How can floodplain maps help communities?

WHAT IS A FLOODPLAIN MAP?

Floodplain maps are an important tool for informing communities about their flood risks and supporting public participation in flood management discussions, providing communities with information about flood risks and helping people make informed decisions about flooding and emergency preparedness, such as evacuation plans, flood-proofing property measures, and insurance needs.

CAUSES OF FLOODING

- High intensity rainfall
- Snowmelt
- Ice jams
- Storm surge
- Human activities

HAZARDS CAUSED BY FLOODING

Floods can cause tremendous damage and are thus considered in many cases to be a natural disaster. Floods can cause significant economic loss, environmental issues, displacement of people and other organisms, damage to properties, infrastructure and public facilities, injury, illness and even death, and extreme natural disasters can cause some people's mental health to suffer.

TYPES

FLOOD INUNDATION MAP

Shows the extent of flood coverage in real or potential flood events of varying degrees. The map helps communities in the floodplain to plan for emergency preparedness efforts.

FLOOD HAZARD MAP

It can show the distribution or extent of water in a real-time event. The map assists in emergency response and preparedness for communities located in floodplains.

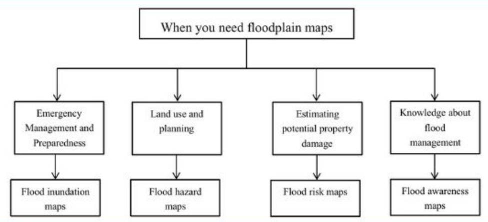
FLOOD RISK MAP

The map illustrates the potential negative economic, social, and environmental impacts that communities may face in a flooding event.

FLOOD AWARENESS MAP

It is narrated along with a flood risk map and shows the flood history of their community. The map also shows the potential for future flooding and the associated risks.

Quickly determine the type of map you need



RECOMMENDATIONS

- Understand the causes of floods and the hazards they pose.
- Learn to use and become accustomed to using flood maps.
- Increase participation in flood risk management decisions.
- Contact your local government to see if the flood maps are up to date, and if they are not, get back to them with this information in time.

The role of floodplain mapping in managing flood risk in Canada

LWS 548 Major Project

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August 17, 2022

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Acknowledgements

I would like to express my deepest gratitude to my supervisor, Professor Julie Wilson, for her patience, understanding and encouragement. This project would not have been possible without the guidance and advice she provided to me.

I would also like to express my gratitude to Dr. Les Lavkulich, Director of the MLWS Program, and Megan Bingham, MLWS Program Assistant, for the guidance and assistance they have provided to me throughout the program. I am grateful to all the teachers I met during this year of study, and I admire their rigorous teaching attitude.

Finally I would like to thank my parents for their constant support and love, allowing me to be brave enough to pursue the life I want.

Executive summary

Effective flood risk management measures need to be put in place in order to reduce the damages caused by floods. This paper reviews the floodplain map as a flood management tool; while maps are a widely accepted and credible source of information to support community decision-making on flood management, mapping technologies are rapidly evolving and many flood maps in Canada are significantly out of date. As communities (re)assess their floodplain information and management strategies, this document provides an information resource and review of important questions to consider in floodplain mapping. Why are floodplain maps important? What are the different types of floodplain maps, and what types of data are needed for their development? How do land use change and climate change impact the reliability of floodplain maps? Which types of flood maps are the most appropriate to support

decisions around different land management concerns/priorities? In addition, this paper presents useful background information for the public, particularly those who are not familiar with flood management. The goal of this paper is to provide information for general public, communities and policy makers to utilize and develop flood management tools prudently, to ensure greater protection from floods.

Introduction

Flooding is a phenomenon in which the water level of lakes, oceans and rivers rises above the normal level and inundates dry ground. While this is a natural process that can have many benefits to a watershed, including transporting nutrient-rich sediments to the floodplain, it is seen as an increasing threat to humans as settlement and development expands in floodplains. Floods not only have a social and economic impact, but they can also be harmful to people's health. Over the past few decades, the frequency and magnitude of floods have continued to increase globally (Jongman et al., 2015).

The risk of flooding is enormous. Floods can occur at any time of the year and are one of the most frequent natural disasters. Floods are usually caused by heavy rainfall, melting snow, storm surges or tsunamis. Floods can cause damage including loss of life, personal property, and national property. The three common types of floods are flash floods , river floods , and coastal floods. A flash flood is a flood that occurs within six hours of a heavy rain or other cause. River flooding occurs when the water level in a river, lake or stream rises and inundates nearby land. Coastal flooding occurs when dry and low-lying land is inundated by seawater. Sometimes floods are very rapid, with water levels rising so quickly in a short period of time that people have minimal time to respond. According to WHO, a two billion people worldwide were affected by floods between 1998-2018. (Wallemacq et al., 2018). This number represents 45% of all people affected by disasters. Those who live in floodplains or lack awareness of flood risks are most vulnerable to losses in floods. The frequency and intensity of floods have been increasing within the last decade, and the likelihood of mega-floods is also increasing due to climate change. In the last 20 years, nearly 150,000 people worldwide have died as a result of floods (Wallemacq et al., 2018). Many of the people who survived the flood also suffer long-term health effects (e.g. Post-Disaster Psychological Trauma) .

In Canada, floods are the most common natural disaster and one of the costliest (Government of Canada 2022). According to scientists, the frequency of flooding along Canada's coasts will increase further as the climate changes this century (Lemmen et al., 2016). In Canada, flood losses in urban areas totaled about $2.4 billion in 2010. By 2030, losses will increase by $4 billion. By mid-century, this figure will grow to nearly $15 billion (Rabson 2020). The number of residents affected by flooding is also gradually increasing. By 2050, flooding in Canada will affect approximately 431,000 people, 230,000 more than in 2010 (Rabson 2020).

Throughout history, floods have caused serious damage in rivers across Canada. In July 1996, severe flooding occurred in Quebec. The flood would kill 10 people, destroy nearly 1,000 homes, displace more than 10,000 people, and cause $300 million in damage (Ha 2012). In the spring of 2013, southern Alberta was hit by one of the most expensive natural disasters in Canada (Mann 2021). Five people died as a result of the flooding and thousands were forced to flee their destroyed homes. In November 2021, British Columbia experienced severe flooding and many people lost their homes. Public facilities were damaged and economic losses were severe. It is estimated that the government will spend up to $9 billion to repair damaged roads, dams, railroads and bridges (Hunter 2022).

The impact of flooding is significant and will continue to increase. Therefore, in order to reduce the risk of flooding, appropriate prevention, preparedness and response measures should be implemented. An essential tool to support flood risk management, and the focus of this paper, is the floodplain map. Floodplain maps are very versatile and serve a range of purposes, including advancing risk assessment, identifying priorities to help high-risk areas, enhancing emergency preparedness plans, Predicting the extent and depth of flooding at specific locations, better understanding current and future flood hazards, etc. Land planning, real estate development, government disaster assistance and emergency management all need the help of floodplain maps. Despite their importance, floodplain maps are an underutilized tool. In a 2021 survey, researchers found that only 38.5% of communities and First Nations in B.C. had created floodplain maps (BC Real Estate Foundation 2021). More than half of all communities surveyed lacked knowledge of in-house flood management (BC Real Estate Foundation 2021).

This paper will focus on flood and floodplain maps in Canada. In this paper, I will first discuss the factors that cause flooding, the risk of flooding. Then the role of floodplain maps will be explained in detail, including how data for floodplain maps are obtained, the factors to be considered in making the maps, the uses of different floodplain maps and the information they provide, and the influence of climate and land use on the occurrence of floods and map accuracy. In addition, this paper explains floodplain maps in a way that people with no background of expertise can understand, helping those who live in floodplains to recognize the importance of floodplain maps, learn and get used to using this cohabitation, and reduce the impact of flooding on themselves in the future.

Methodology

Consulted government websites and literature to conduct a review of the causes of flooding and flood risk in Canada. Conduct an analysis of the current techniques for obtaining data needed to produce floodplain maps. Summarize and compare the different uses of different types of floodplain maps so that the public and communities can make better use of floodplain maps.

Objectives

1. Analyze and synthesize different purposes, and processes of generating floodplain maps.

2. Review different types of flood maps to make recommendations on which are the most appropriate decision support tools for particular management issues or priorities.

3. Discuss the role of land use change and climate change on flood map utility.

4. Provide information on how to make floodplain mapping a more accessible tool for local communities to improve flood management/protection strategies.

Context

Causes of flooding

Floods are natural disasters caused when water in rivers, lakes and oceans rises above normal levels and inundates dry land. Flooding is the most common and expensive natural disaster in Canada (Sandink et al. 2010). There are many factors that contribute to the occurrence of flooding. These factors include heavy rainfall, snowmelt, ice jams, surge storm, human activity, etc (Buttle et al., 2016).

