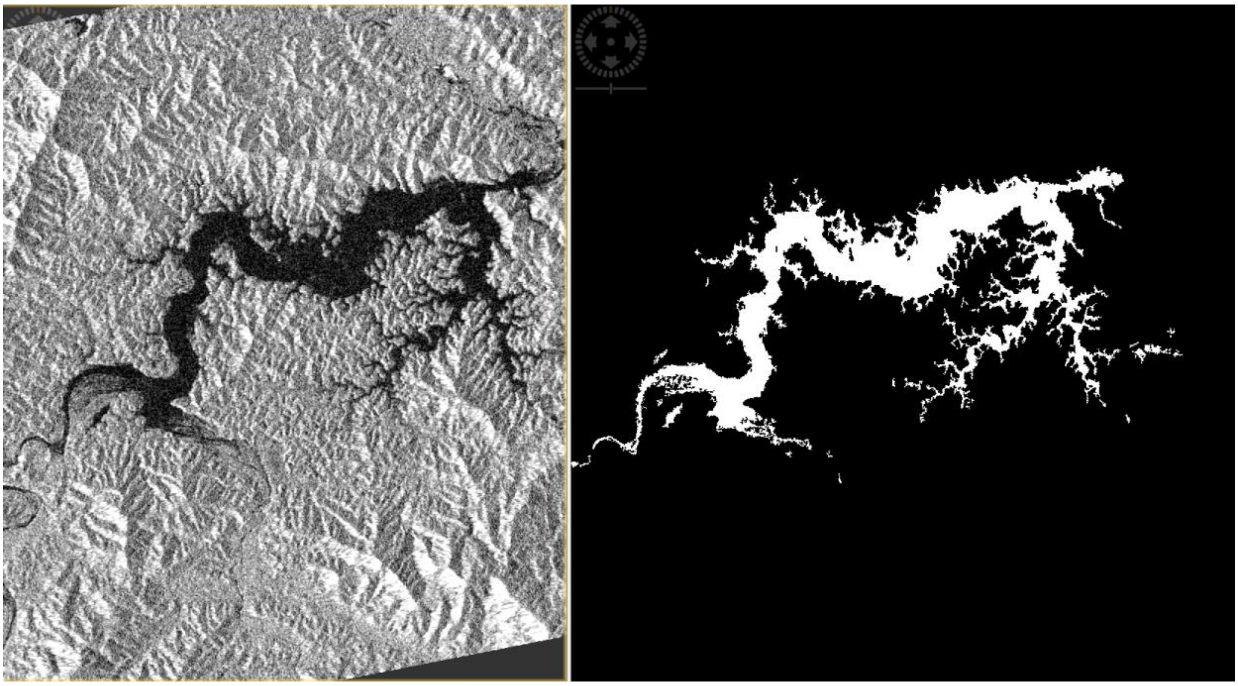

Figure 5. Result of image interpretation determines the area of Ngan Truoi reservoir, Ha Tinh, Vietnam

Computing the relationship between reservoir elevation and water surface area (Z-F)

The Z - F relationship is built based on the actual monitoring water level and the corresponding water surface area which is interpreted from the satellite images. The reservoir area at the time of interpretation is calculated by multiplying the number of pixels. Depending on the resolution of the image, the area of a pixel is $100m^2$ and $400m^2$ corresponding to the resolutions of 10 m and 20 m, respectively.

Computing the relationship between the reservoir area and volume (F-W)

In this study, the lowest water level is called the dead water level (Z_0) while a water level higher than the dead water level (Z_i) is called a useful water level. The reservoir volume that is limited between the dead water level and the useful water level is called the useful capacity. The useful capacity is determined based on a series of data relating to the elevation of the water level and the surface of the reservoir. It is calculated using the pyramid formula (Equation 1).

$$W_i = \sum_{i=0}^{n} \frac{(Z_{i+1} - Z_i)}{3}\left(F_i + F_{i+1} + \sqrt{F_i F_{i+1}}\right) \qquad (1)$$

where:

i is the i^{th} position in the value chain of water level elevation sorted from record 1 to record n,

W_i is the effective volume of the reservoir at water elevation at i^{th} position in the data series;

Z_i is the water level at water elevation at i^{th} position in the data series;

F_i is the surface area of the lake at water elevation at i^{th} position in the data series.

