Probabilistic Cellular Automata Based Approach for Prediction of Hot Mudflow Disaster Area and Volume

Achmad Basuki, Tri Harsono, and Kohei Arai

Abstract—Probabilistic Cellular Automata based approach for prediction of hot mudflow disaster is proposed. Hot mudflow spread like fluid dynamic with velocity, viscosity and thermal flow parameters. Therefore, a prediction model based on fluid dynamic is proposed. We use Cellular Automata approach because that is relatively simple and have a good enough performance for visualization of fluid dynamics. We use much simpler approach based on discrete Cellular Automata model for simulation of hot mudflow with adding some probabilistic parameters based on Gaussian function. We add some new rules to represent hot mudflow movement such as moving rule, precipitation rule, obstacle-changing rule and absorption rule. The prediction results show high accuracy elevation changes at the predicted points and its surrounding areas. We compare these predicted results to the digital elevation map derived from ASTER/DEM. We use some period maps to evaluate the prediction accuracy of the proposed method.

Index Term—Fluid Dynamic, Hot Mudflow, Prediction, Probabilistic Celullar Automata

1 INTRODUCTION

SIDOARJO hot mudflow disaster is one of the biggest unstoppable disasters that occurred on May 29th 2006 suddenly caused by a gas exploration. During the first three years, the disaster destroyed some villages, thousand of houses and buildings, farmings, schools, markets and factories. Over 21,000 people had lost their homes and their works. The weight of the mud on the ground is reported already and is corresponding to the weight for pressing down a large area of Sidoarjo land by approximately one meter. Nowadays mud blows around 150,000m per day [1]. It is also reported that the plumed mud contains 70% of water. It implies that 687,000-barrel water is spread out every day. How big impact of disaster are in environment, economic and human resource in the future if this disaster cannot be stopped [2].

Figure 1 shows how big impact of disaster in environment, economic and human resource in future if no solution can be used to stop it. One possible solution can be used to reduce disaster impact if it cannot stop is spillway to Porong River. This solution can reduce mudflow spreading, but it is not a real solution to help people in the inundated area. They always ask when their home will be surrounding. The other word, the current problem is how to reduce this impact, and disaster impacts that may be reduced by disaster prediction. If inundated area can be predicted before the mudflow comes, government will anticipate more accurately to reducing the impact.

Assuming that mudflow is similar to fluid flow, the fluid-flow model creates the prediction model of mudflow movement. The simple fluid-flow model proposed by Argentini [4]

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Figure 1. Hot mudflow disaster map from SPOT 5 [3]

uses Cellular Automata that are proposed here. This model is useful for visualization of fluid flow phenomena with some parameters such as volume, velocity and obstacle avoidance. This model cannot be used for mudflow simulation because it does not handle viscosity and thermal parameter. The other model is lava flow model proposed by Vicari [5]that is based on a Cellular Automata approach. This model is better model for representation of hot mudflow because it can treat the parameters, volume, velocity, viscosity and thermal situations. The Cellular Automata approach can visualize hot mudflow disaster in free-space area. It, however, is necessary to add some additional approaches for visualization of the actual conditions those are not only natural conditions, but also human factor parameters such as dike, building and road, thus a combination of Argentini's and Vicari's models is proposed. It should be a better prediction model of hot mudflow spreading with a consideration of the human factors. Since the Argentini's model uses limited integer state and Vicari's model uses floating point state, the proposed model uses a discrete model with floating points.

We need prediction model of mudflow movement for determining inundated location in future, but it will be very complex because many parameters have to be considered in this model. A model for predicting hot mudflow needs many parameters not only geological parameters but also social parameters and government policy. In this paper we want to show the simple model of mudflow movement using assumption that mudflow is similar to fluid flow, Albertini [4] and lava flow, Vicari [5]. This model is a preliminary model of mudflow movement.

