Safety Science xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

A dynamic decision support system based on geographical information and mobile social networks: A model for tsunami risk mitigation in Padang, Indonesia

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ARTICLE INFO

Article history:
Received 17 July 2015
Accepted 13 September 2015
Available online xxxx

Keywords:
Dynamic decision support system
Geographic information system (GIS)
Twitter
Emergency evacuation route map
Acquirable affinity information of leader election
Coverage-based probabilistic forwarding message broadcast
Padang, Indonesia
Tsunami risk

ABSTRACT

In coastal cities, population and property are concentrated in small areas, with abundant resources and convenient transportation, but also with potential tsunami risk, as shown by the tsunami disasters of 2004, 2010 in Indonesia. Coastal area citizens need to evacuate to a safe place as soon as tsunamis occur. The prime evacuation time is very critical for them, but it is delayed in practice by complex information transfer processes. In recent years, spatial information has become an important resource used in dynamic decision support for emergencies, and smart phones have become a primary social communication device during interactions in emergencies. This paper outlines the design and development of a prototype geographical information system centric, social media based dynamic decision support system (GIS-SM-DDSS) that integrates geographical information with Twitter technology to enable self-organized information networks to support decision making and collective actions in emergency situations. The actors include government policy makers, policy managers, highly influential social leaders in local communities, and policy executors and urban citizens impacted by disasters. The main system functions include dynamic disaster risk analysis, timely dissemination of evacuation strategies to community residents, and real-time detection of environmental risk and evacuation support. This system is designed as a field experiment in Padang, Indonesia, to help public officials design tsunami risk maps with timely evacuation routes and transmit these maps to influential leaders in local neighborhoods that are exposed to tsunami risk. Each neighborhood leader would then tweet the detailed route to citizens that follow the tweet. The proposed has potential to support evacuation strategies and real-time guidance of communities at risk during disaster.

1. Introduction

In event of a tsunami, urban residents in coastal cities at risk need to evacuate to safe areas. The local government has legal responsibility to develop a tsunami risk map (Billa et al., 2011) and design pre-disaster policies to guide the evacuation process (Comfort et al., 2013). The German undersea infrastructure, used in the 2010 Indonesian tsunami (Steinmetz et al., 2010), is designed to provide to real-time warning information, critical to the decision support system. The warning information, however, is first sent to Badan Meteorologi, Klimatologi, Dan Geofisika (BMKG), the Agency for Meteorology, Climatology and Geophysics, for official interpretation. The information is then disseminated to the public. This extra step requires additional time for validation in a very short window for warning and evacuation. This paper takes a different approach to reduce the audit time and transfer steps required by existence tsunami alert systems to disseminate warning information. The basic tenet of the proposed approach is the development of a warning system, which integrates a GIS with a sensor-based undersea infrastructure and social media, to disseminate valid warning messages to community citizens directly from the local Emergency Operations Center (EOC) to evacuation.

Information technology offers a promising means for decision support in enabling public awareness and action in reducing disaster risk. Among current information technologies, Geographic Information System (GIS) has been used in natural disaster risk assessment (Sinaga et al., 2011; Bakar Sambah and Miura, 2014), risk management (El-heishy et al., 2012), dynamic evacuation decision support modeling (Cova et al., 2011; Zerger and Smith, 2003) and scenarios simulation (de Silva and Eglese, 2010). GIS is

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http://dx.doi.org/10.1016/j.ssci.2015.09.022
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Please cite this article in press as: Ai, F., et al. A dynamic decision support system based on geographical information and mobile social networks: A model for tsunami risk mitigation in Padang, Indonesia. Safety Sci. (2015), http://dx.doi.org/10.1016/j.ssci.2015.09.022

especially useful for community scale online disaster evacuation support, which uses people as sensors to build a dynamic risk monitoring network and database, response actions in real-time (Laituri and Kodrich, 2008), pre-disaster emergency evacuation zoning for disaster prevention and mitigation (Ye et al., 2012), and dynamic evacuation routing (Chitumalla et al., 2008) for communities with high population densities using smart phones (Oxendine et al., 2012).

Citizens in communities exposed to risk heavily rely on online social–technical networks to communicate and organize collective action during disasters and in their aftermath. Social media, such as Twitter, offer public information services, including disseminating warning information from government to the public (Chatfield et al., 2013) and enabling opportunistic communication of critical information among members of communities at risk in emergency situation (Hossmann et al., 2011). Through the use of mobile devices, with well-designed applications, citizens can dynamically form and become part of self-organizing information networks (Wukich and Steinberg, 2013), enabling significant changes in the way communities at risk behave and manage disaster (Lu and Brelsford, 2014). It has been argued that opportunistic, community-driven, self-organized information networks, when supported properly by a reliable and timely warning information system, have great potential to reduce uncertainty in emergency situations with positive psychological effects on members of communities at risk (Umihara and Nishikitani, 2013). Opportunistic routing (OR) in ad-hoc networks, an emerging wireless technology to support device to device peer communication, is a viable solution to enable the spontaneous formation of self-organized citizen networks for collaborative action in emergency situations. Ad-hoc networks represent a class of wireless networks that do not rely on the existence of a wireline infrastructure, such as cellular technology or wireless access points, to achieve communications between different nodes. Such a unique characteristic is not only valuable, but critical, in emergency situations where the breakdown of essential communications is a very likely outcome in most, if not all, tsunami disasters. In opportunistic, multi-hop ad-hoc networks, packets travel opportunistically over available communications paths, enabling rapid dissemination of information among neighboring wireless devices (Biswas and Morris, 2004). The network resource utilization can potentially reach its instantaneous maximum, in spite of volatile changes in network topology and traffic load.

In this paper, we seek to harness the real value and potential of social media and wireless opportunistic routing, to interconnect community members for disseminate information, in the development of a disaster management decision support system. To this end, we propose a framework that integrates GIS and Twitter technology to streamline the tsunami information dissemination process in support of an effective local information system for collective decision making and interaction between the local EOC and the members of the community it serves. (Middleton et al., 2014). GIS-SM-DDSS integrates real-time space and time information, ranging from underwater sensor tsunami warning data to tweets posted by members of communities at risk, and uses opportunistic information exchange between mobile devices to support collective decision making and public actions in disaster management.

When a near-field tsunami is detected, the undersea sensor and optic fiber based warning system relays tsunami alerts to a land-based EOC. In response, the emergency managers (EMs) identify an evacuation route map, using the DDSS, and timely tweet the status of the threat, along with the route map, to community leaders. Using opportunistic wireless communications among mobile devices, community leaders forward the evacuation route map to their followers to guide and assist them with the evacuation plan toward safe shelters. This process is illustrated in Fig. 1, community leaders in different regions of Padang City, depicted in blue circles, interactively engage their followers, depicted in green circles, in the evacuation process to safe shelters. During this interaction, environmental changes that impact the evacuation route, such as the collapse of a bridge on the way to the shelter, reported in real-time by emergency managers or members of the community are conveyed to community residents, along detour information to guide them toward safe shelters.

