International Journal of *Geo-Information*

MDPI

Article

Investigating the Utility Potential of Low-Cost Unmanned Aerial Vehicles in the Temporal Monitoring of a Landfill

Abdullah Harun Incekara [1,*], Ahmet Delen [1], Dursun Zafer Seker [2] and Cigdem Goksel [2]

[1] Department of Geomatics Engineering, Gaziosmanpasa University, Tasliciftlik, Tokat 60150, Turkey; ahmet.delen@gop.edu.tr

[2] Department of Geomatics Engineering, Istanbul Technical University, Maslak, Istanbul 34469, Turkey; seker@itu.edu.tr (D.Z.S.); goksel@itu.edu.tr (C.G.)

* Correspondence: abdullah.incekara@gop.edu.tr; Tel.: +90-554-883-5845

Received: 17 November 2018; Accepted: 7 January 2019; Published: 11 January 2019

check for updates

Abstract: The collection of solid waste is a challenging issue, especially in highly urbanized areas. In developing countries, landfilling is currently the preferred method for disposing of solid waste, but each landfill has a limited lifecycle. Therefore, changes in the amount of stored waste should be monitored for the sustainable management of such areas. In this study, volumetric changes in a landfill were examined using a low-cost unmanned aerial vehicle (UAV). Aerial photographs obtained from five different flights, covering approximately two years, were used in the volume calculations. Values representing the amount of remaining space between the solid waste and a reference plane were determined using digital elevation models, which were produced based on the structure from motion (SfM) approach. The obtained results and potential of UAVs in the photogrammetric survey of a landfill were further evaluated and interpreted by considering other possible techniques, ongoing progress, and the information existing in an environmental impact assessment report. As a result of the study, it was proved that SfM carried out using a low-cost UAV has a high potential for use in the reconstruction of a landfill. Outcomes were obtained over a short period, without the need for direct contact with the solid waste, making the UAV preferable for use in planning and decision-making studies.

Keywords: landfill; compacting; UAV; volume; open dumping; photogrammetry; SfM

1. Introduction

Solid materials that have expired and must be removed from the environment are called solid waste [1]. Household waste, industrial waste, and medical waste constitute the vast majority of this type of waste. Thus, the amount of solid waste generated increases in tandem with urbanization [2,3]. This development, and the necessity of removing the waste, has led humans to develop various disposal methods, from the past through to the present day. The most primitive option is open dumping, which is often preferred by countries with limited feasibilities. Areas where waste is stored irregularly and in an unplanned way, without considering human and environmental health factors, are called open dump sites [4]. Site pollution, waste smell, and even explosions are the main adverse effects of open dumping. Moreover, the interaction of waste with freshwater resources, such as rivers and lakes, endanger all nearby organisms [5]. Currently, landfilling, in which waste is regularly stored in a storage area, is preferred to open dumping. The term "storage area" can also be referred to as a "plot". Landfilling is also differentiated in terms of the recycling and energy production opportunities it presents [2].

A change in the waste storage method used, especially by municipalities, requires sustainable planning in the management of landfills. Variables such as emissions, leachate, and soil properties should all be taken into consideration [5]; this is because each landfill has a certain period of use, as well as an even longer post-closure process, depending on its capacity [6]. The main reason for this effort when the facility is in operation is the continuous storage and compacting operations routinely performed in the landfill by pressing the accumulated waste downwards [7].

A landfill is an active surface and the elements that provide dynamism in the plot have been classified into categories "directly" and "indirectly" within the scope of integrated waste management (IWM), as discussed in detail in [1]. IWM is a system that encompasses every aspect of the process, from the formation of waste to its disposal. It is a complex system that aims to achieve certain economic outcomes, rather than a routine method for dealing with waste. In fact, those factors considered as having a direct effect—such as the transportation of waste from one place to another, the accumulation of waste in a region of the landfill, and the application of procedures to the waste to be disposed—cause changes to the landfill surface. Their physical equivalent is the level of compacted waste, which rises upwards with any increase in the amount of stored waste [1,8]. Based on these references, another factor from the authors' point of view, in terms of IWM, is that of volumetric changes.

Each landfill has its own lifespan; the steady accumulation, storage, and compacting of waste cause volumetric changes, which in turn determine this operation period. There are still facilities where the determination of these changes has been attempted using only terrestrial geodetic techniques. These techniques are mainly based on the collection of a limited number of samples from the surface, using a geodetic measurement instrument such as a global navigation system (GNSS) receiver or a total station. The volume analyses can be carried out with the help of contours derived from these points which have different height values in different positions. However, there has been little study of the use of image data in landfills for similar purposes. In particular, very few researchers have evaluated the use of data obtained using unmanned aerial vehicle (UAV) platforms in such areas.

In the literature, studies relating to the use of UAVs in landfills or similar regions have mainly focused on emission detection [9,10] and accuracy assessments of the UAV [11]. However, reference [12] suggested that the volumetric changes in a landfill could be determined using a digital elevation model (DEM) produced from the height values that relate to the contour lines generated by means of digitization. It was also proposed by [13] that a DEM produced by the interferometric synthetic aperture radar technique could be used to evaluate volumetric changes in landfills. However, in general, studies have progressed towards other areas of interest. Outside of landfills, the utility of UAVs in studies involving accuracy assessment or error in volumetric change analysis has been shown for other geomorphological surfaces, such as glaciers [14,15], open pit mines [16], rocks [17,18], and landslides [19,20]. Various height models—not only DEMs, but digital surface models (DSMs), digital terrain models (DTMs), and normalized digital surface model (nDSM)—have been employed in these studies. The areas where UAVs can be used are assessed in more detail in [21,22].

In this study, it was investigated whether a low-cost UAV can be used in the temporal monitoring of a solid waste storage area based on DEMs and without contour lines. A photogrammetric application was performed within the scope of the "structure from motion" (SfM) technique. Aerial photographs obtained at different times were used and the limitations of the low-cost UAV, as well as its potential use in the landfill area, were examined. Estimated information obtained from local institutions, regarding the population and the amount of waste to be stored, were used in the analyses and discussion. The estimated data of stored waste were adopted due to the inconsistencies between the population statistics obtained from different sources. In this way, the utility of the UAV in the photogrammetric survey of a landfill was evaluated in terms of certain technical and economic aspects. This study was not intended to insistently support the use of a low-cost UAV in such an area for change analysis; it basically states that this popular technology is appropriate for use during the landfilling process. This study appears to be the beginning of an assessment of the UAV in terms of its suitability for such purposes at landfill sites, and it is thought by the authors that this could be further developed thereafter.

Section 2 explains the details of the photogrammetric application, under the sub-titles of study area, data and methodology, and volumetric calculations. The obtained results are then presented together with a discussion to promote a better understanding of the implemented approach.

2. Materials and Methods

2.1. Study Area

The study area was a landfill located in the Tokat Province of Turkey; this storage area is operated by the Solid Waste Disposal Facility (SWDF) of Tokat Province. This landfill (presented in Figure 1) was established to dispose of the solid waste produced by the province's Central, Turhal, Zile, and Pazar districts. The storage area is approximately 4.2 hectares in size. Open dumping was used prior to the establishment of the landfill. Information concerning the open dump sites serving these districts is presented in Table 1. This table represents the primitive practices preceding the establishment of the landfill. An understanding of how waste accumulation was carried out prior to regular storage is important to the mission of a landfill. As mentioned in Table 1, the locations where solid waste was accumulated were all close to the settlement areas in the various districts. Therefore, all nearby organisms were exposed to the negative effects derived from the waste. It was the aim of the SWDF to eliminate these effects (explained more comprehensively in [5]) and to reduce the negative impact of the harmful substances.