The proposed model uses Cellular Automata with stochastic lattice Boltzmann, neighbor weight-moment to determine direction of mudflow movement and Navier Stroke approach to calculate volume of mudflow movement. On precursor model, we can visualize mudflow movement like a combination between fluid flow and lava flow models. Although the model has a good visualization capability of mudflow movement, we have to add some properties, map data and rules to make it better to show the actual conditions that have some obstacles like dikes and building. The proposed prediction model is to inform of where some inundated locations are. It will be used to restrain geological impact of hot mudflow disaster. We use some basic parameters of dynamic system to simulate prediction model. That is an approximation model to describe actual model for representation of actual situations. We use ASTER (Advanced Spaceborne Thermal Emission and Reflection)/DEM (Digital Elevation Model) data for landscape map of the disaster area and its surrounding area on some periods in order to show how the prediction results and the actual situations differ. Prediction accuracy of the proposed method is also compared to the other fluid-flow models with the reference to the ASTER/DEM derived elevation as a true landscape map.

2 THEORITICAL BACKGROUND

2.1 Cellular Automata

Cellular Automata (CA) are a set of array of automaton called cell. They interact one to another cells. Array model of CA is expressed with one-dimensional shape, two-dimensional

(2D) model grids, or three-dimensional (3D) solids. Almost all the cells are aligned at the simple lattice points, but are aligned in a complicated form like honeycomb in other rules. Finally, CA is a simple model to describe the complex system of life.

As simple model, CA only has three fundamental properties, state, neighborhood and program. The state is a given variable for defining each cell. It can be shown in numbers or properties. In simple way, each cell is written as sub-landscape; therefore state is a sum of individual location or type of growing area. The neighborhood is a set of cells. That interact each other in the physical grid, and two fundamental neighborhood models are Von Nuemann Neighborhood and Moore Neighborhood as are shown in Figure 2. The program is a set of defined rules to change state as response in a time depending on its neighborhood. In CA model approach, we can develop some new rules based on state condition and neighborhood.

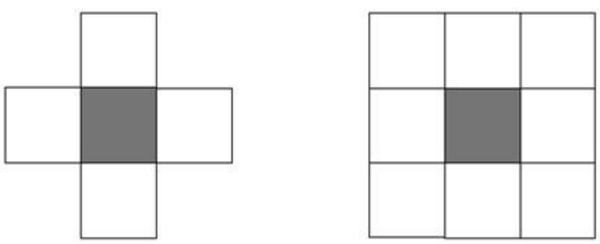

Figure 2. Neighbor model in 2D Cellular Automata (a) The Von Neumann Neighborhood (b) The Moore Neighborhood

2.1.1 *Cellular Automata Algorithm*

Mathematically point of view of cellular automata, the state at position (i,j) at time t written $s_t(i,j)$ will change into $s_{t+1}(i,j)$ in time $t+1$ with rule that can be written:

$$S_{t+1}(i,j) = \bigotimes_{u,v} S_t(i+u, j+v) \tag{1}$$

Where: u, v are position of its neighbors.

Formally cellular automata have three basic components [12] such as:

- A regular lattice of cells covering a portion of n-dimensional space
- A set of

$$S(\vec{r},t) = S_1(\vec{r},t), S_2(\vec{r},t), \cdots, S_m(\vec{r},t)$$

  of Boolean variables attached to site $\vec{r}$ of the lattice and giving a local state of each cell at time $t = 1, 2, 3, ...$
- A rule $R = \{R_1, R_2, \cdots, R_k\}$ which specific function of state $S(\vec{r},t)$ that is written:

$$S_j(\vec{r}, t+\tau) = R_j\{S_j(\vec{r},t), S_j(\vec{r}+\delta_1, t), \cdots, S_j(\vec{r}+\delta, t)\}$$

  Where $\vec{r}+\delta_j$ is given neighbor.

2.1.2 *Fluid Dynamic Cellular Automata*

CA model can be used to describe fluid dynamic phenomena such as fluid flow, lava flow and gases dynamic. There are four types of update state changing model in fluid dynamic CA as is shown in Figure 3, such as growth model [5][8], Icing-Like dynamic model [8], moving model [9] and majority model [10]. These models have different state types and update state rules. Many fluid-dynamic models use growth model and moving model such as Argentini's model and sea-wave simulation. The other models - Icing-Like model and majority model - usually use to append the properties of fluid dynamic such as viscosity as shown as lava flow model and mudflow model.