The remaining paper is organized as follows: Section 2 presents the overall system architecture and users communication in a sociotechnical network based on Coverage-based Probabilistic Forwarding in Ad Hoc routing. Section 3 explains the community leader election principle. Section 4 describes the logic layer structure

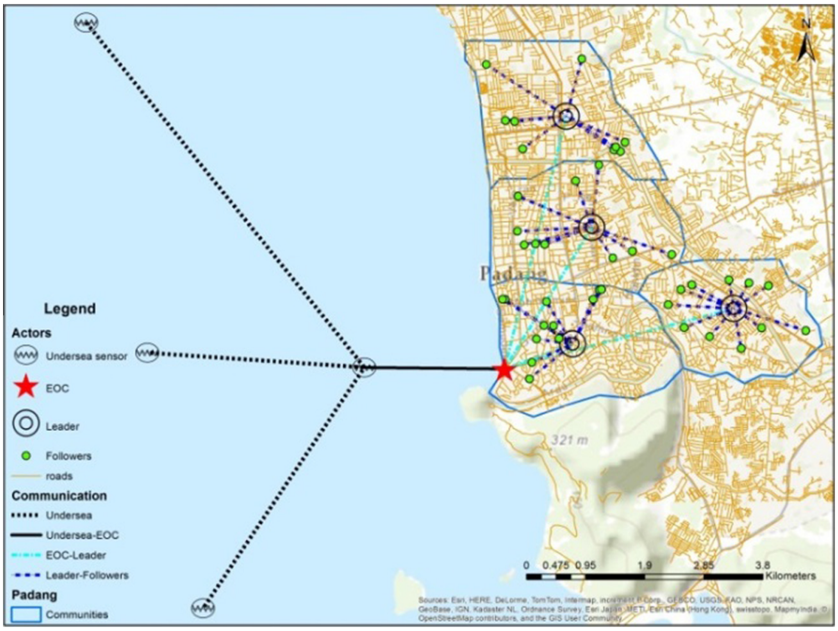

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Fig. 1. Monitor and social network in study area.

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of the Dynamic Decision Support System. Section 5 uses the near-field tsunami risk in Padang, Indonesia as a case study to illustrate the potential application of this DDSS for early tsunami warning and evacuation.

2. Opportunistic infrastructure for tsunami disaster management

The GIS-SM-DDSS architecture is illustrated in Fig. 1. GIS-SM-DDSS supports three primary types of actors, namely policy makers, who develop decision strategies and plans for evacuation, policy communications directors, who communicate evacuation information to the pub, and emergency managers, who direct and supervise the evacuation process. In emergency situations, these actors operate and interact under stringent time constraints.

Representatives of organizations associated with higher levels of government occupy the community EOC (Fig. 2a). Their main functions include managing operational resources and making policy decisions during emergency situations. As soon as they receive tsunami early warning information, the government policy makers, assisted by the DDSS (Fig. 2c), design emergency policies and develop evacuation plans to guide public evacuation, taking into consideration stored information regarding public vulnerability and existing social networks.

Emergency managers are responsible for distributing evacuation information to the public and the media. In the GIS-SM-DDSS framework, the role of emergency managers is to evaluate the potential tsunami risk, identify evacuation routes using spatial maps, and disseminate emergency decisions and policies to community leaders from the EOC, using a range of communication technologies, including Twitter.

In their effort to reach a large portion of the community in timely and reliable fashion, the emergency managers specifically target community leaders, in disseminating evacuation route maps and shelter information. Local leaders forward opportunistically this information to their neighboring followers, who, in turn, forward it to their community members located within their device's transmission range. The process continues iteratively, enabling a human-centric sociotechnical system for information dissemination and community mobilization for collective action and response to tsunami disaster (Fig. 2b). If local neighborhoods are impacted by the tsunami, the community leaders report the damage to the EOC, enabling the EMs to revise evacuation strategies and mitigate the impact of damage on the evacuation process.

The rapid transfer of critical information from government policy makers to emergency managers to the public through interconnected networks of social media, including Twitter and opportunistic wireless networking among mobile devices (Fig. 2b), improves the interaction between all disaster management stakeholders. Furthermore, the multiway feedback process provides valuable real-time decision support to neighborhoods at risk and enhances community resilience to disaster.

3. Socially-aware, leader-centric tsunami information distribution

Social opportunistic networks provide a flexible and cost-effective framework for message exchange and content dissemination among members of a local community. The ability to use opportunistic routing and peer-to-peer wireless communications to distribute important tsunami warning and evacuation information is critical in disaster management, particularly when the wireline communications infrastructure is damaged by the tsunami or when the bandwidth becomes scare due to congestion in emergency situations. Without having to rely on a dedicated fixed infrastructure, content dissemination over large geographical areas can be achieved efficiently with high reliability. The challenge is to develop a scalable and cost-effective approach to achieve community scale content dissemination. To this end, we propose a methodology that integrates the social concepts of community leadership and "affinity" to venues to develop a socially-aware, affinity-based content dissemination infrastructure to support interaction and collective actions in disaster management.

The basic idea of a socially-aware, leader-centric content dissemination infrastructure is to designate selected leaders of a community at risk as "human carriers" of tsunami information, and harness the power of their social status and exposure to community members to achieve community scale dissemination of evacuation plans and critical tsunami information, among "leaders" to "followers", efficiently and in a timely fashion. Realizing this objective gives rise to two challenging issues that need to be addressed.

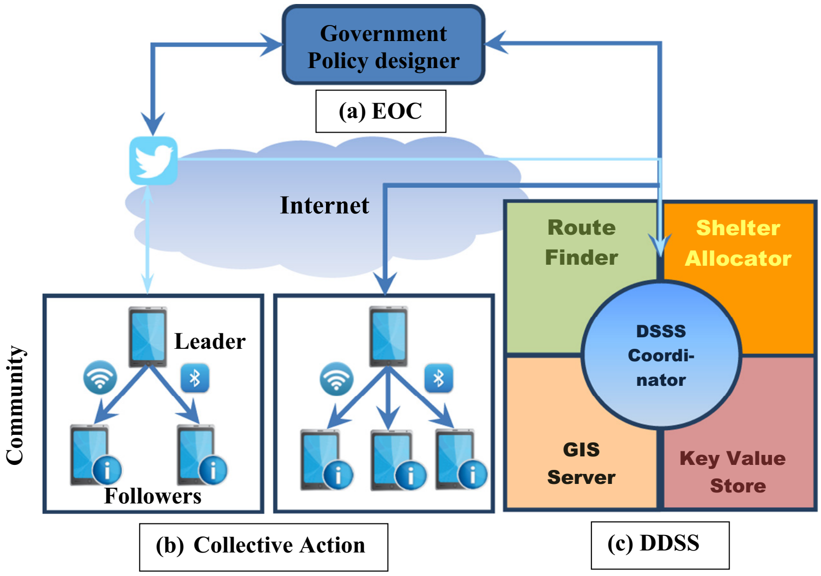

Fig. 2. GIS-SM-DDSS Architecture.

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The first relates to how leaders are to be selected, while the second is concerned with how information can be disseminated in a reliable and cost-effective manner. In the following, we first discuss leader selection, as information carriers. We then present an efficient and cost-effective opportunistic protocol for tsunami information dissemination among leaders and followers, in emergency situations.

3.1. Leader selection

The main design requirements of a leader selection process are neighborhood coverage and scalability. In order to achieve community scale information dissemination, neighborhood coverage must be optimized. Achieving neighborhood coverage requires that each member of the neighborhood be exposed, which high probability, to a leader, or another community member who has been exposed to a leader, shortly after tsunami information has been issued by the EOC. Exposure to an information carrier, be it a leader or a previously-exposed community member, triggers the peer-to-peer transfer of tsunami information from carriers to non-carriers within their vicinity. This process continues until the information reaches the intended members of the communities.

Neighborhood coverage is challenging, particularly in large communities. On one hand, guaranteeing exposure of a community member to a carrier, within the tsunami warning time, calls for the selection of a large number of leaders to ensure high neighborhood coverage. Designating a large number of leaders as neighborhood carriers may have significant impact both on the cost and scalability of the tsunami information dissemination process, particularly in emergency situations. To address this challenge and achieve a balanced tradeoff between minimizing the carriers and maximizing neighborhood coverage, we introduce the concept of “venue affinity” as a metric in selecting carriers and formulate the *leader selection* problem as a minimization problem whose objective is to minimize the number of carriers, while achieving the desired level of neighborhood coverage.

In the following, we first formally describe the minimum leader selection problem. We then propose a heuristic to identify the minimum number of carriers that can achieve the desired level of neighborhood coverage.