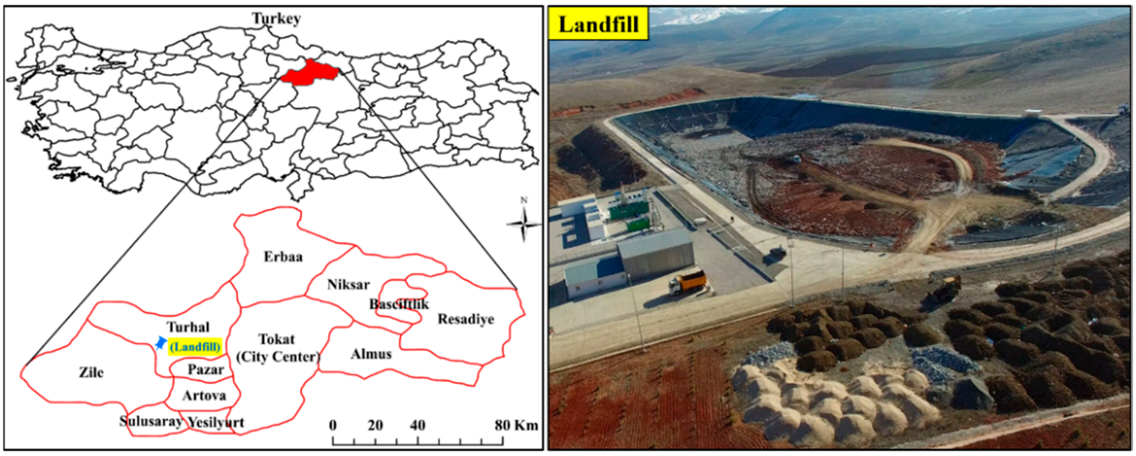


Figure 1. Study area.

Table 1. Information concerning open dumping practices.

District	Location of Open Dump Site
Central District	Next to Yesilirmak River and 5 km away from the center
Turhal	On Tokat road, 2 km away from the center and 100 m away from the Yesilirmak River
Zile	In a rocky area, 5 km away from the center
Pazar	Next to the Yesilirmak River and 2 km away from the residential areas

The largest volume of waste is transferred from the Central District, due to its higher population, and the smallest is sent by the Pazar district. There is a total of three plots for the storage of solid waste; currently only one of them (the one which was investigated in this study) is in operation. When the mission of the existing plot is completed, the others will become operational. According to an Environmental Impact Assessment (EIA) report, the three plots cover a period of 25 years and the activity in the region will end in 2032. The waste accepted for management in the facility is solid waste, collected from the houses in the residential areas; plant waste collected from parks, gardens, and green areas; industrial and commercial waste, which shares certain features of the household waste; and medical waste, from schools, clinics, laboratories, and similar places. The distances between the landfill and the districts are within the range of 10 to 50 km. The closest settlement to the observed plot is 3 km away. Although the location of the region is considered suitable based on these distances, the site detection for potential storage sites is a research topic involving a geographical information system (GIS), which requires a multi-criteria analysis based on different types of maps [23,24].

2.2. Data and Methodology

Aerial photogrammetric application and terrestrial geodetic measurements were carried out in the landfill. Aerial photographs obtained by UAV were used to reconstruct the study area. Setting the ground control points (GCPs) for the area and obtaining the coordinate information of these points constituted the terrestrial part of the study. A GNSS receiver was utilized during the measurement of the GCPs for inclusion in the SfM process later on. A summary of the applied methodology based on these data and hardware is represented in Figure 2. Five flight tasks were carried out over approximately two years. The intervals between flight periods ranged from 181 to 206 days. The low-cost UAV used to obtain aerial photographs was a DJI Phantom 3 Professional, which is a small-sized instrument. Despite being used by many people for hobby purposes, its data acquisition capabilities, assisted by its global positioning system (GPS), enables this type of vehicle to be used in both private and public institutions as well as in academic studies for engineering projects.

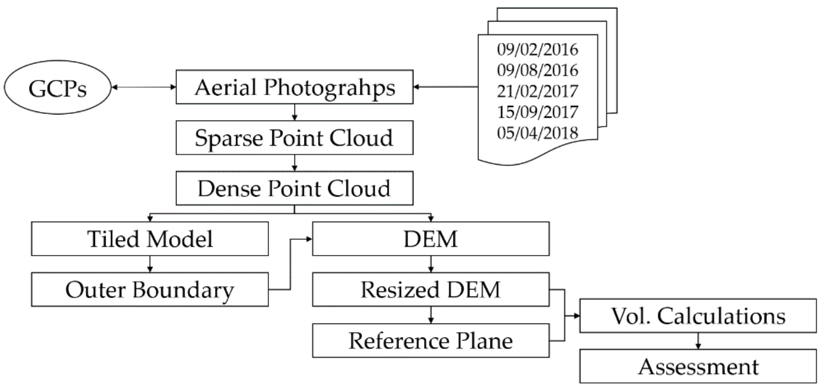


Figure 2. Applied methodology involving integration of ground control points (GCPs) with photographs and production of digital elevation model (DEM).

There were seven GCPs distributed all over the area, which characterized the topography as far as possible. The coordinates of the GCPs were determined by means of the real-time kinematic (RTK)-GNSS technique. The plot has a certain slope due to its design. All GCPs were installed on the road surrounding the storage area in such a way that they were in contrast to the ground, as indicated in Figure 3. For sustainability usage of the GCPs, they were painted just before each flight task.

In each flight, approximately 100 photographs were taken. The flying altitude (distance from takeoff elevation) was about 70 m and the focal length of the camera mounted on the UAV was 3.61 mm, which provided relatively larger aerial photographs. Based on these parameters—and the pixel pitch of the camera, which was 1.56 µm—the ground sampling distance (GSD) values were around 3 cm. The flights were realized to cover a larger region than the area of interest.

The photogrammetric products of the storage area were obtained through the SfM technique. SfM makes use not only of the principles of classical 3D photogrammetry, but also of the fundamentals of computer vision [25]. In order to perform a bundle adjustment, overlapping photographs were used [26]. This can be also employed when points with known 3D coordinate values, to be integrated with the photographs, do not exist [27].

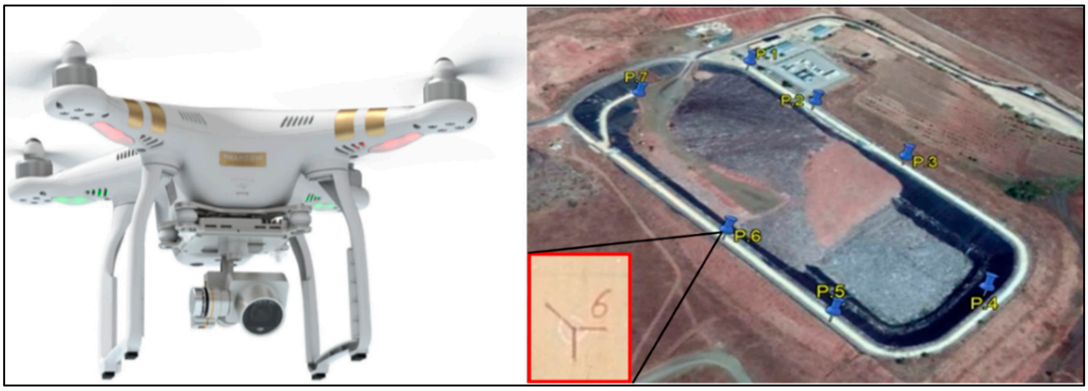


Figure 3. The unmanned aerial vehicle (UAV) employed (**left**) and the distribution of GCPs on the road surrounding the landfill (**right**).