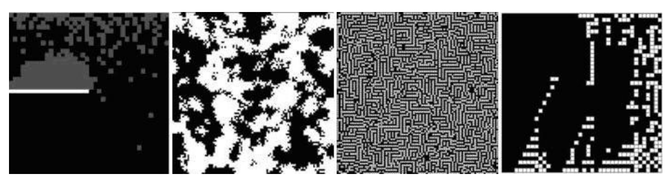

Figure 3. Four update state changing models in Cellular Automata (a) Growth model, (b) Majority model, (c) Icing-like model, (d) Moving model

The main focus in fluid dynamic is update rules, and the main processes are collisions between cells, and cell moving in these rules. Example common rules in fluid dynamic, introduced by Albertini [4] as shown in Figure 4(a), are rules of cell moving because these rules run if the state has fluid particle or $s_t(i,j) = 1$. These rules use Moore neighborhood, and the direction of cell moving depends on neighbor position because it relates on force of particle interaction. These rules also are basic simple rules of fluid dynamic for simulate flood hazard [9]. The result of these rules is shown on figure 4(b).

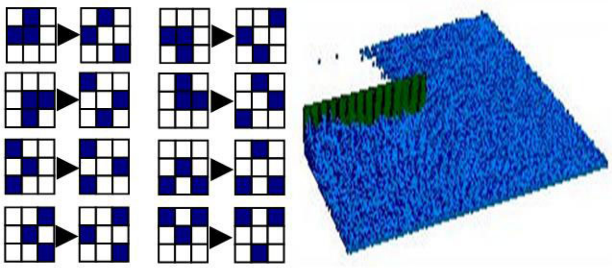

Figure 4. (a) Example rule in Albertini's Model [3], (b) The result for fluid dynamic

Another model for fluid flow model, developed by Avolio [11], is Cellular Automata model for simulation of 1992 Tessina Landslide. This model is mudflow model, and uses Von-Neumann neighborhood. It is quite different with Argentini's model and Vicari's model because this model uses floating point states and the example rules on this model as shown in Figure 5. This model is simple and useful, and has good performance for landslide caused by mudflow. But on high volume mud blows, this model has a problem to identify how much mud will move to other area because there is no eliminated cell on center of mud blows.

Combination of basic rule on Albertini's model, and Vicari's model makes a new Cellular Automata approach to simulate landslide cause by mudflow. We add some probabilities values on transport mass rules to simulate hot mud flow that has a good performance to predict where mud will flow in the future.

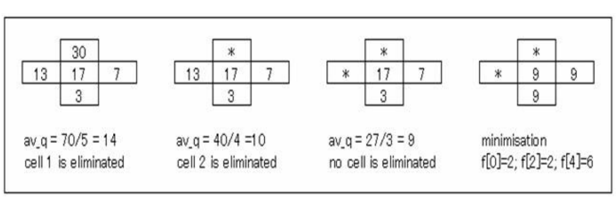

Figure 5. Example rule in Von-Neumann neighborhood model, Avolio[11]

3 Proposed Metodology

Hot mudflow model is similar to fluid dynamic flow model. We, however, need to combine all basic updating state models of CA to make it look like real condition because the state properties in each algorithm is binary state unless growth model, otherwise mudflow model is floating point model. In this research, we combine fluid dynamic flow model from Argentini and lava flow model. Our model uses Argentini's model as primary model because the Argentini's model is very simple model based on growth model to describe fluid dynamic flow with discrete state. The Argentini's model, however, is not enough to describe mudflow because there are how to move and growth fluid particles, but also viscosity, erosion and deposition.

3.1 Variables

As many fluid-dynamic Cellular Automata models, our model uses 2D Cellular Automata with Moore neighborhood (8 neighbor nodes). But we use floating-point states in order to describe current states of mudflow map, it is different with Albertini's model because floating-point state is more easy to define map data similar with real data. The state S is float between 0 and 1. In this research, we define three-type variables: mud $s_t(x,y)$, ground $h_t(x,y)$ and dike (use same variable with ground because the dike have same characteristics