3.1.1. Minimum leader selection problem

We consider a neighborhood composed of M venues and N leader candidate to achieve neighborhood coverage. A venue corresponds to a physical location in the risk neighborhood where social gathering and activity occurs, on a regular basis. Community members, including candidate leaders, visit the venues with varied degree of frequency. The visiting frequency is used to derive a venue affinity metric, which reflects the potential of a leader candidate, when selected as an initial tsunami information carrier, to contribute effectively to community scale tsunami information, in a timely manner.

Based on the above, the minimum leader selection problem can be modeled as an undirected bipartite graph $G = (V, U, E)$. In this graph, $V(|V| = M)$, $U(|U| = N)$ and E represent the set of venues, the set of candidates and the set of edges between venues and candidates, respectively. An edge $(u, v, a_{u,v})$ exists when venue $v \in V$ is visited by candidate $u \in U$ with a *threshold probability*, $a_{u,v} \in (0, 1]$, where the weight, $a_{u,v}$, assigned to (u, v), represents the affinity candidate u has for venue v.

In our model, $a_{u,v}$ denotes the probability of candidate u being present at venue v at any given point of time. Practically, $a_{u,v}$ can be estimated as the ratio of total presence time of u at v, over the observed time duration. Multiple factors can be used to compute the affinity of a candidate to a venue, including the frequency of visitation, leadership, fame, community status, knowledge, trust, and respect that venue visitors have for the candidate. In the bipartite graph, depicted in Fig. 4, the selected weights are 20, 30, 10, 10, 10, 10 and 10 respectively, for a total of 100. These weights can be used to compute the affinity of each leader candidate, $u_i (1 \leqslant i \leqslant 4)$, to each venue, $v_j (1 \leqslant j \leqslant 3)$, taking into other social factors.

For a given $v \in V$, $U_v = \{u \colon u \in U, (u, v, a_{u,v}) \in E\}$ denotes the set of affiliated candidates for a given venue v. For the example depicted in Fig. 3, $U_{v_1} = \{u_1\}$, $U_{v_2} = \{u_1, u_2, u_3, u_4\}$, $U_{v_3} = \{u_1, u_2, u_4\}$. Since each candidate in U_v visits v with probability $a_{u,v}$, then a probability $p_v(U_v)$ with which the venue is visited by all its affiliated candidates can be calculated as follows: $p_v(U_v) = 1 - \prod_{u \in U_v}(1 - a_{u,v})$, where $p_v(U_v)$ denotes the probability of at least one candidate in U_v is present in v, at any time. In the simple case, depicted in Fig. 3, $p_{v_1}(U_{v_1}) = 0.6$, $p_{v_2}(U_{v_2}) = 0.946$, $p_{v_3}(U_{v_3}) = 0.64$.

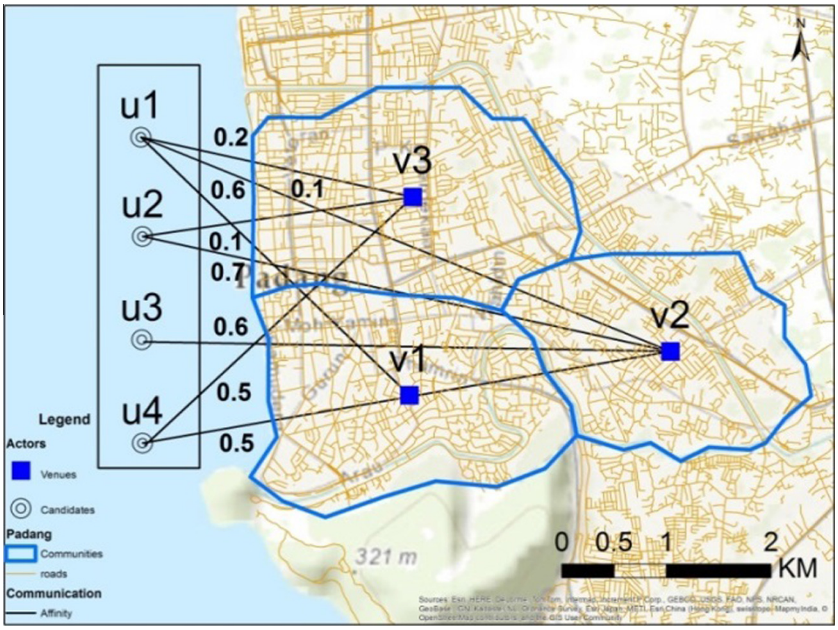

Fig. 3. Bipartite graph composed of venues, candidates and location affinity.

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Given the graph $G = (V, U, E)$, for any subset $S \subseteq U$, the probability $p_v(S)$, with which the venue v is visited by the candidates in S, can be calculated by replacing U_v in the above formula with S. It follows that $p_v(S) \leqslant p_v(U_v)$. Given a pre-specified threshold, τ, if there is a subset $U_{\text{lea}} \subseteq U$ for every $v \in V$, such that the venue could be visited by candidates in U_{lea} with probability $p_v(U_{\text{lea}}) \geqslant \tau$, then we declare that all the venues are covered by U_{lea}. U_{lea} is referred to as the coverage set of V, and the candidates in U_{lea} are called leaders.

The coverage set U_{lea} guarantees with probability threshold τ that at any time, for any venue $v \in V$, there exists at least one affiliated candidate who will carry content. Consequently, non-leaders who visit the venue at some time t will come in contact with the leader and receive content. The challenge is to achieve this exchange efficiently and reliably.

The above challenge can be addressed by finding a subset $U_{lea}^{min} \subseteq U$ that minimizes the number of leaders over all coverage sets of V. This minimization problem, referred to as Minimum Leader Selection (MLS), can be formalized as follows:

$$\begin{aligned}&\text{Minimize}_{U_{\text{lea}} \subseteq U} |U_{\text{lea}}| \\ &\text{Subject to}: \ p_v(U_{\text{lea}}) \geqslant \tau, \ \forall v \in V,\end{aligned} \tag{1}$$

where $p_v(S)$ is the coverage probability of venue v by the members of set S. This probability can be expressed as follows:

$$p_v(S) = 1 - \prod_{u \in S} (1 - a_{u,v}) \tag{2}$$

3.1.2. Affinity metrics for leader selection

Intuitively, the candidates who are more affiliated to venues or perform more actively among the venues, should be more competent to be selected as leaders so as to provide better coverage for the region. Observing the bipartite graph shown in Fig. 4, we identify two leader-centric metrics:

- *Number of visited venues:* For each $u \in U$, $V_u = \{v\colon v \in V, (u, v, a_{u,v}) \in E\}$ denotes the visited venues set of candidate u. $|V_u|$ is the number of the visited venues, corresponding to the node degree in an ordinary graph. The candidates who visit frequently a large number of venues have a larger node degree value, $|V_u|$.
- *Total affinity:* For each u, define total affinity of u as the summation of its affinity to all the venues, $A_u = \sum_{v \in V_u} a_{u,v}$. Obviously, $0 < A_u \leqslant 1$. The candidates who spend more time on certain venues have a relatively higher value of total affinity.

As far as affinity allocation among venues is concerned, relative measure is required to characterize the overall situation of affinity distribution. Given same total affinity, the candidate with unbalanced affinity allocation may have more influence on the coverage of venues. The affinity allocation-based candidate-centric metric is defined as follows:

- *Inverse fairness of affinity:* For each u, define affinity fairness of u as Jain's fairness index in terms of affinity allocation, $F(u) = \frac{\left(\sum_{v \in V_u} a_{u,v}\right)^2}{|V_u| \cdot \sum_{v \in V_u} (a_{u,v})^2}$, $0 < F(u) \leqslant 1$. A larger $|V_u|$ and an unbalanced distribution of $a_{u,v}$ among venues lead to a smaller $F(u)$. Combining the total affinity of u, the inverse fairness metric is defined as: $F_u = \frac{A_u}{F(u)} = \frac{|V_u| \cdot \sum_{v \in V_u} (a_{u,v})^2}{\sum_{v \in V_u} a_{u,v}}$.