Agisoft PhotoScan software was used to apply the SfM procedure. Firstly, a sparse point cloud was produced after the first alignment of the aerial photographs, which were integrated with the coordinates of the GCPs later on. In this step, the points corresponding to each other were detected between the overlapping photographs, and the camera position of each photograph was estimated. At the end of this step, a sparse point cloud was obtained. The software refers to this dataset as the "tie points". In order to optimize the camera positions, the GCPs were integrated with the relevant photographs. This operation contributes to the production of a better model. The locations of the GCPs were checked in each photograph in which they appeared, and the 3D coordinates of the GCPs were imported into the software. Based on the camera positions and GCPs, a dense point cloud was produced by means of densification of the tie points. Reprojection errors ranged from 0.523 pixels to 0.543 pixels. The maximum XY error and Z error, based on the GCPs, were 16.08 cm and 29.07 cm, respectively; both belonged to the flight on 9 August 2016. These error values correspond to a total error of approximately 33 cm for that flight and its processing. The total error values for the other processes ranged from 19 cm to 25 cm. Points measured in the field were not considered separately as control points and checkpoints. Error values were calculated using differences between the field coordinates of all the GCPs and the model coordinates obtained after the alignment steps. An accuracy assessment, based on formulas which have been implemented in many studies, such as [28,29], is given below:

$$RMSE_X = \sqrt{\frac{\sum_{i=1}^{n}\left(X_{i_{model}} - X_{i_{GNSS}}\right)^2}{n}} \tag{1}$$

$$RMSE_Y = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_{i_{model}} - Y_{i_{GNSS}}\right)^2}{n}} \tag{2}$$

$$RMSE_{XY} = \sqrt{(RMSE_X)^2 + (RMSE_Y)^2} \tag{3}$$

$$RMSE_Z = \sqrt{\frac{\sum_{i=1}^{n}\left(Z_{i_{model}} - Z_{i_{GNSS}}\right)^2}{n}} \tag{4}$$

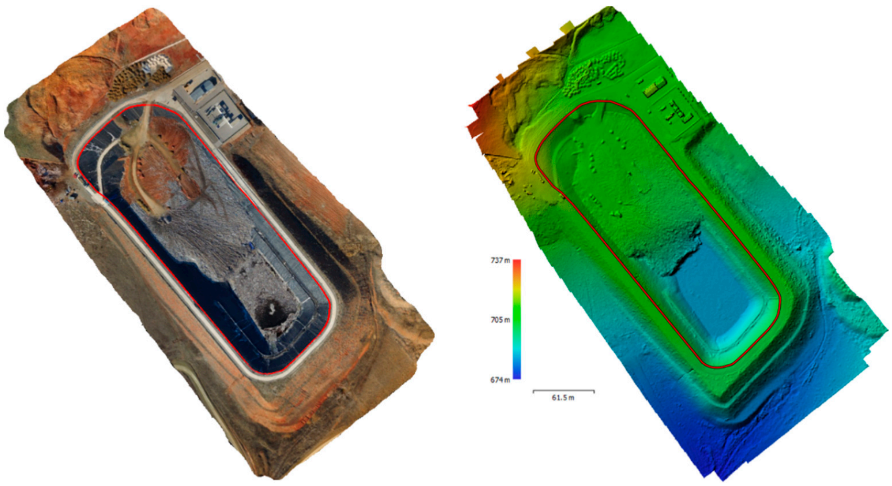
$$RMSE_{Total} = \sqrt{RMSE_{XY^2} + RMSE_{Z^2}} \tag{5}$$

where:

$RMSE$ is the root mean square error,
n is the number of GCPs used,
X_{imodel} is the GCP coordinate of point i on the X-axis,
Y_{imodel} is the GCP coordinate of point i in on the Y-axis,
Z_{imodel} is the GCP coordinate of point i in on the Z-axis,

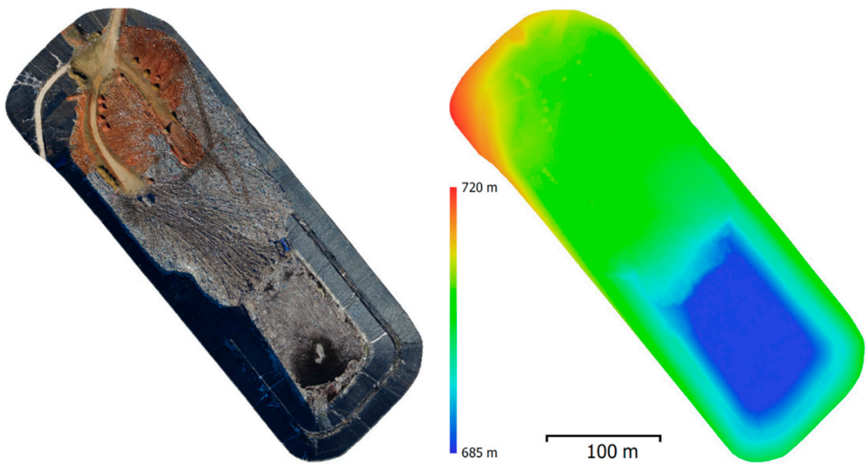
$RMSE_{XY}$ is the horizontal accuracy,
$RMSE_Z$ is the vertical accuracy, and
$RMSE_{Total}$ is the total accuracy.

Two datasets, the tiled model and the DEMs, were derived from the dense point cloud. The reason why a tiled model was preferred instead of a textured model was that it was more capable of representing the study area in qualitative terms. The outer boundary of the plot was formed on the tiled model by regarding the first flight as a polygon. This vector data was then utilized for the other models as well. After eliminating irrelevant points manually, DEMs were produced from the dense point cloud; their resolutions ranged from 10.1 cm/pixel to 12.5 cm/pixel. This variability originated from the differences between the dense point clouds. Slight differences between the altitudes of the platform during the flight tasks caused modest differences between GSD values, and thus resolution differences among the DEMs. Based on the outer boundary formed on the tiled model, the DEM belonging to each flight was clipped; thus, only the storage areas in which solid waste had continuously accumulated were obtained. Figures 4 and 5 present the determined outer boundary on the tiled model and on its corresponding DEM. The clipped DEMs pertaining to each period are represented in Figure 6.



(**a**) (**b**)

Figure 4. (**a**) Outer boundary on the tiled model; (**b**) outer boundary on the corresponding DEM.



(**a**) (**b**)

Figure 5. (**a**) Clipped tiled model which includes only the storage area; (**b**) clipped DEM corresponding to the clipped tiled model.