3. RESULT AND DISCUSSION

This study tests the proposed methodology in constructing Z-F-W curves for three reservoirs of Ha Tinh province, namely Rac, Ke Go and Ngan Truoi (Figure 6). These reservoirs have monitoring stations that automatically measure the water level of the reservoir. The reference data of Z-F-W relationships for Rac, Ke Go, and Ngan Truoi reservoirs are taken from the current reservoir operation rules approved by Ha Tinh province.

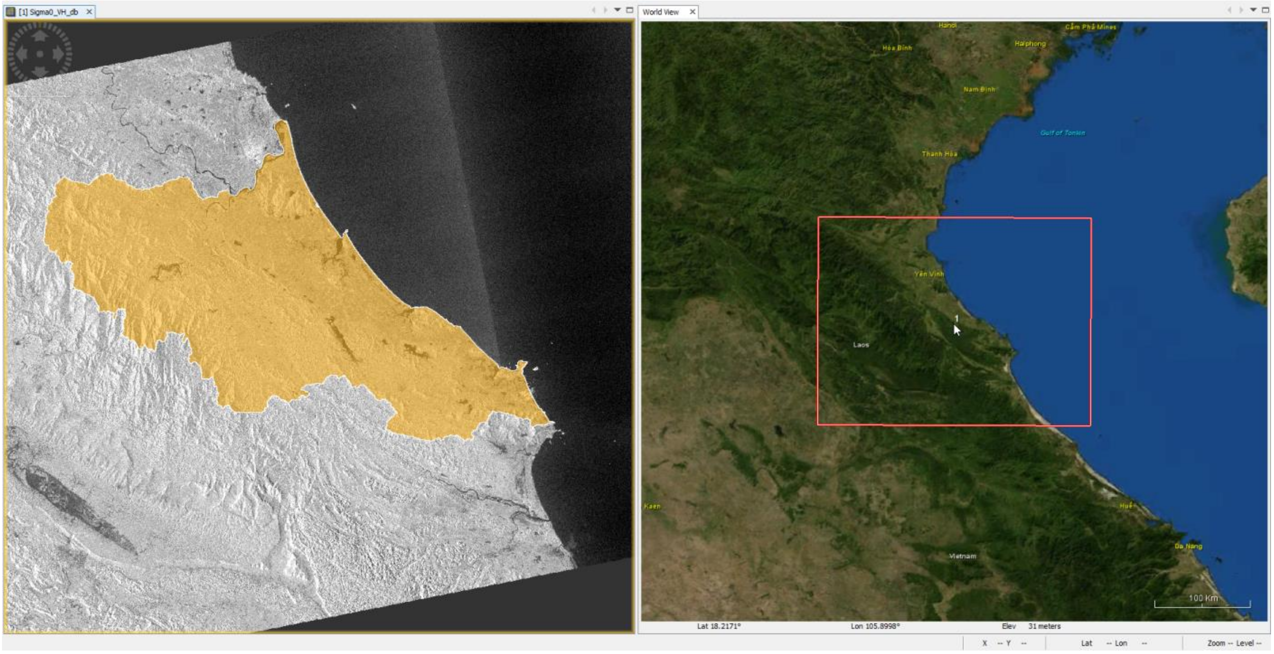

Figure 6. Test area in Ha Tinh province, Vietnam

3.1 The Z-F-W curve of Rac reservoir

Rac reservoir was started construction in 1986 in Cam Lac commune, Cam Xuyen district, Ha Tinh province. This reservoir was handed over to Ha Tinh Irrigation Company for management and operation since 1995. In the period 1991-1994, although it had not been completely built, Rac reservoir was partially exploited to supply water for agricultural production of Cam Xuyen district. In 2012, the reservoir was upgraded and built flood spillway under a reservoir safety program. The spillway shape is Oxipherop type without control gate and the width of 70 m. The Z-F-W curve constructed for the Rac reservoir is presented in Table 1 and Figure 7.