Observing from the viewpoint of venues, the number of affiliated candidates may vary dramatically for each venue. As shown in Fig. 3, venue v_1 has only one affiliated candidate u_1 with probability of 0.6. That affinity is definitely important for the coverage of venue v_1. Apparently, the affinities between candidates and venues have different influence on the coverage of venues. So the metrics based on weighted affinity or expected coverage contribution might be more reasonable than the above candidate-centric metrics.

- *Proportional contribution:* In the affiliated candidates set U_v of venue v, the affinity which takes a greater fraction of the total affinity could contribute potentially more to the coverage probability of that venue. For each pair of v and u, let $d_{u,v} = \frac{a_{u,v}}{\sum_{w \in U_v} a_{w,v}}$ denote the u's expected contribution to v. The smaller the venue's total affinity is, the larger the contribution of each affiliated candidate will be. We define $D_u = \sum_{v \in V_u} d_{u,v}$ as the proportional contribution metric of candidate u.

3.2. Leader section heuristic algorithm

Given the affinity information in Fig. 3, the metric values can be easily calculated for each candidate. Thus a heuristic algorithm can be designed and executed on the basis of metric values accordingly. The simplest method is to select candidates with highest metric values as leaders gradually until the venues coverage requirement has been satisfied. The leaders' selection results based on different metrics are shown in Table 1. Here we present the heuristic algorithm based on these metrics as follows:

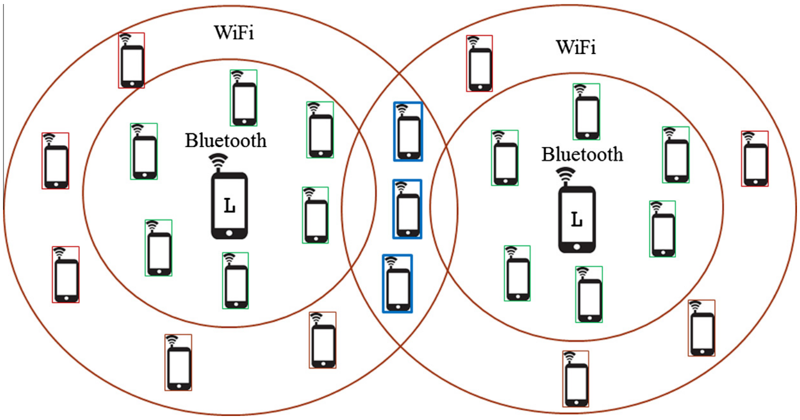

Fig. 4. Policies broadcast in Ad-hoc networks.

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Table 1
Choosing leaders based on different selection metrics.

Metrics	u_1	u_2	u_3	u_4	Leaders set
Number of visited venues $\|V_u\|$	3	2	1	1	$\{u_1, u_2, u_4\}$
Total affinity A_u	0.9	0.8	0.6	0.1	$\{u_4, u_1\}$
Inverse fairness of affinity F_u	1.37	1.25	0.6	1.0	$\{u_1, u_2, u_4\}$
Proportional contribution D_u	1.30	0.49	0.32	0.89	$\{u_1, u_4\}$

```
Algorithm 1: Metric-based algorithm
Input: Affinity matrix $AF(M, N)$, Coverage threshold $\tau$,
  Selection metric $s$;
Output: Minimum coverage set $U_{lea}^{min}$;
Operations:
1: $U_{lea}^{min} = \Phi$;
2: CandidateSet = {all candidates};
3: while size(CandidateSet) > 0
4:   MetricValues = ComputeMetrics(AF, s);
5:   Selected = RecordMaxMetric(MetricValues);
6:   $U_{lea}^{min} = U_{lea}^{min} \bigcup \{selected\}$;
7:   CoverageProb = ComputeCoverage (AF, $U_{lea}^{min}$);
8:   if min(CoverageProb) >= $\tau$
9:     return $U_{lea}^{min}$;
10:  end if
11:  UpdateAffinity(AF, $U_{lea}^{min}$);
12: end while
```

Function *ComputeMetrics*( ) calculates the metric values according to the specified selection metric, in the complexity of $O(MN + N) = O(MN)$. Function *RecordMaxMetric*( ) locates the candidate with maximal metric value in $O(N)$. Again function *ComputeCoverage*( ) computes the coverage probability for each venue in the complexity of $O(MN)$. Function *UpdateAffinity*( ) in step 11 updates the matrix by removing affinity information associated with the selected candidate and the venues whose coverage requirements have been satisfied. The primary purpose of this adaptive operation is not only to reduce the size of the affinity matrix for fast processing, but also to identify the more qualified candidate by re-calculating the metrics under a changed coverage situation. The update operation can finish in $O(MN)$ in worst case. Therefore combined with the outer loop, the metric-based algorithm has total complexity of $O(MN^2)$.

3.3. Coverage-based opportunistic tsunami distribution

The capacity of community collective action (Fig. 2b), a distinguishing feature of community resilience to disaster, reside in their ability to participate in managing and guiding the evacuation process, in emergency situations. Linked directly to the decision support system, community leaders In the GIS-SM-DDSS framework form an Internet of Intelligences (IOI), in which they use their knowledge and intelligence to support the tsunami disaster evacuation process (Huang, 2011). They participate in building rapid response and real-time databases of the disaster area, using mobile social media communication technologies.

Community leaders, as policy coordinators and monitors, act essentially as ‘‘human information hubs’’, which are nested within a physical information technology infrastructure, to support interaction and information exchange between the EOC and the public. A city, composed of several small communities, may elect more than one social leader, to act as information hub, and relay tsunami information from public agencies to community members. The reliance on multiple leaders to cover a small community ensures that information distributed by the EOC reaches its intended recipients in a reliable and timely fashion. When the prescribed tsunami risk and evacuation route maps are tweeted by EOC emergency personnel, the community leaders, currently present in the small community neighborhood, collectively engage in disseminating local maps of evacuation routes and organizing residents of their neighborhood into their effort to relocate into safe shelters.

Community leaders can also be viewed as ‘‘human sensors’’ for the land-based sensor network, reporting changes in environmental conditions to the EOC through smart phones, and helping to update evacuation routes in real-time. They are not only clients of the decision support system, who receive and execute evacuation plans, but also information monitors who use their experience and knowledge to effectively contribute to disaster management, especially when the communications infrastructure is heavily damaged following a tsunami disaster. Firemen and policemen are likely to be the first human sensors to report collapsed bridges and damaged buildings, following an earthquake, and the that the ensuing congestion may have on the planned evacuation route for community neighborhoods.

Urban residents, as the target audience of public policy and evacuation procedures, are social agents with the ability to take voluntary action. They need informed public policies to guide their decisions and sociotechnical systems to provide support, recognize risk, and take effective collective action. Timely dissemination of evacuation directives is especially urgent for vulnerable people like children, women, disabled, and the old. Involving community leaders, with advanced training, in disseminating EOC-issued evacuation route maps to city residents enhances community resilience to tsunami risk.

Designing the technical means to disseminate evacuation directives to highly mobile community of urban citizens is challenging. When access to the Internet is available, community members can use social media, such as Twitter, to access tsunami information. If the Internet becomes unavailable, in the event of a disaster that causes major damage to the wireline and cellular communications infrastructure, opportunistic communication over ad-hoc networks offers a viable solution to information dissemination and coordination among disaster managers and members of the affected community. Careful examination and selection of dissemination algorithms is needed, however, to ensure reliable delivery of tsunami information to communities at risk.

Flooding is the simplest protocol to reliably spread information across an ad-hoc network, in which no direct path from a given source to one or more destinations is available. Due to its inherent simplicity, coupled with its ability to achieve content distribution over large geographical areas, flooding provides a viable solution for information dissemination in ad-hoc networks. The overhead cost such a protocol entails in terms of the number of messages transmitted, however, is prohibitive, especially in bandwidth constrained environments. Probabilistic flooding, also referred to *epidemic* dissemination, has been proposed to overcome the limitation of the basic flooding protocol. Based on this method, a source node rebroadcasts a received message to its immediate neighbors with probability $p(0 \leqslant p \leqslant 1)$ and takes no action with probability $1 - p$.