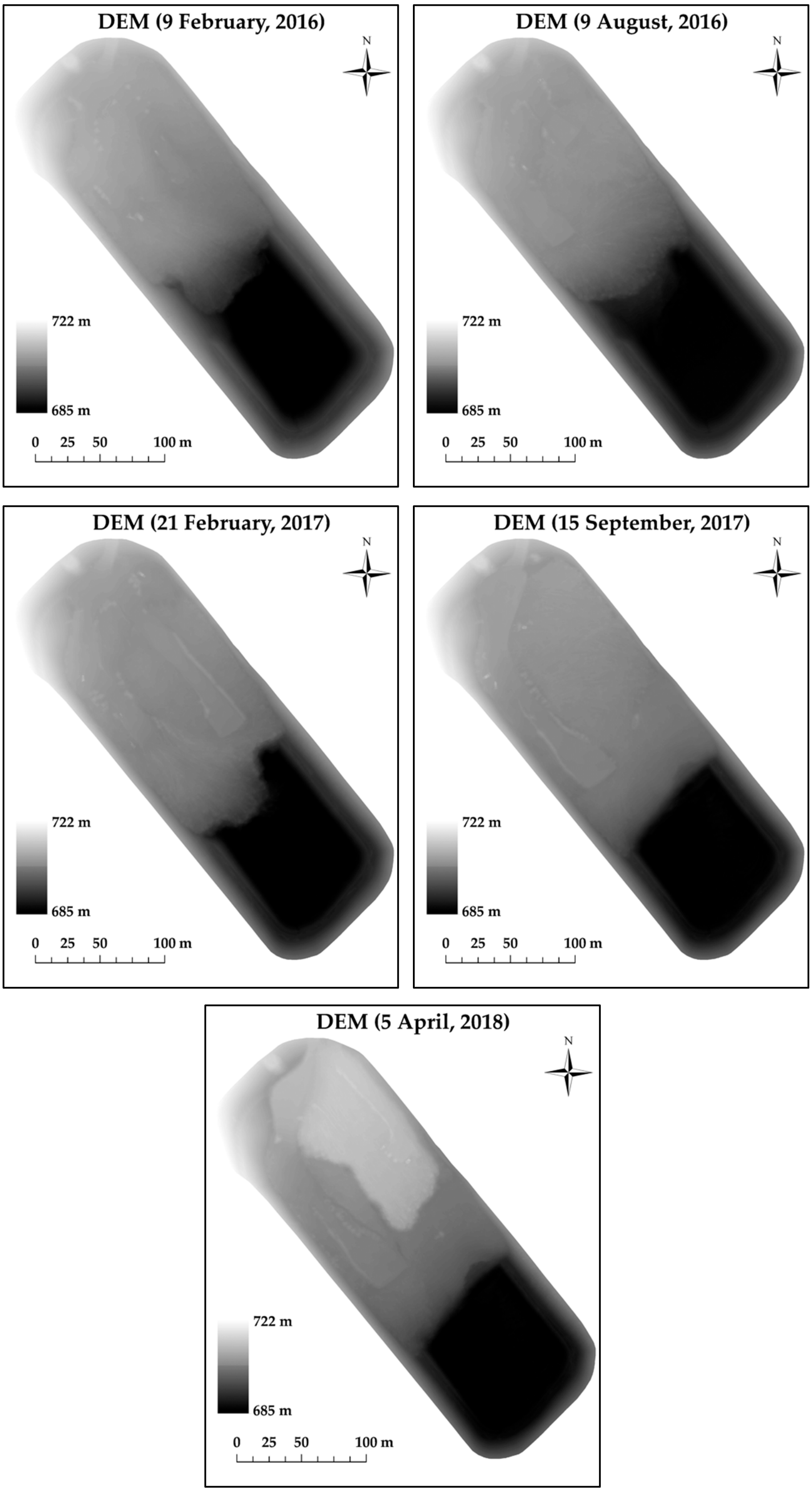
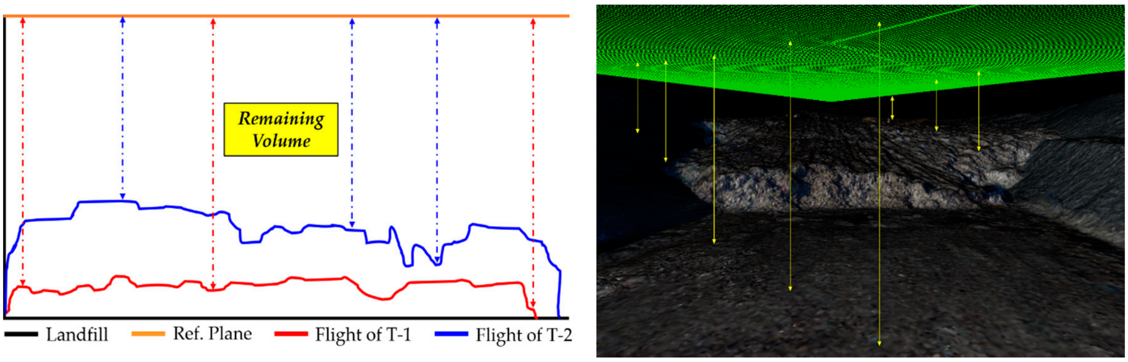


Figure 6. DEMs according to the chronology of data acquisition dates.

2.3. Volumetric Calculations

The approach behind the volumetric calculations involved the calculation of the remaining volume using the DEM relating to each period and a reference plane. As illustrated in Figure 7, a reference plane was established at the top of the plot. The height of the reference plane was kept the same for all the calculations for the consistency of the results. The reference plane was considered as the top cover of the plot and the internal material under the cover was the solid waste. In each calculation, the volume values between the solid waste and the reference plane represented the amount available for storage. The difference between the remaining volume values for each period demonstrated the changes involved in the ongoing operation.



(**a**) (**b**)

Figure 7. (**a**) Theory of volumetric calculations for the remaining volume; (**b**) 3D visualization of the volumetric calculation.

3. Results and Discussion

Within the scope of the volumetric analyses, initially remaining volume values were obtained. Then, the differences between the remaining volume values were calculated. The obtained results were then evaluated according to the time between the data acquisition dates, the information from an EIA report, and the actual equivalents of these predicted values regarding the population and the amount of waste to be stored. The results obtained from the volumetric analyses are presented in Tables 2 and 3.

Table 2. Remaining volume values.

Flight ID	Flight Date	Remaining Volume (m^3)
1	9 February 2016	911,078.9
2	9 August 2016	878,941.9
3	21 February 2017	838,690.5
4	15 September 2017	800,758.6
5	5 April 2018	755,058.4

Table 3. Differences between remaining volume values.

Period	Day	Difference Between Remaining Volume (m^3)	Stored Waste Per Day (m^3)
1–2	181	32,137	178
2–3	196	40,251	205
3–4	206	37,932	184
4–5	202	45,700	226

The amount of waste disposed per day or per year mainly depends on the population. Statistics regarding the total population of the four districts are presented in Table 4. These statistics were obtained from an EIA report and from the Turkish Statistical Institute (TSI) (www.tuik.gov.tr). As in [5], a joint evaluation of the image data with non-spatial data was made.

Table 4. Total population statistics for the four districts obtained from environmental impact assessment (EIA) report and Turkish Statistical Institute (TSI).