Table 1. Characteristic curve of Rac reservoir from results of image interpretation and actual measurement data

Water level (m)	Measured Volume (10^6 m^3)	Number of water pixels	Calculated surface area (km^2)	Calculated volume (10^6 m^3)	Volume error (%)
18.5	61.71	26589	10.6356	61.71	0
19	67.07	29182	11.6728	67.29	0.33
19.5	70.52	29507	11.8028	73.16	3.74
20.5	83.02	32670	13.068	85.59	3.1
21	92.07	33829	13.5316	92.24	0.18
21.5	99.17	34477	13.7908	99.07	0.1
22	106.27	35362	14.1448	106.05	0.21
22.5	113.81	36035	14.414	113.19	0.54
23	121.34	36330	14.532	120.43	0.75
23.5	129.25	37746	15.0984	127.84	1.09

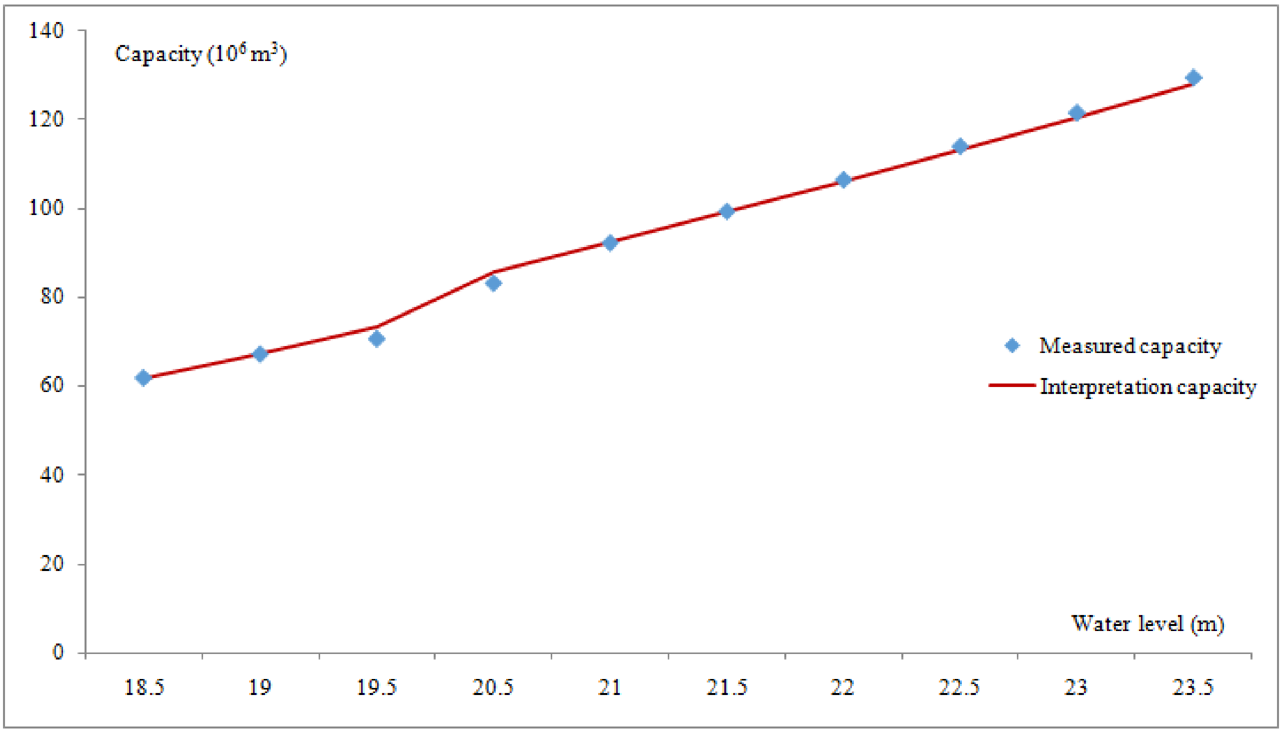

Figure 7. A graph comparing the Z ~ W relationship between the actual measurement and interpretation from Sentinel-1 image of Rac reservoir