The value of the flooding probability, p, is critical to the efficiency of the epidemic dissemination protocol. The lower p is, the fewer messages are broadcast, at the risk of not achieving the desired information dissemination coverage. The higher p is, the larger the number of transmitted messages becomes. The selection of the probability threshold, p, must be such flooded messages will most likely reach all nodes within the intended coverage area. In the following, we discuss four coverage-based forwarding heuristics methods, designed to reflect the changing dynamics of an ad-hoc network during disaster, and reduce the amount of routing

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overhead required to guarantee that effective evacuation policies are broadcast, and to reduce unnecessary rebroadcasts from leader nodes to the public (Fig. 4) (Ling et al., 2005). The different schemes use different approaches to achieve probabilistic flooding over a geographic area.

Area Coverage-based Probabilistic Forwarding (ACPF). In an ad-hoc wireless network, the coverage areas of neighboring nodes are usually overlap, the additional area covered by a node's rebroadcast is a small fraction of the whole node's coverage area. The relative distance between nodes is enough to determine the extra coverage area. The ACPF protocol could exploit the overlap area between a node's own coverage area and its neighbors' coverage area, and reduce the number of duplicate route requests between the two nodes within a neighborhood. In ACPF, the value of p depends on the extra coverage achieved by a rebroadcast of the original request, which the larger coverage area, the higher value p. it could efficiently combine coverage overlap area and local neighboring information into an easily implementable criterion which could achieve efficient route discovery with reduced overhead.

Copies Coverage-based Probabilistic Forwarding (CCPF). Usually, as the number of the overheard duplicate request messages increases, the forwarding probability of the node decreases. The CCPF uses the number of duplicate request messages overheard during a random time interval to determine its forwarding probability p. For example, when a node receives a route request message, it listens for a random time interval. During this period, the node counts the number of rebroadcasts by its neighbors, and uses this number to compute its forwarding probability p.

Area and Copies Coverage-based Probabilistic Forwarding (ACCPF). The ACCPF combines the main features of ACPF and CCPF, it takes advantage of both the transmission area coverage and the number of the overheard duplicates of the same request to determine the value of p. Each node maintains a counter and the smallest additional coverage area for each broadcast message. When a node receives a broadcast message from other node, it computes its forwarding probability p.

Neighbor Coverage-based Probabilistic Forwarding (NCPF). The NCPF could eliminate unnecessary rebroadcast by maintaining neighboring information at each node. In NCPF, a node determines all of its neighbors have been covered by other nodes' rebroadcast. Neighboring information is be used to further reduce unnecessary rebroadcasts within a neighborhood. When one node find all neighbors have already been covered by other nodes' rebroadcasts, the node does not need to forward the routing message any further. Prior to forwarding a route request, a node must first collect neighboring information, this information is then included within the route request. It means the received route request from neighbor node contains a neighboring list.

3.4. Evacuation shelter allocate and route analysis

The DDSS (Fig. 2c) provides real-time tsunami evacuation route map for community leaders in the risk region, to organize effective collective action. It contains five main components including Coordinator, Shelter Allocator, Route Finder, Key Value Store and GIS Server. The detailed functions of each component and their interactive communication processes used to evaluate available evacuation routes reported by the respective community leaders to disseminate updated evacuation policies to their followers are described as follows:

Coordinator: The Coordinator is the communication coordinating agent, who integrates services, monitors interaction, and transfers information for the other four components. The application runs in the leaders' smart phones as, the tsunami disaster warning trigger evacuation route search request, the request of each leader will create a new thread in the DDSS, the thread begins its service from Coordinator and transfer information among other components to get evacuation route map. When environment change, the Coordinator trigger database update, and locates the influenced routes and leaders, then recalculate the available routes and push to affected leaders and tweet to public, to keep the public with timely safety evacuation routes.

Shelter Allocator: The Shelter Allocator allocates the optimal shelters for community leaders, considering the leader's location, number of the followers, status of the road network and environmental conditions of risk. This function evaluates the closest available shelter for the leader with a safety route. This process will form a One to Many relationship table between one shelter and the potential leaders.

Route Finder: The Route Finder finds the optimized route through communicating with the GIS Server-Network Analysis Service, with parameters that include the leaders' location and allocated shelter location, to find the shortest available safety route between the two points with detailed route description. It then returns the route to the leader on a GIS map.

Key Value Store: The Key Value Store (KVS) contains some hush tables, used to manage the relationship of Leader–Shelter–Route. In the tables, the route ID is the Key, the leader ID and shelter ID are the Values to accelerate the DDSS search process when thousands of leaders change their routes at the same time. When a leader gets an evacuation route, the KVS will save the information for the community leader, allocated shelter, available route in the hush tables. When the route changes, the KVS could relocate the relevant leader based on new route details as the route is updated (Fig. 6).

GIS Server: The GIS Server supplies different kinds of services to support the DDSS. The Map Service offers basic street and image maps; the Feature Service offers geospatial feature data updates and modifies data management; the Spatial Analysis Service offers risk region analysis with undersea early warning network information; and the Network Analysis Service offers available shelter and shortest route analysis for community leaders,

The processes of how these components communication to complete a route computation in emergency tsunami disaster are described as follows:

1. Upon alert to evacuation, the DDSS creates a new thread for one leader to search for an evacuation route initiated by the Coordinator
2. The Coordinator Request Shelter Allocator searches for the optimum shelter to match the leader's request, filtering by the number of followers, shelter capacity, and proximity to the leader's location. The DDSS returns one allocated shelter to Coordinator
3. Coordinator Request Route Finder searches to find the best route from the leader's location to the allocated shelter
4. Route Finder Requests route from GIS Server-Network Analysis Service
5. GIS Server return one optimized route to Route Finder
6. Route Finder returns optimized route to Coordinator
7. Coordinator pushes route information to Key Value Store
8. Coordinator pushes route information to the Leader
9. Leader updates barrier and shelter information in Shelter Allocator
10. Coordinator pushes route map to Leader

4. Dynamic decision support system

Based on the early warning information, geographic information, urban service systems information, mobile phone technology, social media platform Twitter and Opportunistic network, the

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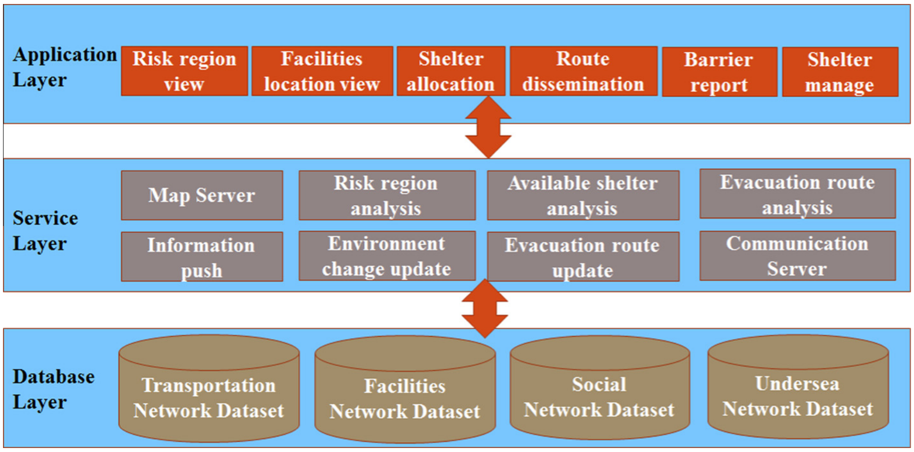

Fig. 5. System logic structure.

GIS-SM-DDSS has a logic structure includes a database layer, a service layer and an application layer (Fig. 5).