	Population Statistics from the EIA Report				Population Statistics from the TSI			
Year	**Central District**	**Turhal**	**Zile**	**Pazar**	**Central District**	**Turhal**	**Zile**	**Pazar**
2008	149,653	119,271	62,211	5928	176,564	87,826	67,224	15,261
2009	154,584	122,375	63,412	6005	182,572	87,233	65,245	15,158
2010	159,587	125,501	64,610	6082	188,173	86,327	63,201	15,048
2011	165,657	128,649	65,876	6158	182,371	85,391	61,619	14,948
2012	169,792	131,816	67,076	6234	182,225	85,923	61,765	15,426
2013	174,985	134,998	68,270	6309	184345	83,036	59,744	14,712
2014	180,233	138,195	69,458	6384	185626	81,813	58,147	14,117
2015	185,531	141,401	70,743	6458	188736	80,171	56,727	13,804
2016	190,876	144,617	71,925	6531	192065	80,239	56,185	13,824
2017	196,261	147,839	73,097	6604	196386	79,844	55,131	13,570
2018	201,681	151,061	74,260	6676	-	-	-	-

The left part of Table 4 shows the statistics obtained from an EIA report. In Turkey, an EIA report must be prepared and then approved for any investment that has a relationship to the environment, such as a nuclear power plant, mine, or dam. Constructions relating to these investments must be carried out within the boundaries specified by the EIA report. In addition, all practices following the start of operations must be performed according to certain restrictions regarding the usage purpose of the area. The EIA report for the investigated landfill was prepared in 2007 and includes statistics estimated for the future. One of the such set of statistics is the population statistics for 2008 to 2018, which were predicted by considering the population growth up until 2007. The other population statistics, on the right side of Table 4, come from the TSI. This is a government agency responsible for annual population censuses. The reason for the differences between the population values obtained from these two sources depends on how these statistics were calculated. The EIA calculated their statistics based on how many people were registered in these districts. For example, any person living in Turhal but registered in Erbaa is not taken into account as an inhabitant of Turhal. On the other hand, the TSI calculates the number of people living in the relevant district at the end of each year, regardless of where the population information is registered. For instance, there are approximately 30,000 students in the Tokat Gaziosmanpasa University; they come from different provinces of Turkey, but they live in Tokat and thus contribute to the amount of solid waste formed there. In short, there is a notable difference between the total population values given by the different sources. For the population, the statistics obtained from the TSI were accepted as correct.

One of the other sets of predicted values related to the amount of solid waste disposed, as presented in Table 5. These statistics were again given as predicted data in the EIA report and correspond to the related population statistics in the left part of Table 4. According to the EIA report, their calculation method for the amount of waste to be stored in the future was based on (1) the fact that the amount of solid waste generated per person increases by 1% each year, (2) the solid waste compaction ratio in the landfill area is 0.75 ton/m^3, and (3) the recycling rate of packaging waste is 12%–15%. The statistics in Table 5 cannot be used as a reference directly, as the population estimations in the EIA report do not reflect reality. However, the estimated amount of waste to be stored can be adapted based on this calculation, due to the fact that the population values taken as a reference for this study are those given by the TSI. This adaptation was used to generate a reference value for the results based on the SfM application.

Table 5. Predicted statistics in the EIA report regarding the amount of solid waste to be stored.

Year	Central District	Turhal	Zile	Pazar	Total (tons/year)	Total (m^3/year)
2008	43,054	28,597	14,916	1204	88,090	117,453
2009	44,919	29,633	15,355	1232	91,471	121,961
2010	46,838	30,693	15,801	1260	94,936	126,581
2011	48,811	31,779	16,272	1289	98,508	131,344
2012	50,839	32,888	16,736	1318	102,151	136,201
2013	52,921	34,018	17,203	1346	105,871	141,161
2014	55,050	35,170	17,677	1376	109,670	146,227
2015	57,233	36,346	18,184	1406	113,580	151,440
2016	59,468	37,545	18,673	1436	117,547	156,729
2017	61,754	38,767	19,167	1467	121,594	162,125
2018	64,092	40,010	19,668	1498	125,722	167,629

The data used in the study ranged from 2016 to 2018, but there were no TSI data available for 2018, since this year has not yet finished. However, only a few items of photogrammetric data exist for 2018. Therefore, statistics relating to 2016 and 2017 were used for the period of approximately two years covered by the study. An illustration of the calculations made for the adaptation is presented in Figure 8.

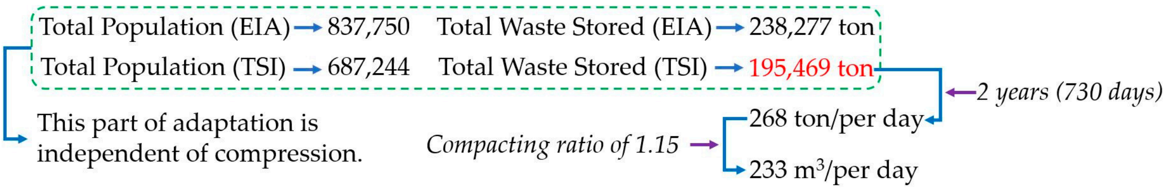


Figure 8. Obtaining per-day volume value by using statistical values in the comparison.

There are three known criteria and one unknown criterion in this adaptation. According to the information from the EIA given in Table 4, a total of 837,750 people contributed to the total waste during the two years; its corresponding value in Table 5 was a total of 238,277 tons of waste. However, based on the information from the TSI given in Table 4, a total of 687,244 people contributed to the waste during two years; this would correspond to 195,469 tons. As a result of this calculation, it was determined that the adopted value for waste per day should be 268 tons. The compaction ratio comes into play here to evaluate the stored waste in terms of m^3. Even if this ratio—which determines the density of waste—is taken as 0.75, following the EIA report, this ratio in the field is actually around 1.15 with the recent technological advances. This is totally facility-dependent information, depending on the weight of the waste truck at the entrance and exit of the facility. There is no possibility of investigating the actual compaction ratio continuously due to the dynamic structure of the surface. Reference [6] also states that all of the variables in the landfilling process are associated with each other, and thus, it is not easy to achieve optimum operation considering all the interactions. The level of compressibility may change depending on the other factors in the plot, as mentioned by [30], such as the transport of leachate and gas emission. Reference [30] also suggests that the compaction ratio can be improved to enhance the actual storage capacity of the landfill, and thus to exploit the area more efficiently. According to [6], the compression ratio is between 0.7 and 0.9, but other variables, like layer height and cover thickness, may cause changes to this. In addition to these references, there is the situation in practice. Normally waste is compacted in the plot, or else it is first compacted in the transfer station and then sent to the storage area to go through the same process again. However, solid waste can also be compacted within the waste collection vehicles themselves. In this way, the solid waste is subjected to multiple compaction processes in different ways. More waste can be stored in each area of 1 m^3 thanks to an increased compaction ratio. Thus, the volumetric value per day for the waste was calculated as almost 233 m^3 (268/1.15). The differences between the remaining volume values in Table 3 also represent the amount of solid waste transmitted to the area. According to the periods between the flight dates, the volume values per day based on the SfM results were 178 m^3, 205 m^3, 184 m^3, and 226 m^3 for Periods 1–2, 2–3, 3–4, and 4–5, respectively. With a compacting ratio of 1.15, it can be seen that the results for Periods 2–3 and 4–5 come close to the value of 234 m^3, given an error limit of 10% in determining the volume of any mass, such as a stockpile, through the photogrammetric method [31]. For this type of comparison, there is no requirement to collect data on the same dates as the statistics obtained from the EIA report and TSI, since they all cover almost the same time period and analyses were performed on a per-day basis.