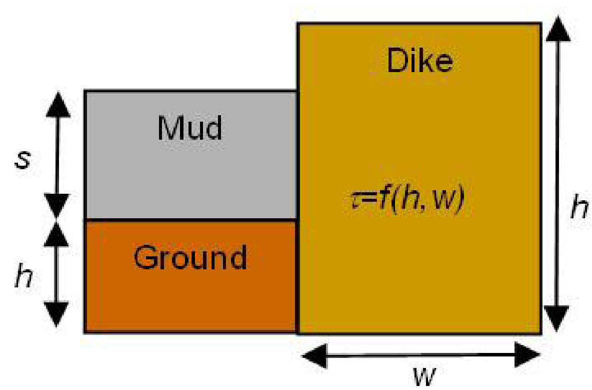

Figure 6. Three type variables

3.2 Rules

We define $s_t(x,y)$ as number of mud particles on node (x,y) in time t, $T_t(x,y)$ is temperature on node (x,y) in time t and elementary rules in update state:

1) Mud blows in the center point (c_x, c_y) with mud volume vol as shown in figure 7, that is written by:

$$S_{t+1}(c_x+\delta_x, c_y+\delta_y) = s_t(c_x, c_y)+vol.G(\delta_x, \delta_y)$$

$$T_{i+1}(c_x+\delta_x, c_y+\delta_y) = T_0 \qquad (2)$$

Where:

(δ_x, δ_y)	is a neighbor points
$G(\delta_x, \delta_y)$	is Gaussian function of mud blow
T_0	is initial temperature on center area of mud blow.

We use uniform temperature on center area

2) Mud is situation at the every lattice point. The mudflows from a higher position to lower neighborhood with probability pv as the function of height different, volume and velocity as is shown in Figure 8. The number of moving mud, which is based on this rule, can be expressed by the following equation:

$$\begin{gathered} m(x,y) = h_t(x,y) + s_t(x,y) \\ s_t(x,y) > 0, m(x+\delta_x, y+\delta_y) < m(x,y) \\ s_{t+1}(x+\delta_x, y+\delta_y) = s_t(x+\delta_x, y+\delta_y) + \varepsilon \\ s_{t+1}(x,y) = s_t(x,y) - \varepsilon \\ T_{t+1}(x,y) = T_t(x,y) - d(m(x,y)), \varepsilon \end{gathered} \qquad (3)$$

Where:

$$\begin{aligned} \varepsilon &= 3\ p_v.D.(1-\tau(x+\delta_x, y+\delta_y)) \\ D &= m(x,y) - m(x+\delta_x, y+\delta_y) \\ pv &= \text{Probability to move} \end{aligned}$$

$d(m(x,y), \varepsilon)$ is function of heat transfer

3) Mud changes its material into solid particles by pvis of the probability as the function of viscosity as is shown in Figure 9. The number of moving mud, which

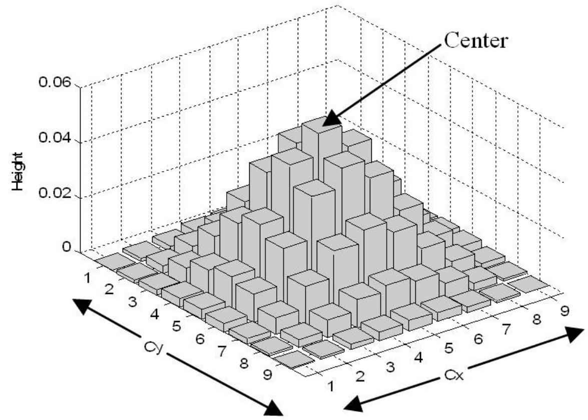

Figure 7. Mud blow in center point (c_x, c_y) and its neighbors

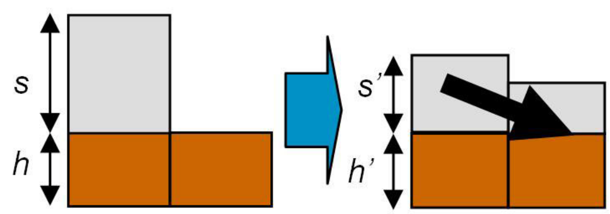

Figure 8. Mudflow rules: moving rule

is based on this rule, can be represented with the following equation:

$$\begin{aligned} s_{t+1}(x,y) &= s_t(x,y) - \alpha, \\ h_{t+1}(x,y) &= h_t(x,y) + \alpha \end{aligned} \qquad (4)$$

Where:

$$\begin{aligned} \alpha &= p_{vis}.\,(1-p_v)\,.P_T/10 \\ P_T &= 2 - e^{-KT_t(x,y)} \end{aligned}$$

K is constants, and $T_t(x,y)$ is temperature on node (x,y) at time t.