4.1. The database layer

The database layer provides spatial and relationship data for the service layer and the application layer. It includes natural features of the environment, such as the rivers, mountains, islands, coastline; the basic manmade physical features of the city, such as roads, bridges and communications infrastructure; facilities of urban service systems, such as hospitals, schools, and gas stations; the identified tsunami risk region, community-leader relationships and user attributes; undersea sensor system, such as sensor locations. Considering only the human-related attributes (not the natural, physical features), the spatial database could be divided into four subsets based on their functions: land-based transportation, critical facilities, social network dataset, and the undersea early warning sensor network dataset. The database components are described briefly as follows:

4.1.1. Transportation network dataset

The transportation network dataset is the base of urban residential activities. It is created based on the polyline layer of the road network and includes simple features (routes/lines and intersections/points), turns, and connectivity of the source features. The transportation network includes other properties of the roadways like bridges, one-way streets, two-way traffic, turn restrictions, overpasses/tunnels, travel time, cost and obstructions, to portray the network connectivity, here, the red lights are not considered as cost in the emergency situation, for keeping them working will delay too much time in the whole operation process. The cost and obstructions are very important characteristics. If there are too many red traffic lights on one route, the travel time will be longer; if one route is blocked by a car accident, this route will not available for the traffic until the accident is removed.

4.1.2. Facilities network dataset

The urban facilities dataset contains hospitals, schools, banks, supermarkets, communications, police stations, gas stations, churches, mosques, and so on. In a normal situation, these facilities are components of different urban sub-system networks; each one has its service area and rules. For instance, in a normal situation, three hospitals form a small service network in one community; their spatial location and construction scale are based on the size of the community's population. During a tsunami response phase, these hospitals would serve as emergency medical facilities, given their height, structural stability and medical standard, to offer first aid service for injured. Their service area needs to be enlarged to accept patients from nearby communities.

4.1.3. Social network dataset

The social network dataset maps the human and organizational relationships in society. People live in social communities in small spatial areas based on administrative units. The social network dataset contains every person who lives in the urban community. During the day, their social relationships may more reflect as workers–leaders, students–teachers, patients–doctors. At night, these relationships may reflect more as friends, families, and neighbors. These relationship networks could be identified on a map, based on people's locations and communications. The structures are very complex. The three main actors – government personnel, district leaders, and community residents or followers – are connected with social network tools, for example, Twitter, via smart phones that are used to tweet evacuation routes and to update emergency information. These three actors build social relationships based on their tsunami evacuation demands, their spatial structure is similar to the classic Tree Structure. That is from government agent to many community leaders, from community leader to his set of followers.

4.1.4. Undersea network dataset

The undersea early warning network dataset is used to manage the undersea sensor data. Ocean engineers will deploy a near-field tsunami detection network with sensor nodes for early detection of tsunami waves and communication of these data to an on-shore receiving station. The main equipment includes an accelerometer, pressure sensor, communications sensor, optical fiber, and gateway. The wideband, high resolution pressure sensor captures "higher" frequency motion signal as well as the lower frequency tsunami wave signal. Any cabled ocean bottom pressure data (Tsushima et al., 2009) and seawater wave deviation signal will be reported to the EOC through a communications sensor based on optical fiber and gateway. The signal information will be saved in the undersea network dataset. Included in the spatial structure of the underwater sensor network are records of a sudden shift in the ocean floor, the speed, height, and direction of tsunami wave characteristics. This dataset would be used to evaluate tsunami risk by analyzing the wave development and timing through underwater communication measures. Potential tsunami risk affecting the area will be communicated transmitted directly to the EOC and communicated by Emergency Managers to the public via the land-based sensor network, described in papers by Santos et al. and Xerandy et al. in this issue.

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4.2. The service layer

The service layer is the core of the GIS-SM-DDSS. It uses data in the database layer to provide real-time dynamic information and functional services for the application layer. The services include analysis of the potential risk region, identification of available shelters, safe evacuation routes, environmental change updates, evacuation route updates, and related functions.

4.2.1. Risk region analysis

The GIS Server offers the risk region spatial analysis service. Its function is to analyze the potential effect of a tsunami on the spatial region. Through access to data from the undersea sensor network, the EMs could get tsunami information which includes undersea earthquake epicenter, magnitude and focal depth, tsunami wave speed and height. Combined with land-based physical and social geographic information, this dataset includes land digital elevation model (DEM), river network distribution, using hydrological models could evaluate tsunami submerged range scenarios. Overlaying the maximum risk region layer on the community social network to include the administrative area, buildings, streets and population distribution layers, the EMs could determine the potential impact of the tsunami on the affected communities and their citizens.

4.2.2. Available shelter analysis

The Shelter Allocator offers available shelter analysis service, its function is to determine the potential evacuation shelters for community residents. In a tsunami event, social facilities like schools, hotels, churches and mosques will serve as shelters. Based on the leaders' location, their follow community population, shelters capacity and road network condition, the EOC evaluate the evacuation routes for the community leaders automatically and timely. Once the shelter allocated to one leader, the shelter's capacity will be reduced corresponding number to save enough space and emergency resources for this leader and his followers. If the capacity is not sufficient for the population, this shelter will not appear on the list of available shelter options, although it is very close to the community leader. If the allocated shelter is reported as collapsed or overloaded, the shelter will be removed from the available list, and an alternative shelter will be allocated to the designated leader, then the Shelter Allocator will compute new alternative route.

4.2.3. Evacuation route analysis

The Route Finder offers the evacuation route computation service. Its function is to identify the optimal evacuation route from the location of the community leader to the location of the allocated closest available shelter. In GIS, we build network dataset based on the transportation network, consider road length as travel cost. The input parameters include location of leader and allocated shelter, transportation network and barriers. Here, the barriers are reported by the community leaders operating in the disaster environment in real-time. The output is the route between the two spatial locations, it is a polyline with detailed roads and turns that is computed from the third-party service – GIS Network Analysis Service-Routing Analysis. The route will be saved in a one leader–shelter–route relationship table. Community citizens at risk could follow this route to evacuate to the assigned shelter.

4.2.4. Environmental change update

The coordinator offers an environmental change monitor and update service. With the development of a tsunami disaster, the environment and urban system infrastructures are likely to be destroyed by the earthquake or catastrophic flooding. Buildings and bridges may collapse; the roads may be congested by cars, all these changes will influence the selection of an evacuation route, as we consider the changes to be s barriers. At first time, the environment conditions are not clear, the evacuation route without consider such information may not fit for the real environment. With more detail site investigation and experience, people will cognize the surroundings risk, especially the newest destroyed conditions, they could be the human sensors to help update these information. The community leaders, firemen, policemen will report these conditions/changes to the EOC during they evacuation and rescue, and EMs update the database through strict inspection. The input parameters include the location of the human sensor, the type and degree of change. The output is the feedback regarding whether information update to the EOC has been received successfully or not.

4.2.5. Evacuation route update

The Key Value Store offers route update service. In case the assigned shelters or identified evacuation routes are no longer available because of a broken bridge or a blocked street, the evacuation route and probably the shelter allocations should be recomputed. The evacuation route function needs to query the affected leaders through the leader–shelter–route relationship table in the Key Value Store, identify the current location of each leader, then recalculate a new route to shelter with the latest information in real-time. This function then "pushes" the revised route map to the affected leader. At the same time, the new shelter and route will be updated in the leader–shelter–route relationship table. A broken path may affect several routes, so all leaders using those paths should be informed as soon as possible of the changes. In this way the leaders can tweet the updated route to their followers (Fig. 6).

4.3. The application layer

The application layer integrates data from the database layer and services from the service layer to provide detailed applications to guide the evacuation process. The detailed applications are described in Section 5, which outlines a field experiment in tsunami evacuation for the city of Padang, Indonesia.