3.2 The Z-F-W curve of Ke Go reservoir

Ke Go reservoir was built on Rao Cai river in Cam My commune, Cam Xuyen district, Ha Tinh province. It is about 20km from Ha Tinh city to the west. The work was started construction on March 26, 1976, and, it began to be used by February 1978. In 1983, the project was completed and officially put into operation. The Z-F-W curve of Ke Go reservoir is presented in Table 2 and Figure 8.

Table 2. Characteristic curve of Ke Go reservoir from results of image interpretation and actual measurement data

Water level (m)	Measured Volume (10^6 m^3)	Number of water pixels	Calculated surface area (km^2)	Calculated volume (10^6 m^3)	Volume error (%)
16.5	39.5	20386	8.1544	39.5	0
19	65	30574	12.2296	64.81	0.29
21	91	39315	15.726	92.69	1.86
21.5	98	40738	16.2952	100.69	2.74
22	105	40880	16.352	108.85	3.67
22.5	113.75	41635	16.654	117.1	2.95
23	122.5	42480	16.992	125.51	2.46
23.5	131.25	46346	18.5384	134.39	2.39
24	140	45259	18.1036	143.55	2.54
24.5	150	47049	18.8196	152.78	1.85
25	160	48574	19.4296	162.34	1.46
25.5	170	50050	20.02	172.2	1.29
26	180	50879	20.3516	182.29	1.27
26.5	191.25	51760	20.704	192.55	0.68
27	202.5	52954	21.1816	203.02	0.26
27.5	213.75	54730	21.892	213.79	0.02
28	225	54833	21.9332	224.75	0.11
28.5	237.5	55877	22.3508	235.82	0.71
29	250	57523	23.0092	247.16	1.14
29.5	262.5	57751	23.1004	258.69	1.45

30	275	58628	23.4512	270.33	1.7
30.5	287.5	58616	23.4464	282.05	1.9
31	300	59507	23.8028	293.86	2.05
31.5	312.5	59787	23.9148	305.79	2.15
32	325	59887	23.9548	317.76	2.23