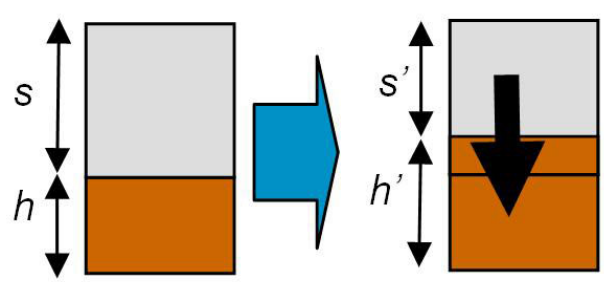

Figure 9. Mudflow rules: viscosity rules.

3.3 Defining Mudflow Model

Mudflow movement simulation use 2D cellular automata with Moore neighbor model (8 neighbor nodes). Every node that flows presents the mud to lower neighbor by probability Pm. Majority algorithms in cellular automata and lattice Boltzmann built many fluid models. This algorithm has rules that will change the state $s_{t+1}(i,j)$ at time $t+1$, with the majority value of neighbor. But these algorithms are still binary composition, and cannot use in our model that have parameter in floating points.

Our algorithm to simulate mudflow as fluid flow is as follows,

- Define $h(x,y)$ height for all point (x,y) as landscape data
- Define mud volume/periods; we convert the real mud volume to number of point volumes.

For each period, it updates map with mud appear in the top of surface.

- Order the height on every neighbor hs.
- Determine percentage of moving to neighbor ps, using neighbor distance and Gaussian Function Interpolation.

$$S_{t+1}(i+\delta, i+\delta) = G(\delta) \quad (5)$$

Where δ is neighbor space, and $G(\delta)$ Gaussian function of neighbor space.

- Using the percentage of moving to neighbor, we choose randomly the direction of mudflow using rejection algorithm.

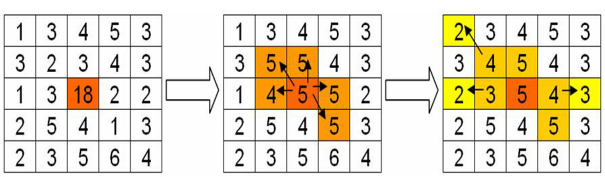

Figure 10. Recursive rules for mudflow movement

Figure 10 shows the simple rule in our model to simulate mudflow movement with constant velocity and viscosity. This rule finds lowest neighbor and arrange that height of center has smoothly slope with its neighbors. In the left picture the center point has maximum difference = 5 with its neighbors. When maximum difference is greater than α (tolerance value to make pile shape), the particle will be move to lower point with probability $G(\delta)$. The right picture shows all points have small differences with each others.

4 Experiment Result

4.1 Data Spesification

We use SPOT-5 of HRV (Satellite Pour l'Observation de la Terre-5/High Resolution Visible) image as a base map as is shown in Figure 11(a). HRV size is 447487 pixels, which is corresponding to 3.7km4km area, it means one pixel has area 8.27m8.21m. We also use ASTER/DEM data for determination the landscape of intensive study area. The spatial resolution of ASTER/DEM is 30m30m. SPOT-5/HRV image have good enough spatial resolution for relief the intensive study area. It, however, has not well information of landscape so that ASTER/DEM data is used for creation of landscape. Re-quantization and interpolation between ASTER/DEM and some height of dike derived from SPOT-5/HRV are required. The resultant images are shown in Figure 11(b). This figure is quantization map in February 2008.

Figure 11. (a) SPOT 5 image [3], (b) Landscape map image after quantization

Sidoarjo hot mudflow disaster is one of big disaster because mud blows around $150.000m^3$ per day, and mud volumes come out. The mud consists 70% of water and its surface temperature is around 90^0C.

4.2 Simulation Result

In order to find inundated area in the future, CA parameters such as spatial resolution and volume scaling have to be optimized for making the prediction much better. We use SPOT-5/HRV data in order to show the disaster area clearly. Figure 12(a) show map of actual disaster area in August 2008 while Figure 12(b) shows its simulation result.