High intensity rainfall has caused flooding across all of Canada's provinces (Watt et al., 1989). In southern Canada, short duration storms are more intense and therefore more likely to cause flooding in small watersheds. Flooding has also occurred in large watersheds when heavy rain falls in extended storm systems covering a wide area (Dingman 2002). Heavy rainfalls in Western Canada are mainly associated with near-surface water vapor over the Pacific Ocean (Roberge et al., 2009). The long-term rainfall generated by these maritime weather systems is an important factor in the occurrence of floods in coastal areas (Buttle et al., 2016). As with the Pacific coast, cities near the Atlantic Ocean are exposed to huge bands of water vapor. Heavy rainfall caused by cyclones and warm streams can lead to an increased likelihood of flooding in areas near the Atlantic Ocean.

Across Canada, runoff flooding from snowmelt is common (Buttle et al., 2016). Flooding caused by snowmelt generally occurs in the spring. In winter, precipitation occurs as snow in many areas, and when temperatures rise, the snow can melt rapidly, resulting in significant runoff. Flooding occurs when runoff enters streams or rivers and exceeds the drainage capacity of the streams and rivers. If heavy rainfall occurs at the same time, then the risk of flooding is increased (Government of Canada 2016). In addition, snowmelt can cause flooding for the important reason that the land freezes in cold temperatures, preventing runoff from infiltrating into the ground and exacerbating the amount of water flowing to streams and lakes (Government of Canada 2016). Flooding caused by snowmelt runoff is largely widespread throughout

Canada.

Ice jams formed during the formation or breakup of ice are also a significant cause of flooding in Canada (Wall et al. 2009). Statistically, more than 60% of flood losses in the Atlantic region are ice related (Government of Canada 2016). Ice jams are formed during the spring thaw when ice breaks up in the upper reaches causing ice to accumulate. When an ice jam is formed, the water flow is impeded. If the ice jam is large enough, it will cause water to flow backward. If the ice jam melts, then the water will overflow the river and flood the lower stream. Melting huge ice jams can produce surge velocities of up to 10 meters per second, causing the water level to rise rapidly and causing severe flooding (Government of Canada 2016).

Different causes of floods are prevalent at different times of year. Floods caused by snowmelt and ice jams are more frequent in the spring, while floods caused by heavy rainfall are more frequent in the summer (Buttle et al., 2016). Flood formation factors vary in different regions of Canada because of differences in hydroclimate, geology, geomorphology, and land cover. Therefore, flood management strategies must be developed regionally and locally.

Human activities can also play a role in the size and frequency of floods. The massive human deforestation has resulted in a lack of trees on the ground to help rainfall and water infiltration into the soil. The loss of tree protection increases the likelihood of flooding during heavy rainfall. The increase in impervious area is also an important reason for the increased probability of flooding. Especially with increased urbanization, the concrete structures of roads, parking lots, etc. do not allow precipitation to seep into the ground, and if there are no adequate facilities to direct and collect the water flow, then the water will collect in low-lying areas and cause flooding. In addition to this, the construction of dikes is potentially dangerous because they can cause the water level of the river to be higher than the surrounding area. If a dike fails, it can cause the river to overflow rapidly, leading to flooding. In 2005, a levee in New Orleans failed, causing flooding that killed hundreds of people (Virine et al., 2019). Human-driven climate change is also indirectly influencing the occurrence of floods. Although climate change is not a direct factor, it exacerbates the factors that contribute to the occurrence of floods (e.g. rainfall and snowmelt) (Denchack 2019). Researchers from the United States believe that it is because of the climate change that flooding in coastal areas of the United States has multiplied in a few decades (Denchack 2019). In many cases, human activities interact with these hazards.

Hazards caused by flooding

Floods can cause tremendous damage and are thus considered in many cases to be a natural disaster. Floods can cause significant economic loss, environmental issues, displacement of people and other organisms, damage to properties, infrastructure and public facilities, injury, illness and even death, and extreme natural disasters can cause some people's mental health to suffer (Jerome 2021).

Today, there is evidence that both flood risk and vulnerability are increasing in Canada (Amin et al., 2018). For example, in Alberta, flooded areas have grown substantially over a twenty-year period since 1992 (Elshorbagy et al., 2017). According to the Canadian Disaster Database (CDD), catastrophic flooding in Canada has increased between 1920 and 2016 (Figure 1).

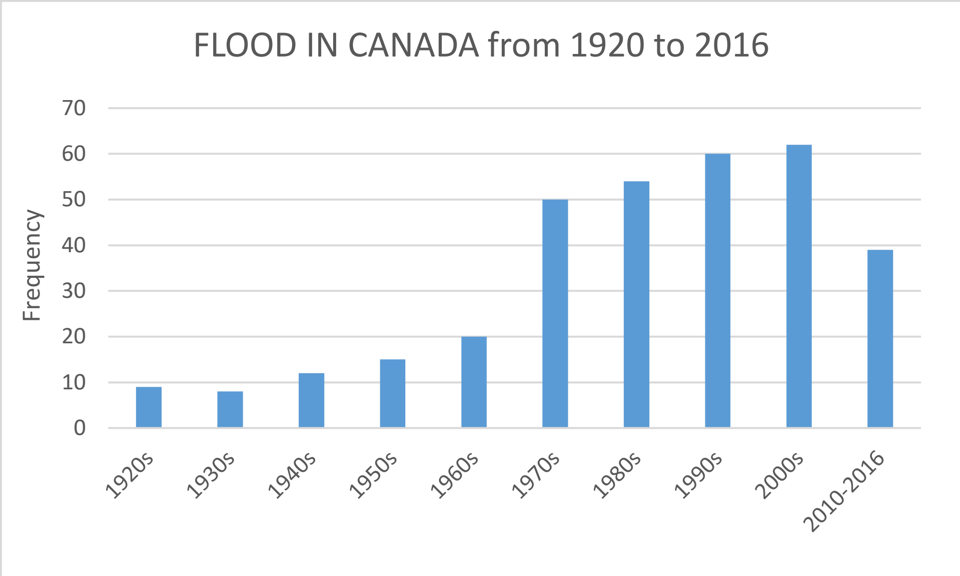

Figure 1. The number of catastrophic floods that occurred in Canada per decade from 1920 to 2016 (Adapted from Freshwater Alliance 2018).

In Canada, flooding is one of the most expensive natural disasters (Etkin et al., 2003). Severe flooding has occurred in various regions of Canada, mostly concentrated in densely populated areas (Burton 2022). In 2013, floods in Alberta were one of the most expensive disasters in Canada, with total damage exceeding $6 billion CAD (Burton 2022). Floods in Toronto in 2013 resulted in power outages for 300,000 residents and cost the government nearly $70 million to remediate (Burton 2022). In 2016, flooding in southern of Ontario affected nearly 2,000 homes (Thistlethwaite et al., 2017). In November 2021, historic flooding occurred in British Columbia and the costs for restoring damages was conservatively estimated to be nearly $9 billion (Hunter 2022). The cost of rebuilding flood-damaged roads was as much as $6 billion, and the damage to infrastructure in the most affected communities reached $1 billion (Hunter 2022). The following table lists the major economic damages caused by the 2021 BC floods.

Losses	Figures

Civic repairs	$1.125 billion
Farm damages	$285 million
Emergency highway repairs	$200 million
Permanent highway repairs	$6 billion
Insurance	$515 million

Table 1. Major economic losses caused by floods in souther British Columbia in 2021(Hunter 2022).

Floods can threaten people's health and lives. In Canada, the average number of deaths per flood is one person (Guha-Sapir et al. 2015). In addition to death by direct drowning, electrocution, or death by debris in a flood, the effects of mold, vector-borne diseases, and various mental health issues are all flood-related health problems (Burton et al., 2016). Flooding can increase chronic health effects such as fractures, contusions, homelessness, and post-traumatic stress disorder (Ramin and Svoboda 2009). During floods, contaminants containing human and animal waste have the potential to enter drinking water systems (Batterman et al. 2009). Because drinking water is polluted, the probability of human and livestock illness increases (Ahern et al. 2005). The growth of mold in building infrastructure post-flood has the potential to cause respiratory illness for inhabitants (Hulin et al. 2012). Some studies showed an increase in post-traumatic stress disorder, anxiety and depression after flood events, when people realized they were living in a floodplain (Burton et al., 2016).

Seasonal flooding can bring important nutrients to river water (Peters et al., 2016). Occasional floods have a positive effect on the ecological diversity of rivers (Tabacchi et al. 1998). However, extreme flooding is the main factor that disturbs the ecology of rivers. In some cases, flooding can alter the chemical composition of water bodies, and sediment loading and transport can lead to important geomorphic changes in the river environment and have an impact on aquatic life (Milner et al. 2013). For example, flooding that occurs in winter can have a negative effect on the juvenile survival of Atlantic salmon (Cunjak et al., 1998). Some studies have shown that flooding can affect the number of fish spawners (Peters et al., 2016).