The interpretation of the results for this type of area, with a dynamic structure and several variables, can be quite complex. Firstly, in Turhal and Zile, mostly outward migration occurred from 2008 to 2017. In addition, the predicted values based on the population-waste projections from the EIA report have not been as expected in reality. From the graph in Figure 9, it is clear that the population has not tended to increase linearly. Thus, the reference source used for the population statistics was the TSI. Accordingly, there may not have been a 1% increase per year in the amount of waste per person, as no progress was made during this period in either the industrial or the agricultural status of the districts in question. This notion may also be supported by [3], which reported—on the basis of several experiments—that waste generation may not always be proportional to changes in population, due to certain other factors such as education level and recycling facilities.

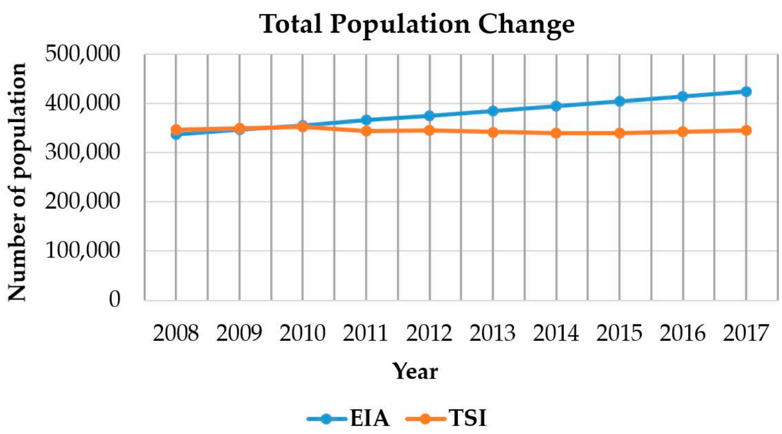


Figure 9. Total population change for the four districts from 2008 to 2017, according to different sources.

One exceptional case concerned the transfer stations in both the Central District and Turhal. Transfer stations are used to minimize the cost increase due to the long-distance transportation of waste from municipalities situated far away from landfill facilities, using waste collection vehicles. Transportation using regional collection vehicles, where the distance from the collection areas to the storage area is short, is more economical. If the distance between the storage area and the collection areas is long, the transfer of waste to larger-volume vehicles in the transfer stations is preferred. In Central District and Turhal, municipal collection vehicles bring waste to the transfer stations instead of to the landfill directly. These transfer stations are areas where waste is temporarily stored before being transported to the landfill. The waste is then transported from the transfer station to the landfill using large-volume vehicles at regular intervals. Therefore, it may not be possible to bring all of the waste generated in the Central District and Turhal to the landfill during the day.

The changes in the daily amount of waste for different periods were due to different amounts of waste being produced at different times. The amount of waste produced may change seasonally. In fact, this is the situation not only for landfills but also for many other geomorphological surfaces and phenomena, like erosion [17]. Additionally, leachate can affect the remaining volume values, and thus cause differences between them. As a result of the compacting process, the leachate emerges and accumulates in the lower end of the storage site as a result of the slope of the plot. This water stack is periodically removed from the plot, but its level can be in the range of 5% and 35% during operation, as mentioned in [30]. In the presence of leachate, the occurrence of the points of this region in the formation of DEM may affect volume calculations. Another factor with unclear effects is the significant increment in waste disposal that occurs during times of religious celebration times.

Another possible factor which may have affected the proximity of the SfM results to the predicted 234 m^3 level concerns the distribution of the GCPs. If a photogrammetric product of sufficient quality in terms of quantity is to be produced, GCPs have to be marked on the surface homogeneously. Height information from different locations should be utilized. Similarly, spatial information from different points should be included in the process. As indicated in Figure 3, the GCPs were all in different locations with different heights. However, there were no GCPs inside the landfill, as this was not possible. Unfortunately, it was also not always possible to attain the optimum distribution of GCPs across the area of interest, due to field conditions as mentioned in [32,33]. Therefore, even if it was possible to reach a total error value up to cm-level with the help of seven GCPs, errors in the X, Y, and Z axes are likely to increase towards the inner parts of the plot. The elimination of this situation was attempted by performing the flight task across a wider area than the storage area, as can be seen in Figure 4. In Figure 4a, it can be seen that a larger region was included in the flight task; had this not been done, a product similar to Figure 5a would have been immediately obtained. In this way, it was tried to locate the frame formed by the GCPs towards the center of the area. The study discussed in [29] demonstrated that GCPs should be distributed on the edge of the study area in order to obtain a better horizontal accuracy; however, this design may not be effective in cases where depth information is also crucial. A stratified distribution of the GCPs, which corresponds to a design characterizing the topography with its every aspect, was suggested by these authors for vertical accuracy. However, there was no prominent difference between the total error values in that reference, probably due to their study area covering almost 18 hectares. The storage area in this study is 4.2 hectares, and the area included in the SfM process (which includes the area surrounding the plot) was about 10 hectares. Therefore, it was not considered that the employed distribution was in a position to make a significant impact to the volume analysis. In previous studies in which UAVs were used for waste or something similar, GCPs were either not included [34] or not properly determined [35] as part of the SfM procedure. GCPs were employed in order to strengthen the model in terms of accuracy in this study.

In addition to the inclusion of GCPs in the process, the more accurate the coordinates of the GCPs, the more accurate the resulting product. At this point, it may be considered that measurement technique has a significant impact on the coordinates of GCPs, and that longer measurements should have been performed for each point. It was noted in [36] that the relative positioning according to which static observations were carried out did not provide a remarkable increment in the accuracy of the resultant photogrammetric product. Thus, the RTK-GNSS technique was preferred to determine the coordinates of the GCPs and to complete the field work in less time.

After a flight task, the XY and Z error values, based on the camera locations, were in the order of meters, due to the capability of the GNSS module mounted on the low-cost UAV. The accuracy values obtained without using any control point cannot satisfy the requirements of the analyses. For this reason, aerial photographs are supported by GCPs in order to guarantee the required quality of the resulting product in terms of quantity. However, if there is no sufficient broadcast at the time of flight, the spatial accuracy of the coordinated photographs may be lower than expected. This may cause lower model accuracies despite the existence of GCPs, and variabilities as presented in [37]. Accuracy and error assessment are also crucial at this point. Points in the field were not used separately as control points or check points. The flights were always carried out in the same area. Thus, they constituted repetitive measurements of the same locations. Furthermore, the platform, the equipment mounted on it (such as the camera), and the GCPs were always the same, in addition to almost the same flight parameters, such as altitude, coverage area, and number of camera positions, being employed. This situation can enable a high precision between periods, and thus a high level of accuracy for the relative changes determined between the DEMs. For this reason, it was considered that the inner accuracy assessment, based on Formulas 1 to 5 given above, was enough to guarantee the reliability of the volumetric calculation results in this study. Period 1–2 and period 3–4 cover almost the same months. It is expected that results from these periods are close to each other and the daily storage amount is higher for the latter. Obtained results for the amount of stored waste per day in Table 3 (178 m^3/day and 184 m^3/day) confirm this situation. This is also valid between periods 2–3 and 4–5.