5. Padang tsunami evacuation

In the risk region of Padang City, Indonesia, the number of Twitter users with geolocation information is 79 at 2014-11-07 00:00:00 (Fig. 7a). This figure is, simply computed from space, compared to about 1% of all tweets that contain geotagged metadata and are sent from the user's actual mobile devices with GPS and his home location (Middleton et al., 2014). There are almost 8000 people using Twitter in this area at that time. Padang City is an appropriate testbed for using the DDSS to guide community evacuation during tsunami.

The community leaders install the DDSS APP in their smart phones, they not only could view the tsunami risk, but also obtain real-time evacuation route information disseminated from the EOC (APP interface shown as Fig. 7b). This APP will help community leaders to recognize real-time tsunami risk, and organize community citizens to take rapid and effective collective evacuation action.

Assuming the undersea early warning sensor network monitor a severe earthquake just happened in near field sea of Padang City (Fig. 1), generated serious tsunami waves are flooding toward the city, the following steps will introduce how the leader use the APP in the community evacuation processes.

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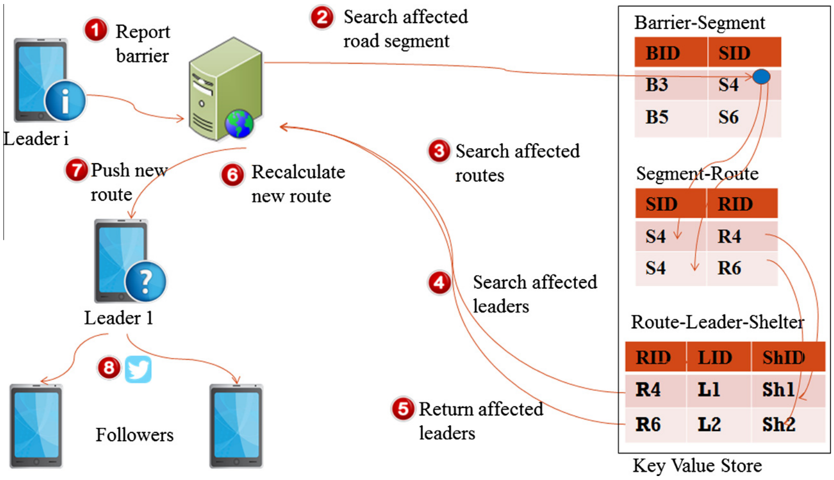


Barrier-Segment

BID	SID
B3	S4
B5	S6

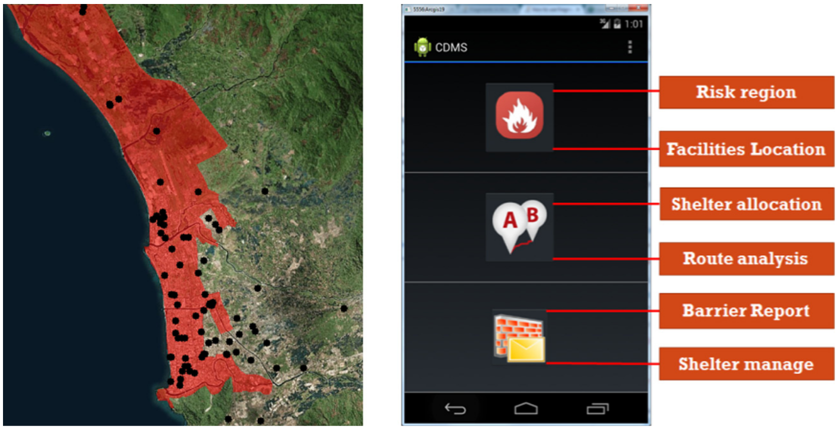
Segment-Route

SID	RID
S4	R4
S4	R6

Route-Leader-Shelter

RID	LID	ShID
R4	L1	Sh1
R6	L2	Sh2

Fig. 6. Real-time route update.



(a) Twitter location (b) APP Interface

Fig. 7. Main interface and Twitter user location.

5.1. Risk information dissemination

5.1.1. Risk region visualization

As soon as the EOC receives the undersea early warning information, the EMs evaluate the potential tsunami flood risk area and identify the threatened communities, using the risk region analysis function and urban system geospatial information to determine the emergency evacuation directives. The EMs then notify the public of tsunami risk, sending risk maps from community leaders through social media—the DDSS APP with Twitter installed in smart phones. The risk region spatial visualization in a smart phone is very effective for the residents to recognize tsunami risk.

The elected leader in community No. 5 (Fig. 8a, the fifth rectangle from upper map) is a respected government official. He will get notification in his phone, then he wake up the APP sleeping in background to understand the disaster situation, he will find the risk region (polygon) covers 6 collective action communities (rectangles) in the coastal area, there are many potential available shelters (points) which are dispersion in his community.

5.1.2. Facilities location visualization

Other than shelters, he could view more emergency facilities, like the closest hospitals and fire stations, the road network condition on evacuation map (Fig. 8b). With these risk and facilities information, the leader is able to recognize the tsunami risk degree, identify available resources, design mobilize action within the region, avoid uncertainties in the real situation, and adapt readily using available evacuation procedures to avoid casualties and property losses.

5.2. Evacuation route analysis and dissemination

5.2.1. Shelter allocation

The leader needs safety route to lead the community citizens to evacuate to safe shelters. The DDSS automatically locates the leader's spatial location in his action community (green[1] point, Fig. 9a), based on community population-800 followers, shelters capacity and road network condition, the Shelter Allocator evaluates the closest available shelter for the community leader and push the shelter to the leader, then the shelter location shows in the screen of the leader's phone (red point, Fig. 9a). The capacity of this shelter will reduce the population demand to guarantee they could get enough room and resources when arrival the shelter.

5.2.2. Route Finder and dissemination

When the leader confirms the shelter, he operates the APP to run Route Finder function. It finds the safety closest route from the leader to the allocated shelter and push the route to the leader,

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[1] For interpretation of color in Fig. 9, the reader is referred to the web version of this article.

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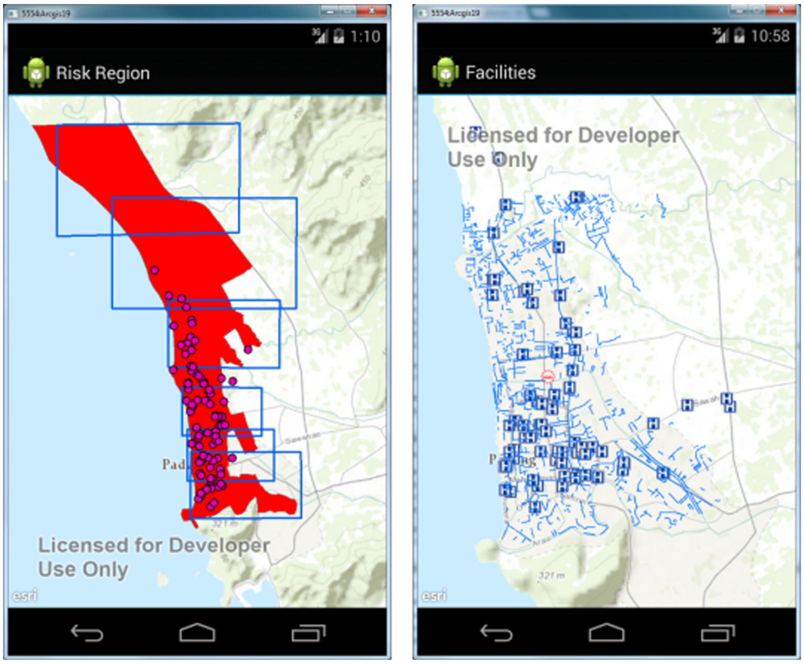

(a) risk region (b) facilities

Fig. 8. Tsunami risk map.

through access ArcGIS Server (blue line, Fig. 9b). The route contains many road segments, the DDSS automatically updates the leader–shelter–route relationship in ⟨Key, Value⟩ Store, here, the road leader and segment ID are the Keys, shelter ID, follow number and leader ID are the Values respectively (Tables 2 and 3).