Flooding associated with the effects of climate change is predicted to increase during this century, particularly in coastal areas of Canada (Hunter 2022). Especially for the coastal areas of Canada, the disaster caused by flooding will be more severe. According to Canada's Bedford Institute of Oceanography, sea levels will rise rapidly this century, ranging from 26 centimetres to 1 metre by the end of the century . Therefore, reducing flood hazards is a matter of urgency. We need to use and develop important tools to support communities in managing flood risk. Floodplain maps are a very important tool among these management measures. It can play a huge role in the management of flood risk, helping communities to reduce the damage caused in floods.

Floodplain mapping

What is a floodplain map?

In order to reduce flood hazards, areas prone to flooding must be identified first. One of the ways to achieve this is by generating floodplain maps. Floodplain maps can show the risk of flooding to particular areas. Floodplain maps are a tool to inform communities of their flood risks and to support flood management with public participation (Minano et al., 2018). Floodplain maps can show the regular location of water flow channels, ground contours, flood levels and floodplain boundaries, and the height and extent of 100- or 200-year floods (National Research Council 2007). A 100-year flood means that in any given year, there is a 1% chance of flooding in the floodplain (Albertawater 2014). A 200-year flood means that in any given year, there is a 0.5% chance of flooding in the floodplain (Albertawater 2014).

Maps can also define flood hazard areas and serve as a tool to determine if areas located near rivers, lakes, or oceans need flood insurance (National Research Council 2007). Homeowners, insurance agents and lenders can use floodplain maps to identify flood insurance eligibility, requirements and costs (Kousky 2018). For example, developers can reduce potential damages before buying a property by first understanding the likelihood of flooding in the area and building a home away from the floodplain. Insurers can tailor their insurance plans more accurately based on the likelihood of regional flooding. Floodplain maps can show existing flood risks to assist decision makers in understanding current and future flood hazards, developing contingency plans, advancing risk assessment efforts, identify priority areas for flood risk reduction measures, and helping floodplain communities become more resilient (BC Real Estate Foundation 2015). Overall, floodplain map is an effective tool to protect people, property and the country. Its specific function will be described in detail in the next section.

Where to find floodplain maps?

In Canada, local governments have developed flood maps to support the development and implementation of local flood management and flood regulations. These maps are available to the public and if people want to find the most up-to-date flood maps for their local community, they can go to the city's website for access. Flood Smart Canada can also help the general public and the communities quickly find maps of floodplains in each Canadian province.

Different kinds of flood maps

In order to provide the community and the public with a more detailed understanding of how to find flood maps for their needs, I am presenting this section on the different types of flood maps. Natural Resources Canada (NRCan) has classified flood maps in order to provide more detailed and professional management of floodplains. In the Federal Floodplain Mapping Guide series published by NRCan in 2017, four major map types are identified that cover a wide range of mapping activities (Government of Canada 2017). The four kinds of maps are 1.flood inundation map, 2. flood hazards map, 3. flood risks map, 4. flood awareness map. These different types of flood maps disseminate local flood information to support different decisions.

1.Flood inundation map

A flood inundation map can show the extent of flood water inundation for a particular site (e.g. community located in floodplain) that has occurred in the past and the potential extent of inundation that is predicted for possible future floods (Government of Canada 2022). The map is primarily intended to help with the advancement of flood emergency response plans. In addition, NRCan's Emergency Geomatics Service can also obtain flood inundation maps by monitoring images in real time for timely response after a flood occurs. Online real-time maps can be accessed for potential damage estimates based on historical flood data and flood inundation extent (USGS

2018). After a timely response to a flood, the government can perform a risk analysis of the flood through inundation maps, such as ecological and environmental assessments (USGS 2018). The map is suitable as a communication tool between the local government and the public. For example, evacuation routes can be shown to the public when they are presented with a flood emergency plan (Minano et al., 2018). In addition, to complement the evacuation effort, flood inundation maps also show some infrastructure, such as fire stations, as well as roads and bridges that were impassable during the flood event (Minano et al., 2018).

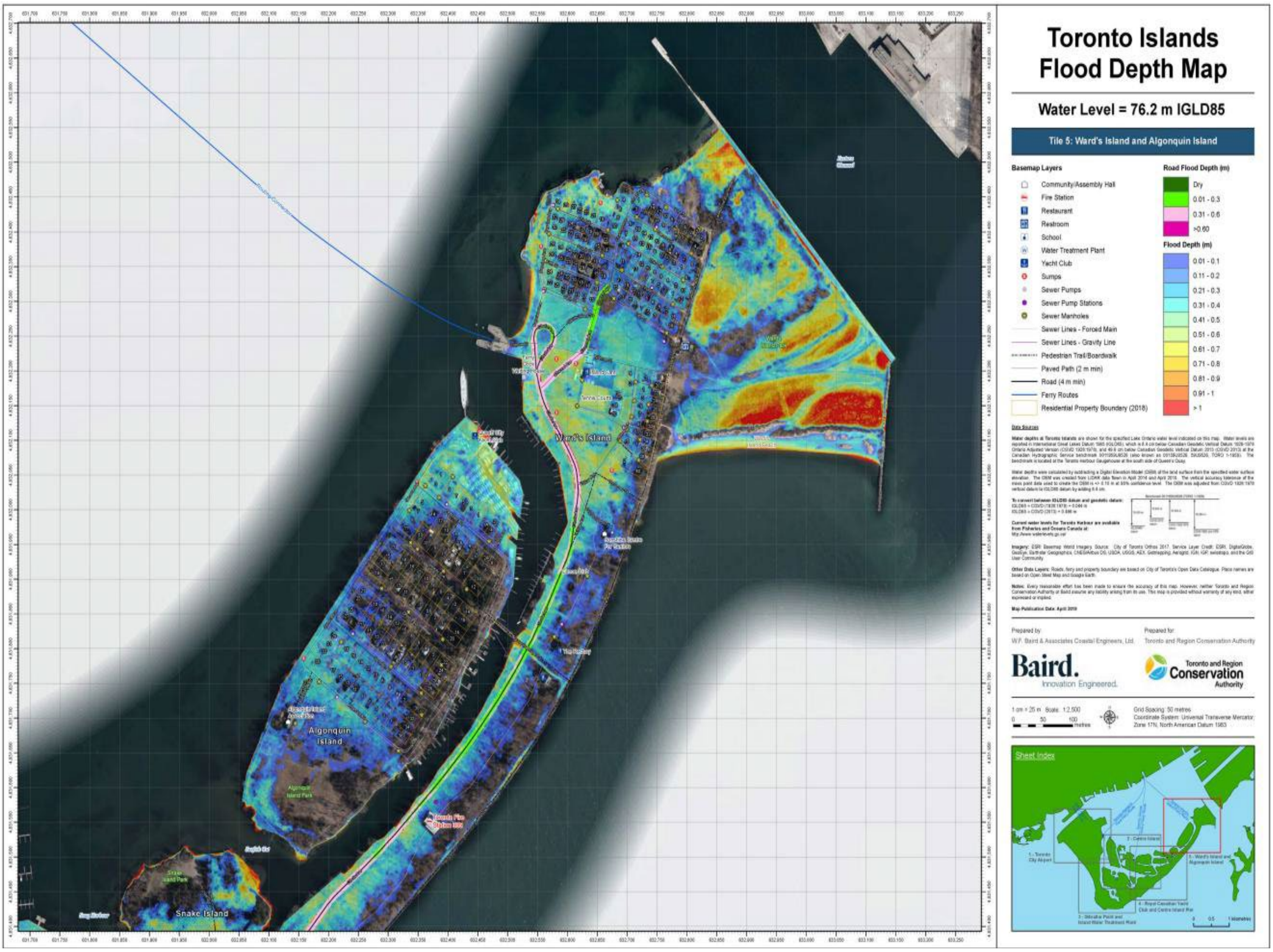

Figure 2. Flood Inundation Map. The red area represents the area flooded to a depth

of more than 1 meter. In addition, the map also includes restrooms, fire stations and other public facilities, so it is easy to see if these facilities are within the inundation area (Government of Canada 2022).

2.Flood hazard map

Flood hazard maps are often used as regulatory maps for land planning and use, and are available to various government departments as well as the public, with the intent of helping to build resilient communities (Government of Canada 2022). This is an engineering map that shows the results of hydrological and hydraulic investigations (Minano et al., 2018). The map shows the areas where flooding is likely to occur under different conditions, as well as the intensity and magnitude of the flooding (Government of Canada 2022). As an example, the map in Figure 3 shows the hazard caused by flooding that occurs under a 100-year storm. Flood hazard maps facilitate the rapid identification of areas at risk of flooding and also help prioritize mitigation and response efforts (Bapulu et al., 2005). Specific actions include changing land use plans, implementing specific flood protection measures, and establishing contingency plans. Flood hazard maps can raise public awareness of the likelihood of flooding and the risks involved, and allow for proactive action. The map is designed to be intuitive for public viewing (Figure 3). The public can get information about flood risk prevention measures directly from the online flood hazard map by entering the address (Minano et al., 2018).