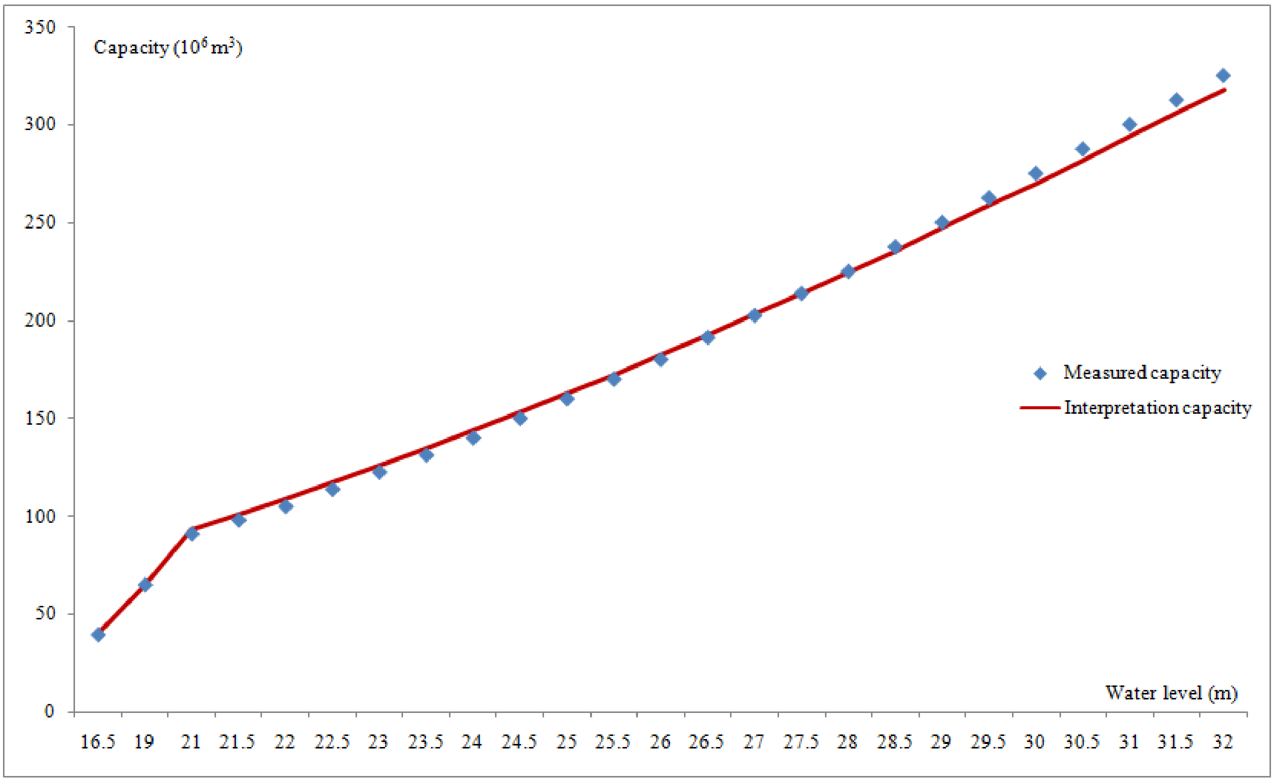

Figure 8. A graph comparing the Z ~ W relationship between the actual measurement and interpretation from Sentinel-1 image of Ke Go reservoir

3.3 The Z-F-W curve of Ngan Truoi reservoir

Ngan Truoi Reservoir was started construction by the Ministry of Agriculture and Rural Development and the People's Committee of Ha Tinh Province on June 14, 2009. This reservoir irrigates about 32,334 ha of agricultural land in Huong Son, Vu Quang, Duc Tho, Can Loc and Nghi Xuan districts and a northern part of Thach Ha district and Hong Linh town. The Z-F-W curve of Ngan Truoi reservoir is presented in Table 3 and Figure 9.

Table 3. Characteristic curve of Ngan Truoi reservoir from results of image interpretation and actual measurement data

Water level (m)	Measured Volume (10^6 m^3)	Measured area (km^2)	Number of water pixels	Calculated surface area (km^2)	Area error (%)	Calculated volume (10^6 m^3)	Volume error (%)
27.5	103.01	13.4201	127286	12.7286	5.15	103.01	0
28	110.28	14.0318	111067	11.1067	20.85	108.96	1.2
29	124.82	15.2552	121166	12.1166	20.57	120.57	3.4
30	139.36	16.4786	127294	12.7294	22.75	132.99	4.57
30.5	146.63	17.0903	151344	15.1344	11.44	139.95	4.56
31	153.9	17.702	170663	17.0663	3.59	148	3.83
31.5	163.92	18.1773	151273	15.1273	16.78	156.04	4.81
32	173.94	18.6526	176464	17.6464	5.39	164.23	5.58
32.5	183.96	19.1279	185212	18.5212	3.17	173.27	5.81
33	193.98	19.6032	192275	19.2275	1.92	182.71	5.81
33.5	204	20.0785	190586	19.0586	5.08	192.28	5.75