In the initial stage, the Internet is available, although the phone base stations are destroyed by severe earthquake, the community leader tweets the route map to the followers through Twitter, and the information will be useful to a wide range of users. After a short time, the Internet is not available because the base station service the community is complete collapsed, the leader change to use the Coverage-based Probabilistic Forwarding in ad-hoc network, with wireless communication technologies, WIFI, that are feasible in small spatial scale.

5.3. Route real-time update

5.3.1. Barrier report

When the leader follows the evacuation route, moves from the start location (Fig. 9b) to a new location (Fig. 9c), where he finds one important bridge in his evacuation route collapse by fallen tree, he operate the report function in his phone to report the new situation to EOC, he chooses the point barrier type which express the tree damage (Fig. 10a), then draw the barrier at the accurate location on the map and save (Fig. 10b), this information is reported to the EOC database in real-time. The report process trigger affected route update immediately.

Table 2
Leader–shelter relationship table.

Key	Values	
Leader ID	Shelter ID	Follow number
5	240	800

Table 3
Leader–route relationship table.

Key: Segment ID	Value: Leader ID
12363	5
12364	5
12368	5
12287	5
12647	5
9829	5
9880	5

5.3.2. Shelter management

The DDSS tracks and manages the shelters situation independently and timely, when the shelter is assigned to the leader with his followers, the capacity is automatic reduced 800 accordingly. At the same time, with the consumption of resources dynamic change, the EMs need to manage the shelter attributes, in the shelter management interface, the EMs select the designated shelter (Fig. 10c), then edit the resources attributes (Fig. 10d), to make sure the water and food in the shelter are enough to support 800 people to stay 2 days, when these resources are not adequate, it need supplementary immediately. If for some reason, the shelter is damaged or it is not possible to access it due to road damage, the shelter is removed from the shelter list and leaders being guided there are detoured to some other shelter.

5.3.3. Route update

After the leader reported the tree damage, his evacuation route is not available, the DDSS locate the leader and allocated shelter from ⟨Key, Value⟩ Store based on the road segment ID affected by the fallen tree, recalculate a new route from the leader's real-time location to the allocated shelter, then push evacuation route for the affected leader, then the leader tweet the new route to his followers as soon as possible (Fig. 9c and Table 4).

The shelter allocate, route find and barrier report cycle processes continued, until at last, the leader ensures that all 800 followers in his service – covered region get the route map. And all of them followed the leader reach the allocated shelter safely.

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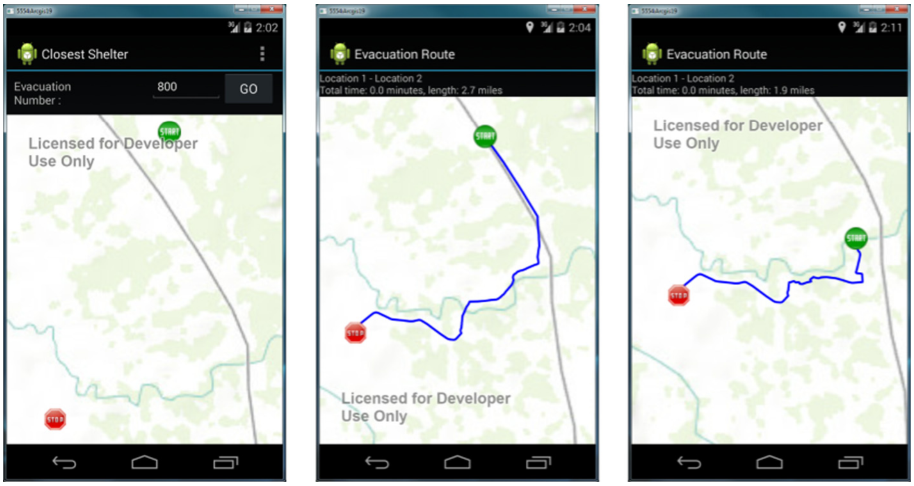


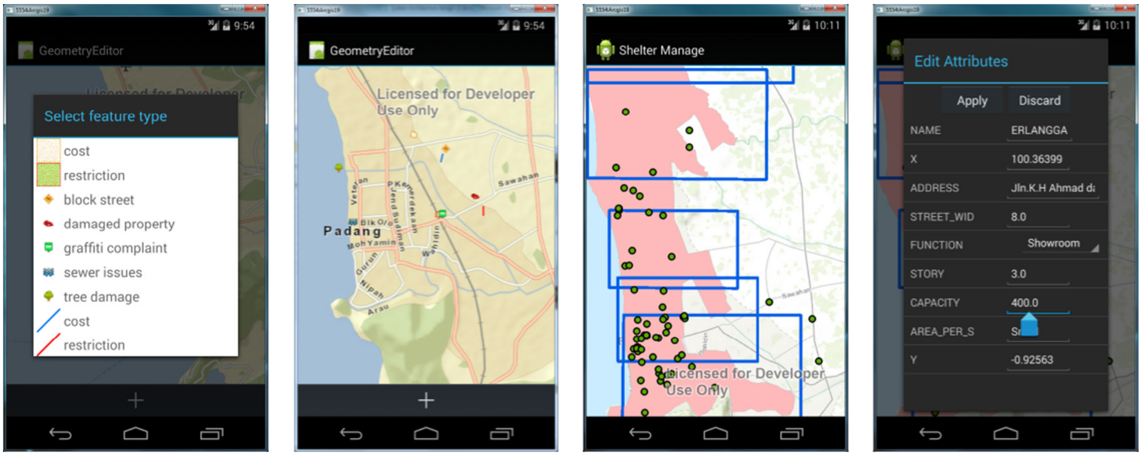
Evacuation Number : 800

Location 1 - Location 2
Total time: 0.0 minutes, length: 2.7 miles

Location 1 - Location 2
Total time: 0.0 minutes, length: 1.9 miles

(a) shelter choose (b) original route (c) updated route

Fig. 9. Evacuation route map.



NAME ERLANGGA
X 100.36399
ADDRESS Jln.K.H Ahmad da
STREET_WID 8.0
FUNCTION Showroom
STORY 3.0
CAPACITY 400.0
AREA_PER_S Sr
Y -0.92563

(a) barrier type choose (b) add on map (c) shelter choose (d) capacity change

Fig. 10. Barrier Report and shelter manage.

Table 4
Leader–route relationship update table.

Key: Segment ID	Value: Leader ID
12284	5
12287	5
12647	5
9829	5
9880	5

6. Conclusion

The GIS-SM-DDSS gives collective action support for public evacuation in tsunami disasters. The Mobile-GIS provides real-time spatial visualization of tsunami risk and resources, the Emergency Operations Center analyzes the evacuation route to a safe area. The leaders are election based on the acquirable affinity information which reflects the relationships between candidates and their visited community. When the Internet is available, the Emergency Managers push the evacuation routes to local community leaders through the social media platform, Twitter, then tweet to their community citizens. When Internet is not available, the Opportunistic network – Coverage-based Probabilistic Forwarding in ad-hoc routing will work. The leaders will monitor and report environmental situations changing in real-time to guarantee the latest information update for the policy design. The public evacuates to assigned shelters that follow the detailed evacuation policies.

In the Padang, Indonesia case, the GIS-SM-DDSS builds a communication network between government and public, using the community leader as middle actor to disseminate the evacuation routes. Combined with the undersea sensor network, it composes a dynamic decision support system that transmits data from undersea sensors to land-based Twitter network for detecting, mitigating, and building community resilience to tsunami hazards.

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Please cite this article in press as: Ai, F., et al. A dynamic decision support system based on geographical information and mobile social networks: A model for tsunami risk mitigation in Padang, Indonesia. Safety Sci. (2015), http://dx.doi.org/10.1016/j.ssci.2015.09.022