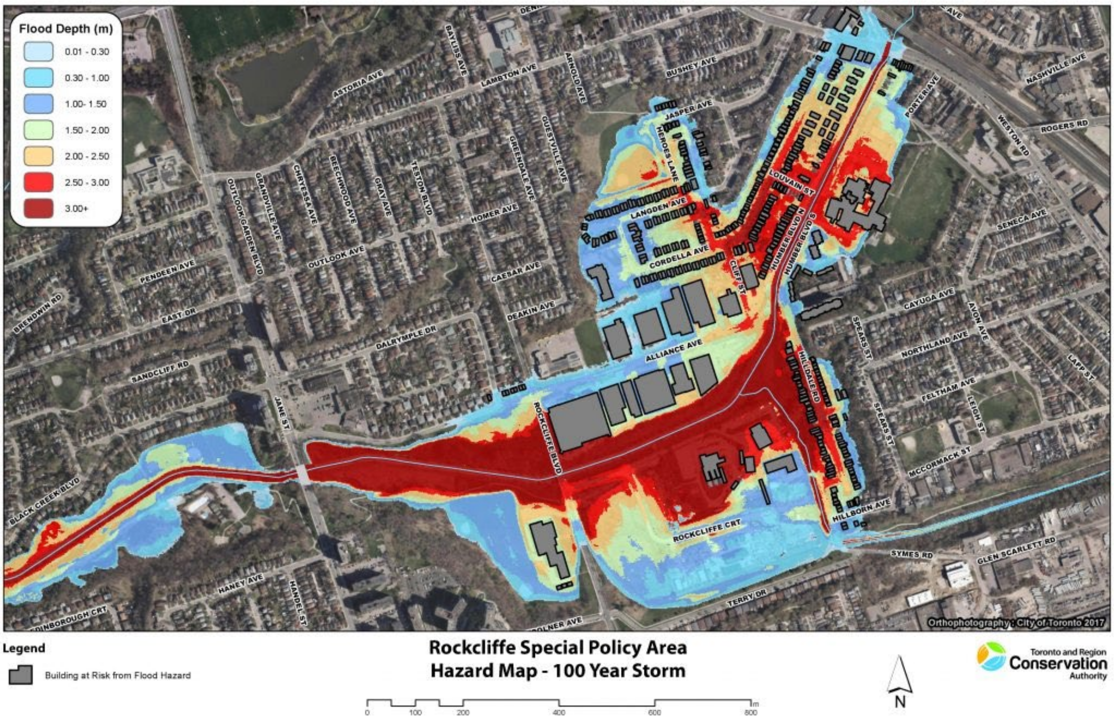

Figure 3. Flood Hazard Map. The dark red area indicates a flood depth of more than 3 meters under a 100-year storm (Government of Canada 2022).

3.Flood risk map

A flood risk map shows information about the economic, social and environmental damage caused by flooding (Government of Canada 2022). For those living in floodplain areas, flood risk maps are important in order to protect their property and lives (Minano et al., 2018). The map could speed up the effectiveness of flood risk management, such as prioritizing and focusing mitigation efforts on the worst-affected areas (Minano et al., 2018). Risk is usually expressed in terms of economic loss. For example, where the 0.2% AEP (annual exceedance probability) flood causes the most property damage, or calculate the potential damage to buildings from flooding of various probabilities occurring in any given year (City of Vancouver 2016). In cases involving damage that cannot be measured economically, the flood risk map can display scores that can be used to contrast flooding in different areas

(City of Vancouver 2016). The map can be divided into three different categories based on risk: low, medium and high (Minano et al., 2018). In addition, flood risk map can improve government efficiency and results. This is because flood risk management in highly affected areas can significantly reduce economic losses. These flood risk management include land use regulations as well as increasing the prevalence of personal insurance (Minano et al., 2018).

Figure 4. Flood Risks Map. The risk level is divided into high, medium and low levels to make the map more intuitive (Government of Canada 2022).

4.Flood awareness map

A flood awareness map is a communication tool, tailored for a community within the floodplain area (Minano et al., 2018; Government of Canada 2022). Flood awareness maps can include explanatory text and historical water level photos (Minano et al., 2018). They are designed to be easy for the public to view and understand. People can act in advance based on the information on the map. In addition to informing specific communities of historical flooding, the map can also show predictions of potential damage to the environment, housing, infrastructure, and more from future flooding (Minano et al., 2018). This type of map can also accompany information about public subsidies for flood control and the limitations of disaster assistance programs (Government of British Columbia, 2017). For example, disaster relief may not be available to those who refuse to purchase insurance and for secondary property including cottages (Government of British Columbia, 2017). Flood awareness maps and communication campaigns serve to inform the public of this information in advance to avoid problems in subsequent flood assistance, if needed.

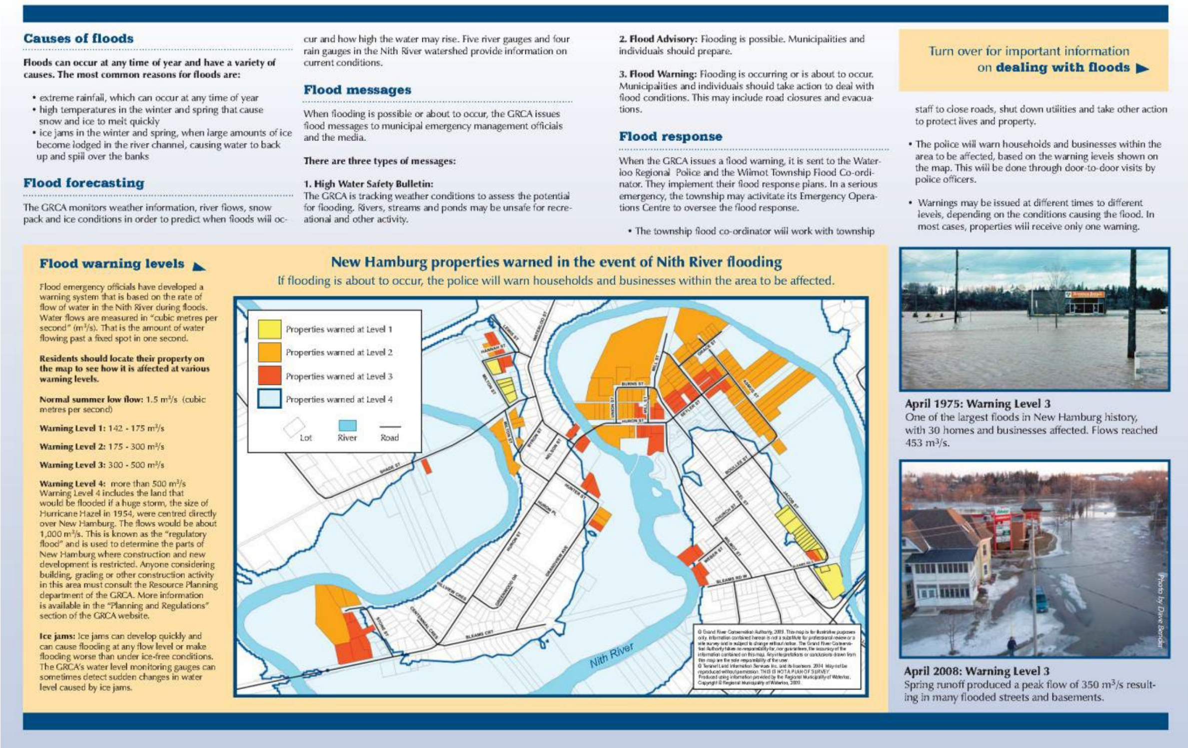

Figure 5. The Flood Awareness Map will inform the public about floods and historical floods. The map is easy to understand and facilitates public action on floods (Government of Canada 2022).

As mentioned above, different maps provide different information and have different emphases, and they require different data (Table 2). For example, in contrast to the flood hazard maps, the flood inundation maps do not provide photographs of historical floods and water depths. This is a weakness of the flood inundation maps and may need to be viewed in conjunction with the flood hazard maps when the public and communities want to understand historical flood events.

Flood map types	Data requirements
Flood inundation map	Surface Features; reservoir; rainfall; water level; tide level; coastal dyke; discharge; land use condition.
Flood hazard map	Historical Flood Information; water depth and extent; topographic information; land cover; rainfall; surface Features; flow direction; soil physical information (Doong et al., 2016).
Flood risk map	The return period of the flood; the extent and depth of flooding; Exposure of people and assets to flooding and the vulnerability of at-risk elements to flood damage (Apel et al., 2009).
Flood awareness	Historical photos of the flood; information about emergency planning; Information about flood insurance and municipal subsidy programs .

Table 2. This table describes the data requirements for different maps.

Different methodologies and data needs for floodplain mapping

The accuracy and reliability of the floodplain map is the basis for its use by the public and the community. In this section I will describe the data acquisition techniques for floodplain maps and the data requirements.

Floodplain maps are commonly created using satellite and/or aerial imagery (Syifa et al., 2019). After various processing techniques, these images can be used to predict the likelihood of flooding in a certain area and to create floodplain maps (Munawar et al., 2022).