A similar study to this one, in which the utility and capability of UAV was investigated in relation to a municipal landfill, can be found in [11]. On the other hand, in that study, the landfill was considered merely as a study area to assist in investigating the accuracy of UAV photogrammetry with terrestrial geodetic techniques. Implementing low-cost UAVs in SfM applications has become common in recent years; however, studies have mostly dealt with comparisons of the UAV's accuracy with other techniques, such as laser scanning [38–40] and terrestrial measurements [41]. However, laser scanning, for example, is now considered a source of complementary data in the monitoring of volumetric changes, rather than a way of validating SfM results [17]. This study has moved this area of research one step further by investigating the volumetric changes in a landfill. In addition, our study involved five flights, which enabled the possibility of a real-world test.

4. Conclusions and Recommendations

Landfills are areas that must be kept under routine monitoring within the IWM framework. This is compulsory, not only for economic reasons, but also for reasons of efficiency. Necessary tests of certain variables can be conducted in the field, which should be followed up. Volumetric changes are also of importance in decision-making. Any rise in the amount of solid waste stored should be monitored from the start of the landfill's operation until its closure.

The number of samples belonging to the surface is important in determining the volumetric changes. A low number of samples cannot accurately reflect the changes in the landfill. Thus, traditional in-situ surveys may not be preferable for landfill areas. In addition to their technical deficiencies, these surveys are time-consuming and dangerous, putting surveyors in direct contact with the solid waste. Herein, SfM applied using UAV is more useful in many ways. The UAV's affordability, its portability due to its weight and dimensions, its capability of low-altitude flight (which enables better GSD and accuracy), its ability to acquire data from difficult regions, its full reflection thanks to its ability to photograph with different angles, and its automation make its use more preferable. Even if low-cost UAVs, such as the DJI Phantom—or similar models, like Mavic or Spark—are not considered professional vehicles, a sufficient size of point cloud can be obtained with the contribution of the landfill structure and its environment. The fact that there are lots of color changes, which enables pixel value variability, has a positive effect on the performance of image-matching algorithms. One of the most obvious drawbacks concerns the unpredictability of broadcast quality at the time of flight, but this situation should not constitute a major problem given the correct flight timing and planning.

In these and many other studies, the sufficiency of UAVs was demonstrated by the same data sets produced by other techniques. For all that, since this is now an acknowledged phenomenon, studies should go further than simply verifying the resulting products obtained from image data using terrestrial geodetic techniques or laser scanning.

Future studies may take the form of an evaluation of other factors that are effective in the operation of the landfill. This may help provide better results in volume analyses. In addition, UAVs integrated with RTK modules can be included in the investigation of landfills, in order to reveal the effects of GCP distribution on the volumetric changes. Another key issue concerns the technique of acquiring photographs. Cameras mounted on low-cost UAVs generally have rolling shutters, mechanisms in which the photographed region is obtained by scanning in strips. This working principle can cause distortions for photographs taken in motion. A detailed investigation of the rolling shutter effect, determining the degree to which the desired accuracy is affected, may help provide better results.

Author Contributions: Conceptualization, A.H.I. and A.D. Data collection, A.D. Methodology, A.H.I. and D.Z.S. Data processing, A.H.I. Supervision, D.Z.S. and C.G. Literature surveys, A.H.I and C.G. Writing—original draft preparation, A.H.I. and A.D. Writing—review and editing, A.H.I., D.Z.S, and C.G.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Seadon, J.K. Integrated waste management—Looking beyond the solid waste horizon. *Waste Manag.* **2006**, *26*, 1327–1336. [CrossRef] [PubMed]
2. Mohee, R.; Mauthoor, S.; Bundhoo, Z.M.A.; Somaroo, G.; Soobhany, N.; Gunasee, S. Current status of solid waste management in small island developing states: A review. *Waste Manag.* **2015**, *43*, 539–549. [CrossRef] [PubMed]
3. Grazhdani, D. Assessing the variables affecting on the rate of solid waste generation and recycling: An empirical analysis in Prespa Park. *Waste Manag.* **2016**, *48*, 3–13. [CrossRef] [PubMed]
4. Maheshi, D.; Steven, V.P.; Karel, V.A. Environmental and economic assessment of 'open waste dump' mining in Sri Lanka. *Resour. Conserv. Recycl.* **2015**, *102*, 67–79. [CrossRef]
5. Manzo, C.; Mei, A.; Zampetti, E.; Bassani, C.; Paciucci, L.; Manetti, P. Top-down approach from satellite to terrestrial rover application for environmental monitoring of landfills. *Sci. Total Environ.* **2017**, *584–585*, 1333–1348. [CrossRef] [PubMed]
6. Cuartas, M.; López, A.; Pérez, F.; Lobo, A. Analysis of landfill design variables based on scientific computing. *Waste Manag.* **2018**, *71*, 287–300. [CrossRef] [PubMed]
7. Sumathi, V.R.; Natesan, U.; Sarkar, C. GIS-based approach for optimized siting of municipal solid waste landfill. *Waste Manag.* **2008**, *28*, 2146–2160. [CrossRef] [PubMed]
8. Wiesmeth, H.; Häckl, D. Integrated environmental policy: A review of economic analysis. *Waste Manag. Res.* **2017**, *35*, 332–345. [CrossRef] [PubMed]
9. Emran, B.; Tannant, D.; Najjaran, H. Low-Altitude Aerial Methane Concentration Mapping. *Remote Sens.* **2017**, *9*, 823. [CrossRef]
10. Tanda, G.; Migliazzi, M.; Chiarabini, V.; Cinquetti, P. Application of close-range aerial infrared thermography to detect landfill gas emissions: A case study. *J. Phys. Conf. Ser.* **2017**, *796*, 1–10. [CrossRef]
11. Gasperini, D.; Allemand, P.; Delacourt, C.; Grandjean, P. Potential and limitation of UAV for monitoring subsidence in municipal landfills. *Int. J. Environ. Technol. Manag.* **2014**, *17*, 1–13. [CrossRef]
12. VIncent, R.K. RemotSe ensinfgot SolidWasteLandfillasnd HazardoWusasteSites. *Photogramm. Eng. Remote Sens.* **1994**, *60*, 979–982.
13. Karathanassi, V.; Choussiafis, C.; Grammatikou, Z. Monitoring the Change in Volume of Waste in Landfill Using SAR Interferometry. In Proceedings of the 32 EARSeL Symposium 2012 Advances in Geosciences, Mykonos Island, Greece, 21–24 May 2012.
14. Immerzeel, W.W.; Kraaijenbrink, P.D.A.; Shea, J.M.; Shrestha, A.B.; Pellicciotti, F.; Bierkens, M.F.P.; de Jong, S.M. High-resolution monitoring of Himalayan glacier dynamics using unmanned aerial vehicles. *Remote Sens. Environ.* **2014**, *150*, 93–103. [CrossRef]
15. Gindraux, S.; Boesch, R.; Farinotti, D. Accuracy Assessment of Digital Surface Models from Unmanned Aerial Vehicles' Imagery on Glaciers. *Remote Sens.* **2017**, *9*, 186. [CrossRef]
16. Esposito, G.; Mastrorocco, G.; Salvini, R.; Oliveti, M.; Starita, P. Application of UAV photogrammetry for the multi-temporal estimation of surface extent and volumetric excavation in the Sa Pigada Bianca open-pit mine, Sardinia, Italy. *Environ. Earth Sci.* **2017**, *76*, 103. [CrossRef]
17. Obanawa, H.; Hayakawa, Y.S. Variations in volumetric erosion rates of bedrock cliffs on a small inaccessible coastal island determined using measurements by an unmanned aerial vehicle with structure-from-motion and terrestrial laser scanning. *Prog. Earth Planet. Sci.* **2018**, *5*, 33. [CrossRef]
18. Kasprzak, M.; Jancewicz, K.; Michniewicz, A. UAV and SfM in Detailed Geomorphological Mapping of Granite Tors: An Example of Starościńskie Skały (Sudetes, SW Poland). *Pure Appl. Geophys.* **2018**, *175*, 3193–3207. [CrossRef]
19. Niethammer, U.; James, M.R.; Rothmund, S.; Travelletti, J.; Joswig, M. UAV-based remote sensing of the Super-Sauze landslide: Evaluation and results. *Eng. Geol.* **2012**, *128*, 2–11. [CrossRef]