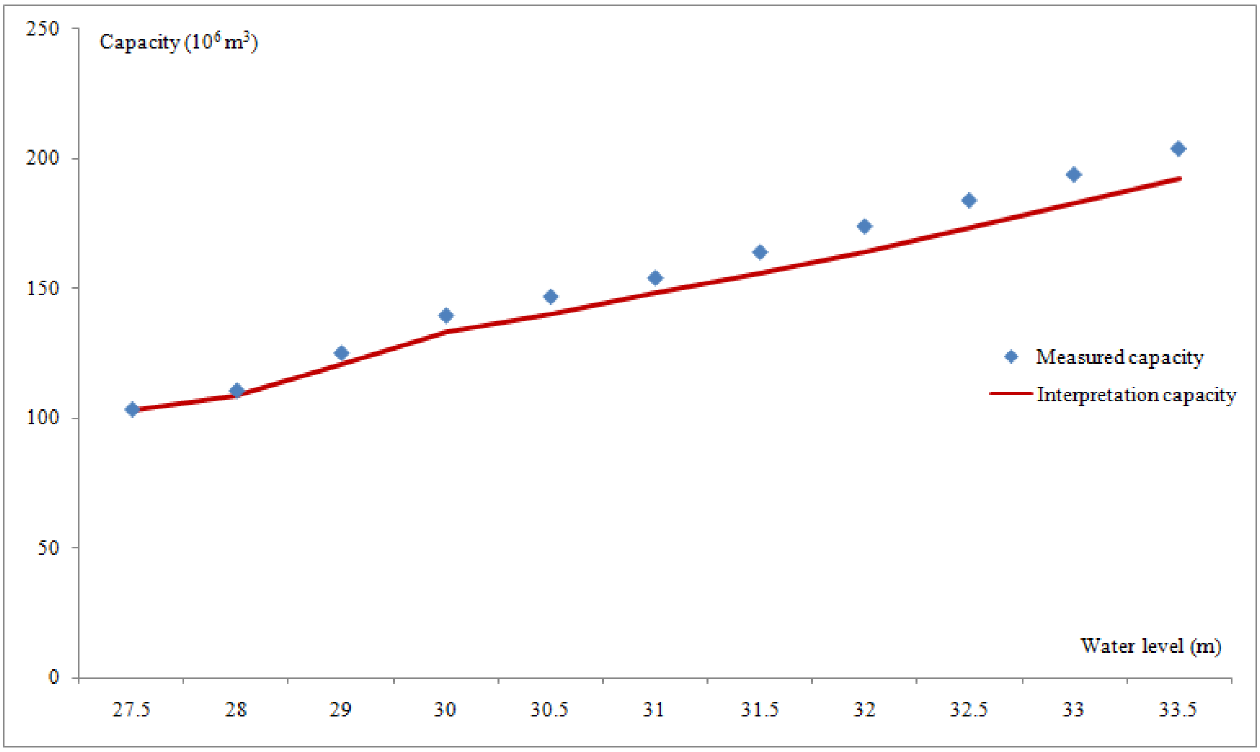

Figure 9. A graph comparing the Z ~ W relationship between the actual measurement and interpretation from Sentinel-1 image of Ngan Truoi reservoir

3.4 Discussion

In this study, the computed Z ~ W relationships are verified for three reservoirs and the Z ~ F relationship is only verified for Ngan Truoi reservoir which the reference surface area is available. It is found that most computed reservoir volumes reasonably agree with the actual volumes. The correlation coefficients between the calculated and actual volumes are close to unity, as seen in Figures 7, 8 & 9. With respect to relative errors of the calculated volumes, the average errors are attained 1%, 1.5%, and 4.1% for Rac, Ke Go, and Ngan Truoi reservoirs, respectively. Additional analyses of calculated surface area are then performed for Ngan Truoi. Results show that the correlation coefficient is attained at 0.93 and the average relative error is about 10.6 %. This indicates that errors in defining the surface area of the reservoir tend to be larger than the volume errors. However, the information about reservoir volumes is more important than the surface area for developing reservoir operation rules.

4. CONCLUSION

This study presents the method and results in defining reservoir characteristics through the Z-F-W relationship based on Sentinel-1 satellite image interpretation and observation data. The result of the image interpretation demonstrates usefulness with the accuracy of over 95%. On this basis, it is possible to quickly determine the characteristics of the reservoirs with no available data. The established the Z-F-W relationships can promote effective management and operation of the reservoirs.

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