Figure 13 shows the comparison between map of actual disaster areas colored in blue area and the simulation result colored in red area, respectively. The magenta colored area shows the intersection between map of actual disaster area and the simulation result. In this figure, although there is some different areas between map of actual disaster area and the simulation result, the direction of mudflow and inundated area are quite similar between both. Although the simulation result that is shown in the figure is derived from CA, it is possible to create a new model of mudflow with some other adding parameters such as dike and mud parameters. On this simulation, we find the same inundated location on the outside of dike. The inundated location in our simulation result is on the east and south that same with the real condition of hot mudflow disaster. The overlay of the new inundated area between real map and simulation result is 36.44%. This result shows that our algorithm can predict the future inundated area in the correct direction of mudflow using ordinary resolution landscape map on ASTER DEM or high resolution landscape map on SPOT 5.

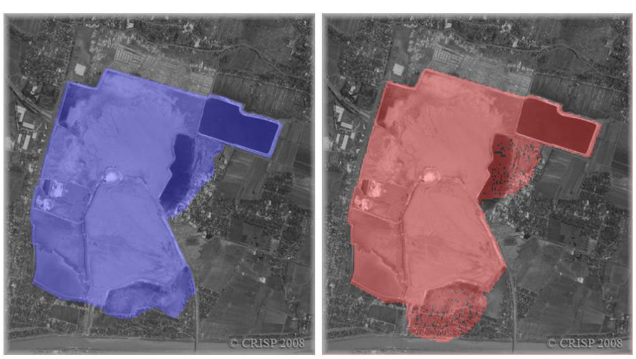

Figure 12. Actual disaster area maps of disaster area on August 2008 (a), and the simulation result map(b)

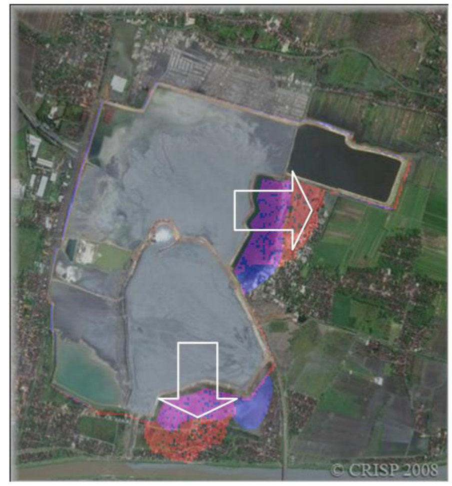

Figure 13. Comparison between simulation result and actual disaster area map

The important parameter on our simulation is lattice size or resolution. Table 1 shows the simulation results that are based on the map resolution that are shown in Figure 11. In the simulation, we use the resolution of 5.71m-20m for a pixel. The simulation result of the intersection area shows that prediction accuracy is increasing in accordance with increasing resolution as shown in figure 14. It implies that the CA approach needs a high-resolution map to improve the accuracy.

Table 1
Simulation result based on resolution

Resolution		Area(%)	
Pixels	**Meters**	**Intersection**	**Error**
200x200	40.00	92.13	7.87
400x400	20.00	93.53	4.47
500x500	16.00	94.00	6.00
600x600	12.67	94.73	6.27

Our Cellular Automata approach is also more accurate than the previous approach such as Vicari approach for hot mudflow disaster that occurs on the plane area with many structures such as building and road. We compare our approach with the Vicari approach because Vicari approach has more similar parameters than other approaches such as Argentini approach.

Figure 15 shows comparison of our approach and Vicari approach for hot mudflow disaster. Both approaches show the correct direction and

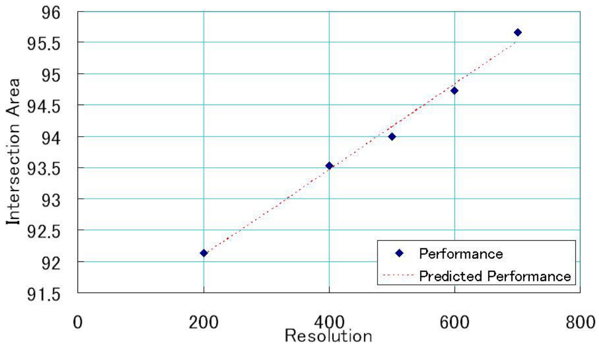

Figure 14. Simulation result based on resolution

location, but our approach has better result on detail locations. Our approach is obtained the improvement on detail locations. The Vicari approach has the intersection area about 36.29%, and our approach has the intersection area about 36.44% on resolution 400x400.