20. Turner, D.; Lucieer, A.; de Jong, S. Time Series Analysis of Landslide Dynamics Using an Unmanned Aerial Vehicle (UAV). *Remote Sens.* **2015**, *7*, 1736–1757. [CrossRef]
21. Colomina, I.; Molina, P. Unmanned aerial systems for photogrammetry and remote sensing: A review. *ISPRS J. Photogramm. Remote Sens.* **2014**, *92*, 79–97. [CrossRef]
22. Pajares, G. Overview and Current Status of Remote Sensing Applications Based on Unmanned Aerial Vehicles (UAVs). *Photogramm. Eng. Remote Sens.* **2015**, *81*, 281–330. [CrossRef]
23. Yazdani, M.; Monavari, S.M.; Omrani, G.A.; Shariat, M.; Hosseini, S.M. Landfill site suitability assessment by means of geographic information system analysis. *Solid Earth* **2015**, *6*, 945–956. [CrossRef]
24. Colvero, D.A.; Gomes, A.P.D.; da Cruz Tarelho, L.A.; de Matos, M.A.A.; dos Santos, K.A. Use of a geographic information system to find areas for locating of municipal solid waste management facilities. *Waste Manag.* **2018**, *77*, 500–515. [CrossRef] [PubMed]
25. Martínez-Espejo Zaragoza, I.; Caroti, G.; Piemonte, A.; Riedel, B.; Tengen, D.; Niemeier, W. Structure from motion (SfM) processing of UAV images and combination with terrestrial laser scanning, applied for a 3D-documentation in a hazardous situation. *Geomat. Nat. Hazards Risk* **2017**, *8*, 1492–1504. [CrossRef]
26. Mlambo, R.; Woodhouse, I.; Gerard, F.; Anderson, K. Structure from Motion (SfM) Photogrammetry with Drone Data: A Low Cost Method for Monitoring Greenhouse Gas Emissions from Forests in Developing Countries. *Forests* **2017**, *8*, 68. [CrossRef]
27. Westoby, M.J.; Brasington, J.; Glasser, N.F.; Hambrey, M.J.; Reynolds, J.M. 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology* **2012**, *179*, 300–314. [CrossRef]
28. Liu, Y.; Zheng, X.; Ai, G.; Zhang, Y.; Zuo, Y. Generating a High-Precision True Digital Orthophoto Map Based on UAV Images. *ISPRS Int. J. Geo-Inf.* **2018**, *7*, 333. [CrossRef]
29. Martínez-Carricondo, P.; Agüera-Vega, F.; Carvajal-Ramírez, F.; Mesas-Carrascosa, F.-J.; García-Ferrer, A.; Pérez-Porras, F.-J. Assessment of UAV-photogrammetric mapping accuracy based on variation of ground control points. *Int. J. Appl. Earth Obs. Geoinf.* **2018**, *72*, 1–10. [CrossRef]
30. Gao, W.; Xu, W.; Bian, X.; Chen, Y. A practical approach for calculating the settlement and storage capacity of landfills based on the space and time discretization of the landfilling process. *Waste Manag.* **2017**, *69*, 202–214. [CrossRef]
31. Yakar, M.; Yilmaz, H.M.; Mutluoglu, O. Close range photogrammetry and robotic total station in volume calculation. *Int. J. Phys. Sci.* **2010**, *5*, 86–96.
32. Cook, K.L. An evaluation of the effectiveness of low-cost UAVs and structure from motion for geomorphic change detection. *Geomorphology* **2017**, *278*, 195–208. [CrossRef]
33. Tien Bui, D.; Long, N.Q.; Bui, X.-N.; Nguyen, V.-N.; Van Pham, C.; Van Le, C.; Ngo, P.-T.T.; Bui, D.T.; Kristoffersen, B. Lightweight Unmanned Aerial Vehicle and Structure-from-Motion Photogrammetry for Generating Digital Surface Model for Open-Pit Coal Mine Area and Its Accuracy Assessment. In *Advances and Applications in Geospatial Technology and Earth Resources*; Tien Bui, D., Ngoc Do, A., Bui, H.-B., Hoang, N.-D., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 17–33, ISBN 978-3-319-68239-6.
34. Martin, C.; Parkes, S.; Zhang, Q.; Zhang, X.; McCabe, M.F.; Duarte, C.M. Use of unmanned aerial vehicles for efficient beach litter monitoring. *Mar. Pollut. Bull.* **2018**, *131*, 662–673. [CrossRef] [PubMed]
35. Messinger, M.; Silman, M. Unmanned aerial vehicles for the assessment and monitoring of environmental contamination: An example from coal ash spills. *Environ. Pollut.* **2016**, *218*, 889–894. [CrossRef] [PubMed]
36. Puniach, E.; Bieda, A.; Ćwiąkała, P.; Kwartnik-Pruc, A.; Parzych, P. Use of Unmanned Aerial Vehicles (UAVs) for Updating Farmland Cadastral Data in Areas Subject to Landslides. *ISPRS Int. J. Geo-Inf.* **2018**, *7*, 331. [CrossRef]
37. Tahar, K.N.; Kamarudin, S.S. UAV Onboard GPS in Positioning Determination. *ISPRS Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2016**, *XLI-B1*, 1037–1042. [CrossRef]
38. Glendell, M.; McShane, G.; Farrow, L.; James, M.R.; Quinton, J.; Anderson, K.; Evans, M.; Benaud, P.; Rawlins, B.; Morgan, D.; et al. Testing the utility of structure-from-motion photogrammetry reconstructions using small unmanned aerial vehicles and ground photography to estimate the extent of upland soil erosion: Unmanned aerial vehicles and ground photography to estimate erosion. *Earth Surf. Process. Landf.* **2017**, *42*, 1860–1871. [CrossRef]

39. Salach, A.; Bakuła, K.; Pilarska, M.; Ostrowski, W.; Górski, K.; Kurczyński, Z. Accuracy Assessment of Point Clouds from LiDAR and Dense Image Matching Acquired Using the UAV Platform for DTM Creation. *ISPRS Int. J. Geo-Inf.* **2018**, *7*, 342. [CrossRef]
40. Gonçalves, G.R.; Pérez, J.A.; Duarte, J. Accuracy and effectiveness of low cost UASs and open source photogrammetric software for foredunes mapping. *Int. J. Remote Sens.* **2018**, *39*, 5059–5077. [CrossRef]
41. Kršák, B.; Blišťan, P.; Pauliková, A.; Puškárová, P.; Kovanič, Ľ.; Palková, J.; Zelizňaková, V. Use of low-cost UAV photogrammetry to analyze the accuracy of a digital elevation model in a case study. *Measurement* **2016**, *91*, 276–287. [CrossRef]