Digital Elevation Models (DEM) provide important topographical and other landscape information to model inundation areas and generate floodplain maps (Figure 7). There are various techniques for generating DEMs. Different mapping methods provide DEM data with different levels of accuracy, which directly affects the accuracy of flood maps and flood prediction models (Erpicum et al., 2010). The high-resolution DEMs data are processed to provide accurate topographic information for flood models to calculate flood inundation extent and depth (Muhadi et al., 2020). Therefore, the high-resolution DEM can provide reliable flood simulation results, improve flood prediction accuracy and help flood management (Erpicum et al., 2010). This paper focuses on the most commonly used methods that can provide high data accuracy.

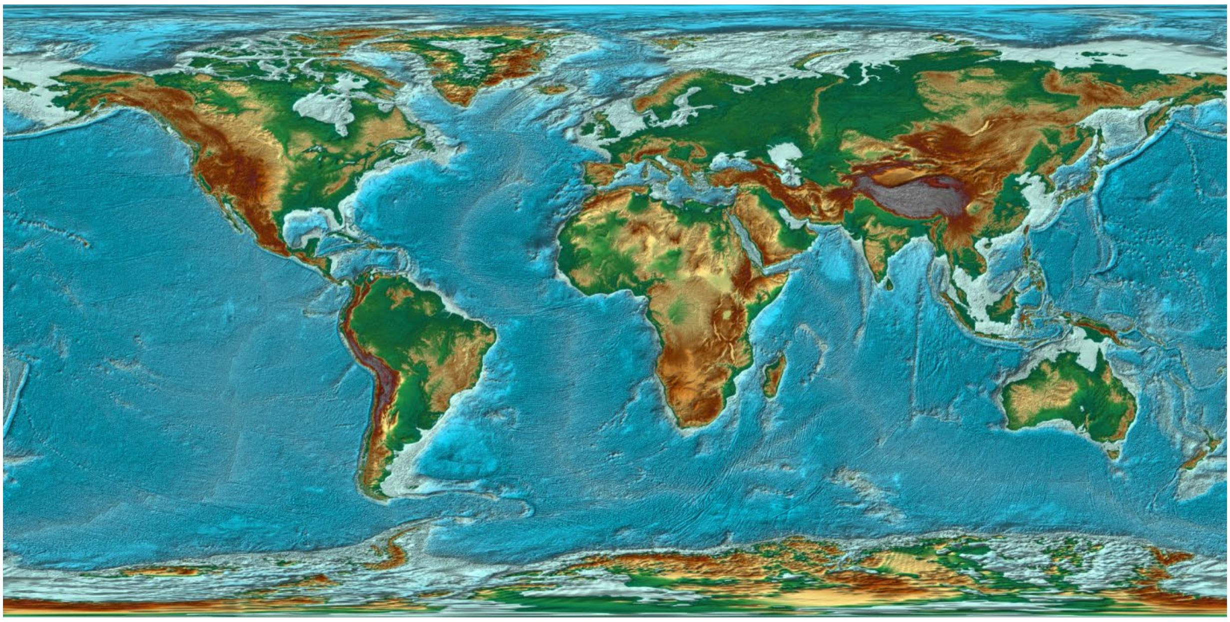

Figure 6. Digital elevation model map of an area (Adapted from Kevin Gill).

The use of LiDAR data in flood mapping

Methods of collecting data are continually advancing, enabling the creation of more accurate maps of floodplains. Light Detection And Ranging (LiDAR) systems can enhance and improve the management of flood risk (Muhadi et al., 2020). The principle of LiDAR systems is that light is emitted from a laser, propagated to the Earth and reflected from objects such as trees, buildings, roads, and bridges, and the time from emission to transmission back to the laser is recorded (Muhadi et al., 2020). LiDAR systems can be used in airborne and terrestrial applications to produce 3-D maps (Figure 8) (Muhadi et al., 2020). Airborne LiDAR is a sensor mounted on an aircraft, while terrestrial LiDAR collects data on the ground. These two systems can both collect point cloud data and obtain images synchronously (Muhadi et al., 2020). LiDAR data measurements can be acquired during the day or night and in cloudy conditions (Transportation Research Board 2018).

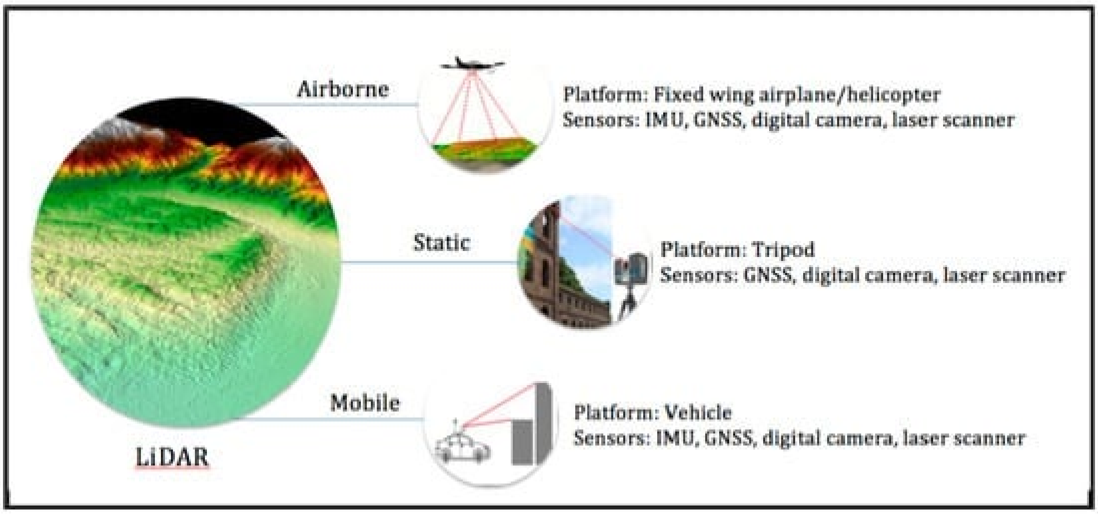

Figure 7. The principle of operation of different types of laser scanning (Muhadi et al., 2020).

Airborne LiDAR

The system components of a typical airborne LiDAR include a laser scanner, instruments for precise navigation, and photographic or video recording equipment (Crane et al., 2004). The aircraft carries a laser scanner that flies over the target area and emits a laser with a wavelength of 1000-1600 nm (Muhadi et al., 2020). The light is reflected by different objects on the ground and then transmitted back to the sensor, which records the return signal. The distance (r) is calculated by calculating the time (t) difference between the emitted laser and the returned signal (Zhao et al., 1988):

$r = ct/2$

c is the speed of light, which has a value of ~ 3*108 m/s.

Aglobal positioning system (GPS) and inertial measurement unit (IMU) are needed for calculating accurate data. The GPS supplies the absolute position of the sensor (x, y, z) and the IMU keeps track of the sensor's angle (roll, pitch and heading) (Muhadi et al., 2020). These tools guarantee powerful real-time computing capabilities. The photographic or video recording equipment are used to provide color information to represent real-world colors (Muhadi et al., 2020).