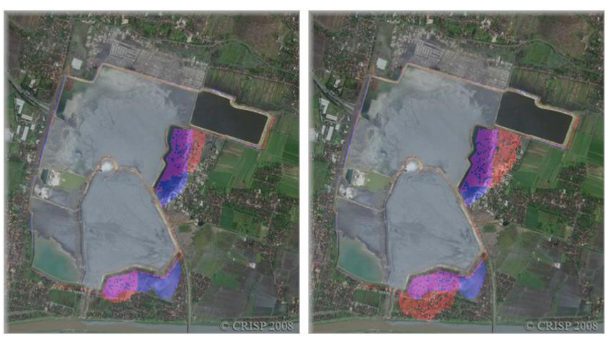

Figure 15. Comparison of our approach and Vicari approach on the hot mudflow

Another simulation result of elevation changes at hot mudflow erupted areas is shown in Figure 16. This result shows that mud elevation is changed depending upon the initial and the final conditions. This simulation will show the mud height changing on red line area.

Figure 17 shows the one-dimensional profile of the mud elevation changes. The red line shows the mud elevation at the initial state that we take the landscape data of February 2008. The green line shows the mud elevation at the final state, three months later from the initial state. The average elevation difference between the initial and the final state is 1.01meter. It implies that the mud elevation changes about 0.3meter per-month from February 2008 to August 2008, and the real mud height changing is about 0.4meter per-month on the center area or inside the dike [1].

Figure 16. Location and direction of observation; (a) south area; (b) north-east area

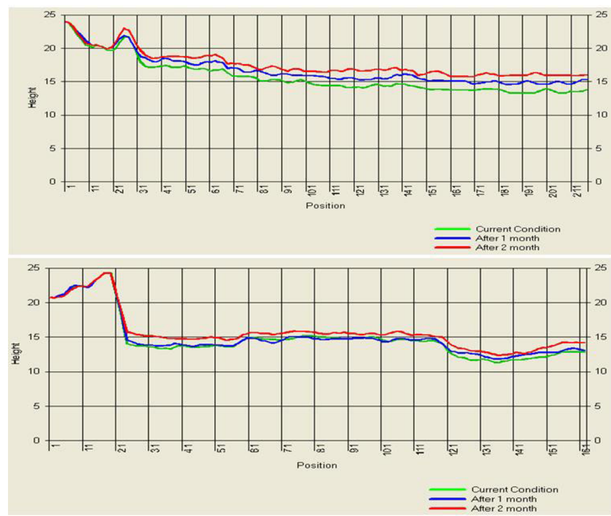

Figure 17. The mud height at every point along at red line area in Figure 16.

5 Conclusion and Discussion

Cellular Automata approach is a model-based approach that depends on some parameters such as resolution, neighborhood, and rules. This model is accurate when the resolution is appropriate for representation of particles or cells. Meanwhile the proposed model makes a relaxant on the required resolution. Even for the minimum resolution of 100×100 pixels, the proposed method makes an enough simulation result (the maximum resolution is 2000×2000 pixels). The minimum resolution is corresponding to $37m \times 40m$ a pixel that is also corresponding to the lower resolution of ASTER/DEM data with $30m \times 30m$ so that the proposed method is justified and evaluated with ASTER/DEM data. The maximum resolution (700×700 pixels) of simulation result is shown here. This resolution corresponds to $10m \times 10.71m$ a pixel. It is concluded that the proposed method is valid for detection and prediction of hot mudflow spreading direction and volume as well as appropriate inundated areas that are situated surrounding areas.

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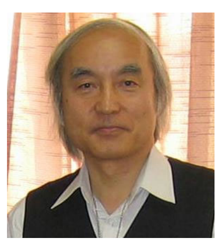

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