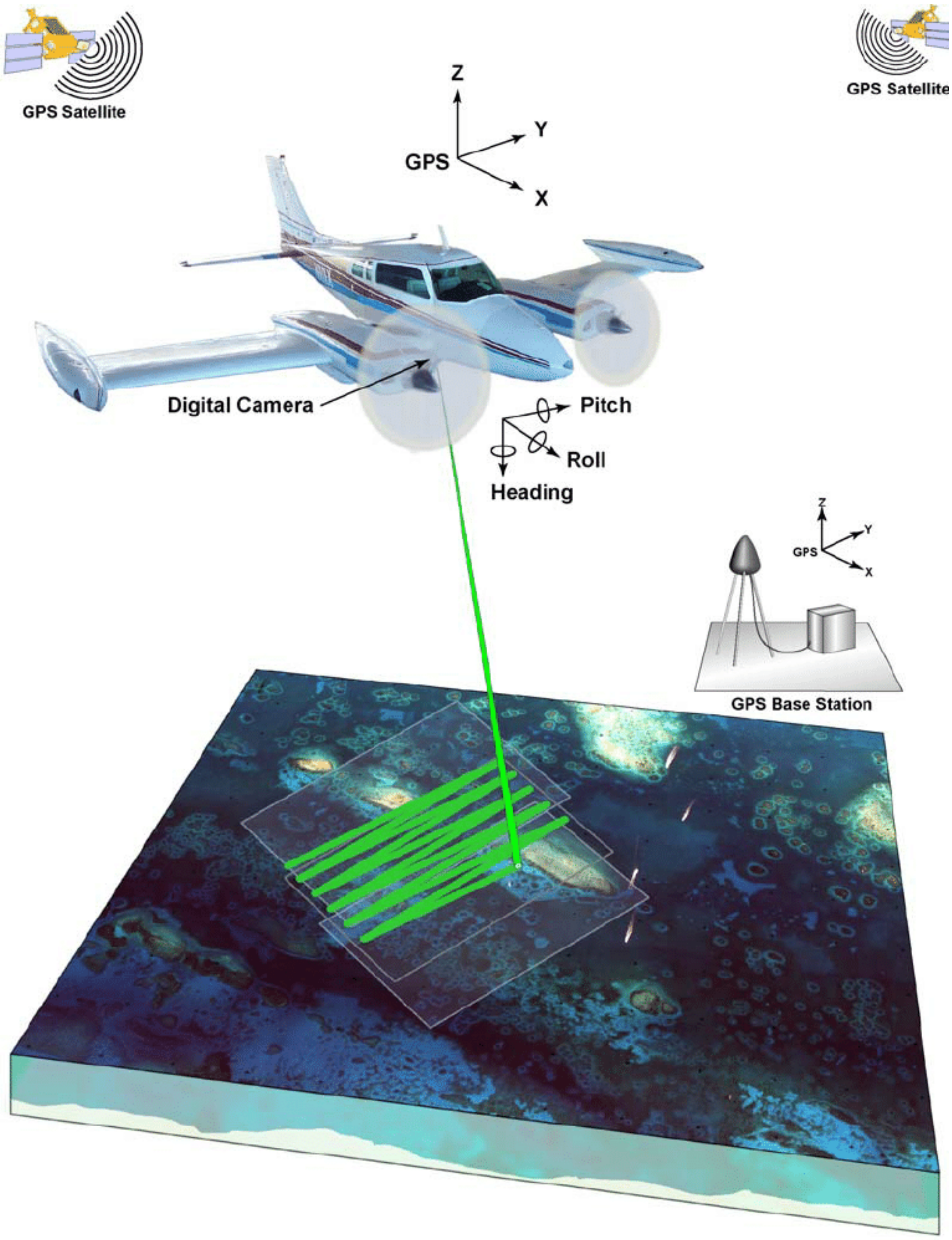

Figure 8. System composition and working principle of airborne LiDAR. Airborne LiDAR components typically include a laser altimeter, an instrument used to determine the aircraft's aircraft position and altitude, and a camera (USGS 2001).

Terrestrial LiDAR

Terrestrial LiDAR is mainly used for topographic and geomorphological mapping (Muhadi et al., 2020). The laser used for Terrestrial LiDAR emits a laser wavelength of approximately 500-600 nm (Dong et al., 2018). Terrestrial laser scanning ranges from 100-300 meters (Olsen 2009).

Terrestrial LiDAR includes static laser scanner and mobile laser scanner (Muhadi et al., 2020). The static scanner sensor is mounted on a tripod in a fixed position. The components of the static laser scanner consist of a ranging unit, a scanning mechanism, a laser controller, a data logger and a digital camera (Muhadi et al., 2020). The laser scanner works by emitting a beam of infrared laser light onto a rotating mirror, which deflects the laser. When the laser hits an object it is reflected back to the scanner, creating a 3D geometry (Stenz et al., 2020). Because it is static, the scanner position is fixed and a point cloud with good geometric quality can be obtained (Thenkabail et al., 2015).

The terrestrial mobile laser scanner follows a similar principle to airborne LiDAR, except that the carrier of the laser is located on a moving vehicle at the ground surface (Muhadi et al., 2020).

The advantages of using LiDAR data in floodplain mapping

The advantages of LiDAR systems are high data accuracy, large point density and wide coverage area. Airborne LiDAR can provide the ability to acquire data quickly, at a speed of about 50 km^2/h (National Research Council 2007). The main advantage of terrestrial LiDAR is that it can provide a higher point density of about 100 points/m^2 (Transportation Research Board 2013). In contrast to other techniques for obtaining DEMs, LiDAR systems can provide DEM data with higher resolution and accuracy. (Merwade et al, 2008). LiDAR systems can also measure the extent and depth of flood water inundation after a flood has occurred (Muhadi et al., 2020). It can reduce disasters caused by flooding as well as help governments with flood management. For example, when flooding is severe, DEM data can be used first to identify areas that need to be prioritized to provide appropriate flood risk management in time to reduce further hazards (Muhadi et al., 2020).

The challenges of LiDAR systems

Although LiDAR has many advantages, there are some challenges in its use. The urban landscape is complex, so there can be difficulty in detecting certain features with accuracy, such as railroads, roads, viaducts, rivers, riverbanks and other landscapes (Abdullah et al., 2012; Wedajo et al., 2017). LiDAR technology can have challenges in detecting water bodies with accuracy, due to light absorption and refraction (Cook et al. 2009). Moreover, most rivers contain suspended sediment, which may absorb and refract the light and affect the accuracy of the detection results (Hohenthal et al 2011). Errors and discrepancies in the detection of these types of features using LiDAR can affect the accuracy of flood prediction models. This is because some minerals in the sediment can cause incorrect reflection of the laser gravel beam (Hohenthal et al 2011).

In addition to this, it takes longer time to complete DEM visibility analysis through LiDAR (Muhadi et al., 2020). One study showed that DEM data generated by LiDAR takes 28 minutes, while DEM data generated by SAR (Synthetic Aperture Radar) takes only 19 seconds (Abucay et al., 2020). However, this does not have serious implications. The researchers believe that this problem will be solved automatically with the progress of computer technology (Muhadi et al., 2020).

The use of SAR in flood map

Like LiDAR, Synthetic Aperture Radar (SAR) can map floodplains in any weather and at any time of day (Elkhrachy 2022). The spatial resolution of SAR can reach 30 meters to less than 1 meter (Shen et al., 2019). SAR has been used to produce flood maps since 1980, and the technology has made considerable progress in the accuracy, speed, and other aspects of obtaining data today (Shen et al., 2019).

The principle of SAR to obtain data is to detect the roughness of different ground covers (Shen et al., 2019). When illuminated by a radar antenna, the scattering intensity is different for water-covered and vegetation-covered ground (Shen et al., 2019). The different scattering intensities determine the strength of the signal returned to the sensor (Dasgupta et al., 2018). The complex ground environment contains different media. The density, shape and relative permittivity of the media will determine the strength of the received signal (Dasgupta et al., 2018).

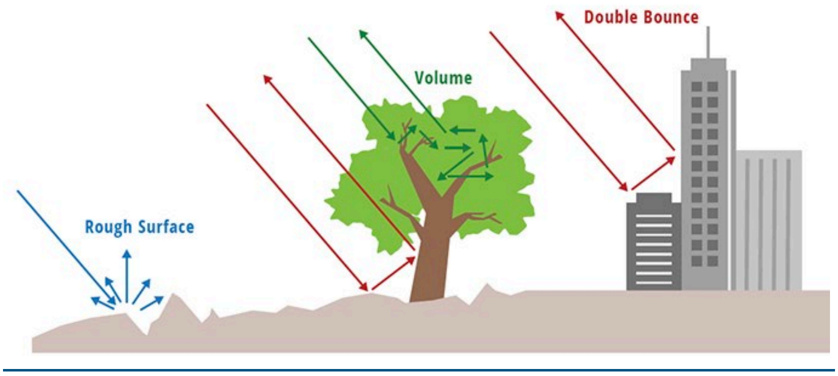

Figure 9. Different surfaces will have different scattering mechanisms . For example, rough surfaces produce scattered reflections; urban buildings produce high intensity reflections; and vegetation produces many reflections but is highly attenuated due to multiple reflections between leaves (Credit: NASA SAR Handbook).

Synthetic aperture radar typically measures two coordinates, one along an axis parallel to the direction of flight and the other from the radar antenna to the point being measured (National Research Council 2007). The direction of the radar antenna is perpendicular to the flight path and is referred to as the "range direction". The role of the antenna is to transmit pulses and record echoes (National Research Council 2007). These echoes are processed by image algorithms to form a composite image of the object.

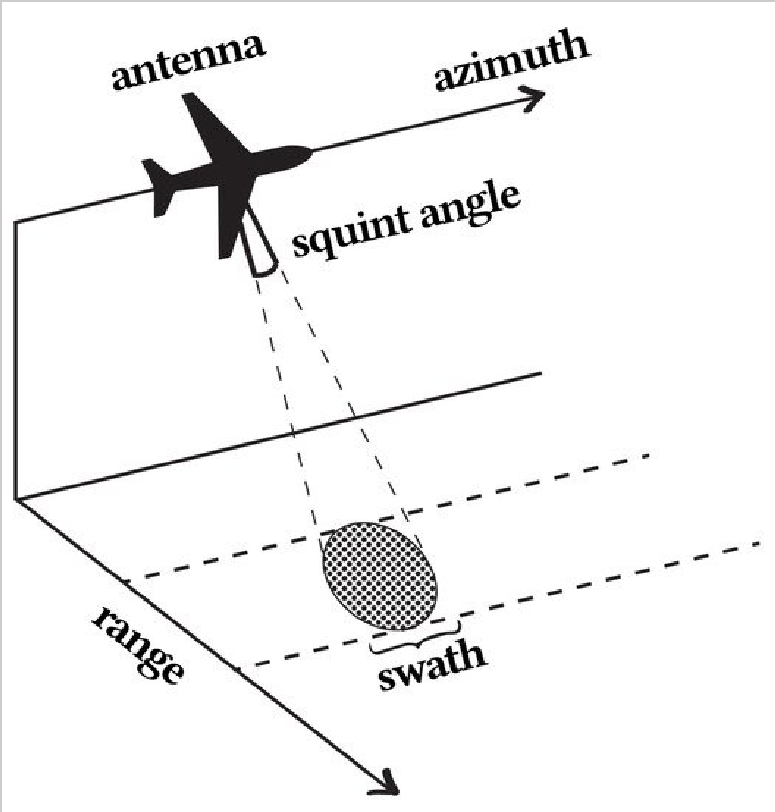

Figure 10.This figure shows a SAR system in operation. The direction of flight is called the azimuth direction, the direction of the antenna is the range direction, and the area illuminated by the antenna is called the swath (Cruz et al., 2022).

However, there are limitations in using SAR technology in densely vegetated areas because it is difficult for radar to penetrate vegetation canopy (Muhadi et al., 2020). Different wavelengths have different penetrating power. For example, a 3 cm X-band radar can barely penetrate a coniferous forest, while a 23 cm L-band signal can pass through the forest (Mendes et al., 2019).

Some researchers analyze the impact of different DEM sources on the accuracy of flood analysis, comparing the flood models produced under different techniques with historical records (Papaioannou et al., 2016). It has been shown that DEM data generated by LiDAR are more reliable than DEMs generated by other techniques (Sanders 2007). The results of the study show that the reliability of DEMs data has a great influence on the flood prediction results, so LiDAR may be a more reliable technique (Muhadi et al., 2020).

Floodplain mapping using DEM

DEM plays an important role in modeling flood maps. The DEM can be used to obtain data on topography, elevation, slope gradient and hydrological features. Hydrologic features may include topographic features of the hydrologic region (e.g., plateau, basin), the area of the watershed, or soil features of the hydrologic region (e.g., sandy soil, silty soil, infiltration rate of the soil). In addition to this, the DEM can be used to divide the watershed into several sub-basins to determine the peak discharge of water flow in different reaches. This allows a more detailed record of hydrological changes. Apart from that, climate data including rainfall should also be considered in the mapping. All climatic characteristics of a region (e.g., average annual rainfall) need to be determined and should also be recorded if there have been frequent and intense rainfall events in the region recently. This is because heavy rainfall can affect the flow and velocity of rivers. Land use also needs to be recorded. Urbanization leads to an increase in impervious area, and it has been confirmed by researchers that the increase in impervious area can further contribute to an increase in inundated areas (Apollonio et al., 2016). In addition to this, the map can also show the purpose of land use. For example, the percentage and distribution of land use types (e.g., commercial, industrial, residential land) within the watershed needs to be taken into account. This record will make evacuation after a flood much easier.

Taking the example of creating a floodplain map of Bujumbura city (mountainous area). The data mentioned above identify those areas that are prone to flooding during rainfall. These places are likely to be areas with an elevation of less than 920 meters above sea level, or areas with a slope of less than 10 degree. The factors should be weighted according to the different effects of elevation and slope on the severity of flooding (Niyongabire et al., 2016). And there are different weighting criteria within the same factor. For example, an area with a slope of 0 degrees has a different likelihood of flooding in the event of heavy rainfall than an area with a slope of 5 degrees(Niyongabire et al., 2016). The specific process is shown in Figure 11.

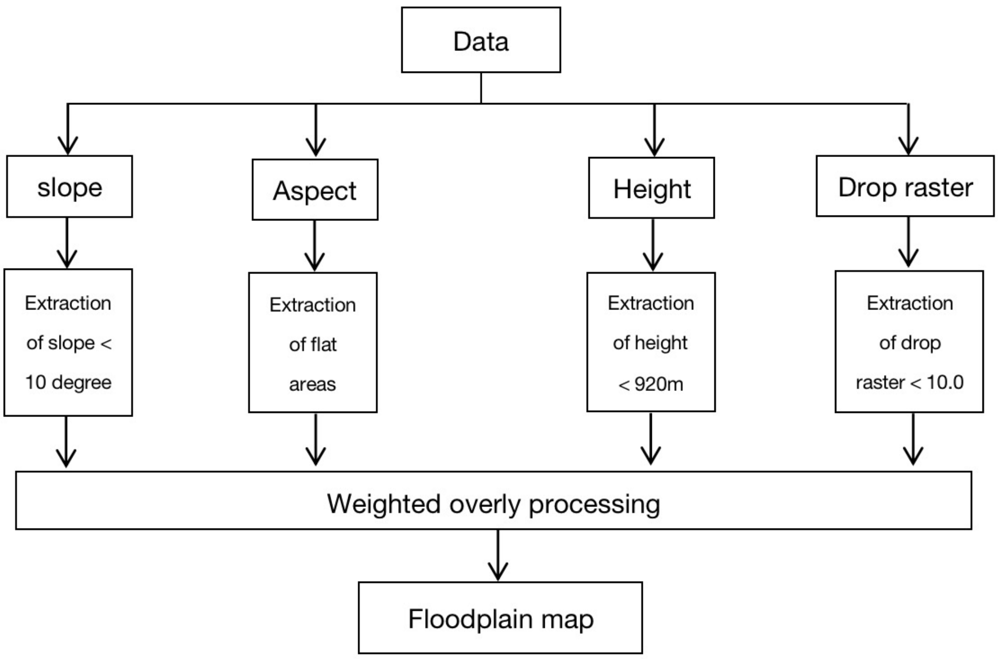

Figure 11. Take the example of creating a map of flood-prone areas in a mountainous region, and overlay different parameters to create a complete map (Adapted from Niyongabire).

Floodplain mapping needs under changing land use and a changing climate

Global climate and land use are constantly changing. In the previous section, it was described that the production of floodplain maps requires attention to climatic factors and land use factors, and this section will focus on how climate change and land use change affect the impact on flood magnitude and frequency.

Climate change is closely related to hydrological changes (Church et al., 2018). Changes in land use may affect runoff formation and flood potential (Church et al., 2018). These changes can alter the frequency and magnitude of flooding, so flood forecasting systems should be periodically reviewed and updated as necessary to take these factors into account and ensure the accuracy of floodplain maps.

Impact of climate change on floodplain map updates

Climate and flooding are closely related. Data show that more than 4 million Canadians currently live in floodplains and that these people will be at greater risk because of climate change (Chattha 2021). Canada is warming twice as fast as the global average. In B.C., for example, some researchers predict that the average temperature will increase by 3.8 degrees Celsius by the end of the century (Church et al., 2018). When temperatures rise, it can cause glaciers to melt causing sea levels to rise and increasing the risk of flooding. Some studies have shown that for every degree of warming of the atmosphere, it can hold about 7% more water (Perkins 2011). . The greater the moisture content, the higher the likelihood of short-duration intense rainfall. For example, in 2018, Ottawa experienced a six-day period of extreme heat followed by extreme rainfall that caused flooding in several areas (Canadian Disaster Database 2019).

Researchers from Canada were motivated by the 2021 floods in B.C. to use climate models to study the effects of global warming on flood events (Weber 2022). They found that such catastrophic weather extremes are predicted to increase as greenhouse gases continue to enter the atmosphere (Weber 2022). In addition, researchers found that the frequency of floods, which used to occur once every 200 years, could triple by 2099 (Patel 2021). Experts from the University of Manitoba believe that climate change is changing the frequency of 100-year floods (Dangerfield 2019). Canada's environment minister says this increase in frequency is already happening in Quebec, New Brunswick and Ontario (Dangerfield 2019). Researchers even predicted that each person would experience an average of two mega-floods in their lifetime (Patel 2021).

Canada is a coastal country with the longest coastline in the world, with a total length of 243,042 km (Statistics Canada 2016). The impact of a coastal flood would be enormous. According to statistics, a total of 4.8million people live in coastal areas across Canada (Statistics Canada 2022). Warming causes water to expand due to temperature, glaciers to melt, and eventually sea levels to rise, causing coastal areas to be exposed to increased risk of extreme flooding. Because of the rising sea level, some researchers even believe that Richmond, BC and The Tantramar Marsh in NB will be flooded by the sea in 100 years (Cain 2017).

Impact of land use change on floodplain map updates

Land use change can also have an impact on flood map updates. Some data show that land use in Canada is constantly changing. Between 2010 and 2015, approximately 2,258 km^2 of forest was converted to cropland and approximately 1,215 km^2 of cropland and forest was converted to settlement across Canada (Government of Canada, 2022). The increase in population has caused large-scale and continuous impacts and changes in land use, and has further caused an increase in the frequency and magnitude of flooding.

Unsuitable land activities can lead to an increase in the frequency of flooding. On agricultural land, heavy agricultural machinery is often used, which can lead to soil compaction and result in lower soil infiltration rates. When the soil infiltration rate decreases, surface runoff increases. In addition to this, agricultural intensification also leads to soil erosion and reduced storage capacity, therefore the reduction of stored water and increased runoff. Increased surface runoff can further increase soil erosion. This is a vicious circle.

In Canada, the conversion of forests to cropland is the largest land use change in recent decades. In areas such as Toronto, London, Halifax and Saint John, more than 80% of the forest became settlement between 1971 and 2011 (Government of Canada, 2022). The conversion of forest to cropland means that a large number of trees need to be cut down, which will reduce soil interception and evaporation, thereby increasing early soil moisture while reducing the storage capacity of the soil and further increasing surface runoff.

The process of urbanization has also led to the transformation of forests into settlements. While the urban area has increased, the landscape has changed from natural to man-made, and the flow and storage of rainwater has changed (Feng et al., 2021). The increase in impervious area (e.g., roads, parking lots) reduces the natural infiltration of rainwater, resulting in increased surface runoff, and this runoff accelerates into nearby streams, increasing the risk of flooding due to increased stream velocity in a short period of time (Feng et al., 2021). Researchers from the United States have statistically found that the maximum discharge of rivers increases during urbanization, leading to an increased likelihood of flooding. (Konrad 2003). Some researchers have found that in London, Ontario, the percentage of urban area has doubled in sixteen years, and forests are decreasing at an alarming rate (Birupama et al., 2007). This change has led to higher peak flows of drainage during rainfall. To reduce the risk of flooding, authorities should pay attention to land use near the Thames River watershed and analyze local hydrological changes in time. Because of the high urban population, the damage caused by urban flooding is significant. For example, the urban flooding that occurred in Toronto in 2013 caused over $1 billion in damage (Sandink et al., 2021).

Both climate change and land use change will have an impact on hydrology. The conversion of forest to cropland and urban areas leads to changes in evaporation, water storage, and surface runoff. Climate change can alter evaporation rates, affect ground absorption, alter snowmelt rates, cause sea level rise, and contribute to the frequency and magnitude of water flow peaks (NRC 2018). Hydrologic changes can affect flood risk, further creating the need for floodplain map updates.

Therefore, changes in climate and land use can lead to changes in flood frequency and the need to update floodplain mapping. Generally speaking, flood maps reviewed every five years (Khaliq 2019). Federal Emergency Management Agency (FEMA) considers the flood risk level to be "unknown" if the flood maps have not been reviewed in a five-year period. For example, in 2017, following severe flooding in Montreal, there were reports that the floodplain data used for the heavily affected area, Rivière des Prairies, was from 1978. It was because of the old data that important information was not predicted and evacuation efforts were compromised. In BC, all of the flood maps are over 15 years old, and it is clear that the older maps have not been updated with changes in land use (Ebbwater 2015). If it were possible to review the maps every five years, the accuracy of the flood maps would be greatly increased.

A floodplain map that provides an accurate depiction of risk should also include projections of the future, such as sea level rise, and population growth. The following factors can be considered in assessing the need for map data updates when conducting a review of flood maps (APEGBC 2017).

1.Attention to land use change is important and needs to be reviewed for hydrologic changes resulting from land use change. For example, community growth or rapid urbanization can lead to significant land use changes and a significant increase in impervious area, resulting in reduced land infiltration capacity and an increased likelihood of flooding. In addition to this, major infrastructure such as dams need to be shown on the map if they are built in the floodplain because in some cases flooding can also occur if a dam is not built properly or if a dam collapses due to heavy rainfall. FEMA recommends that dam builders coordinate with the government to provide them with an inundation map of dam failures or potential large flood outlets to help the government incorporate this information into emergency action planning, evacuation planning, and community planning efforts.

2.Flood risk in floodplains is not static because of climate change. And the impact of climate change can only be reflected in the last 10 years of measurements. Future design water level projections corresponding to 100- or 200-year return periods derived from this short-term experience will be unreliable. Therefore, updating the floodplain maps needs to reflect the latest weather change impacts. For example, USACE (United States Army Corps of Engineers) requires that climate change impacts on coastal floodplains be considered when updating maps, including historical data on sea level rise, intermediate projected rise, and worst-case projected rise (Khaliq 2019). According to the NRC(National Research Council Canada)'s calculations, it costs far less to update maps at least every five years to account for the effects of climate change flood risk than the damage caused by flooding (Khaliq 2019). In BC, to consider the impact of climate change on the official floodplain maps of the Lower Fraser River, the NRC recommends that the limitations and uncertainties of the data be reviewed as a matter of priority and that ongoing research be conducted to address the limitations and uncertainties of the floodplain maps (NRC 2018).

3.Terrain change. When the land elevation changes, the floodplain map data needs to be updated in time. For example, in New Orleans, USA, parts of the area had experienced rapid subsidence and a new flood map was needed to avoid or reduce the impact of catastrophic flooding (Dixon et al., 2006).

Conclusions

Floodplain maps are an important tool to develop flood risk management strategies that help communities and citizens make informed decisions. There is no single type of map that is appropriate for all flood management needs. To help the community and the public determine which types of maps are appropriate for different management issues or priorities, I will make the following conclusions (Figure 12).

1.When flood contingency plans and emergency management need to be established, flood inundation maps are useful to help residents determine evacuation routes in the event of a flood.

2.Flood hazard maps are used when land management and planning are required. The map is prepared for management purposes. When disaster relief is required, the flood hazard map can be used to prioritize mitigation and flood response efforts. Flood hazard maps allow to determine the predicted flooding under different scenarios (e.g. 100-year events) in order to implement specific flood prevention measures.

3.Flood risk maps can identify areas where economic, social and environmental damage is most severe and ensure that the area is helped first, accelerating the efficiency of flood risk management.

4.Flood awareness maps are educational. It is a tailor-made map for residents and communities. The map raises public awareness of the potential hazards of flooding and facilitates their timely response before a disaster occurs.

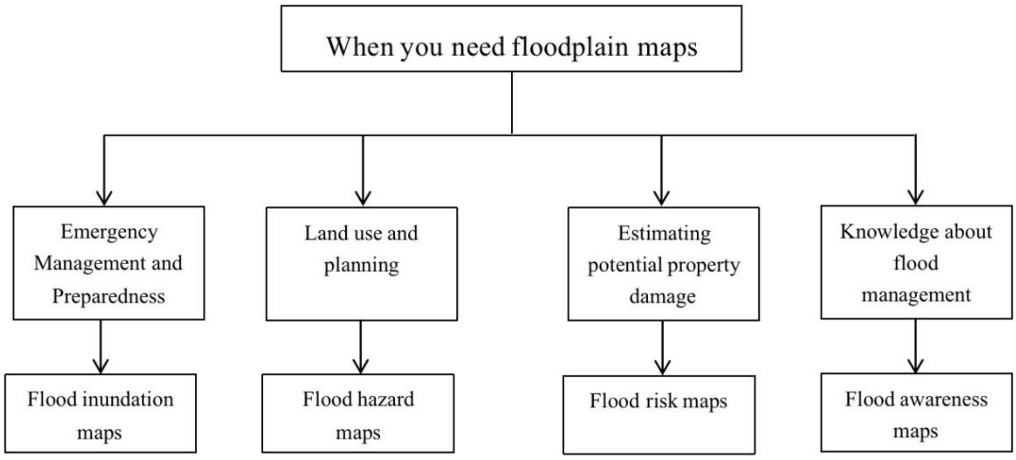

Figure 12. The diagram guides users in determining the type of map that communities and the general public need (Adapted from APEGBC 2017).

Advances in flood maps and their widespread use have allowed people living in floodplains to reduce the risks associated with flooding. The development and use of floodplain maps has increased awareness of flooding and reduced the social, economic, ecological, and personal property damage caused by flooding.

Flood maps are widely accepted on the premise that they can provide accurate information. The types of flood maps are accurately differentiated, allowing different maps to show the different effects of flooding, and helping communities and the public identify the different types of maps to use in different situations. In addition to this, land use and climate should also be looked at in order to get maps with accurate information, to obtain the latest changes in land cover and the latest changes in climate, and to ensure that outdated floodplain maps are updated. Only by ensuring the reliability and accuracy of flood maps is the key to making the public want to use this flood risk management tool.

Recommendations

Based on the above discussion, some key recommendations can be made.

1.In the United States and some European countries, flood maps are publicly and freely available. However, for Canadian citizens, flood maps are not easily accessible, and many lack knowledge of flood management (Minano et al., 2018). Studies have shown that 94% of households living in flood plains do not believe they are at potential flood risk (Thistlethwaite et al., 2017). Online and easily accessible floodplain maps allow the public to be more informed about floods and flood maps and can better protect their property and safety.

2.Communities and residents located in floodplains need to become accustomed to using flood maps and checking them regularly for updates, actively participate in flood risk management decisions and support government flood risk management initiatives.

3.The collection and attention to up-to-date data on land use change and climate change is important to ensure that citizens' property and safety are not compromised as a result of old maps. Timely and updated information is essential to the accuracy and reliability of floodplain maps.

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