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VIEWPOINT

AI and data science for smart emergency, crisis and disaster resilience

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Abstract
The uncertain world has seen increasing emergencies, crises and disasters (ECDs), such as the COVID-19 pandemic, hurricane Ian, global financial inflation and recession, misinformation disaster, and cyberattacks. AI for smart disaster resilience (AISDR) transforms classic reactive and scripted disaster management to digital proactive and intelligent resilience across ECD ecosystems. A systematic overview of diverse ECDs, classic ECD management, ECD data complexities, and an AISDR research landscape are presented in this article. Translational *disaster AI* is essential to enable smart disaster resilience.

Keywords Emergency · Crisis and disaster · AI for disaster management · Data science for disaster management · Smart disaster resilience · Disaster AI · COVID-19

1 Introduction

Emergencies, crises, and disasters (ECDs) have been increasing in frequency, ferocity and their scale and extent of devastating impacts. For example, COVID-19 has caused 6.5 M deaths, 623 M confirmed cases, and trillions of dollars in losses to date. In 2020, the 389 reported global natural disasters caused over 15k deaths, 98 M infected people, and over US$171Bn losses.[1] In 2022, Hurricane Ian killed at least 126 people and costed over US$67Bn in the USA. The 2022 Pakistan Flood alone deluged 1/3 land, killed over 1700 people, and affected 16 M children. Australian national Disaster Assist database recorded 40 severe natural disasters to date in 2022, compared to 47 in 2021 and 46 in 2020. The 2019–2020 bushfire season killed 34 people and destroyed 10k buildings. New ECDs emerge every day and become increasingly common, uncertain but devastating. Technological disasters such as cyberattacks, AI weapons, and information disorder, and other emerging events such as geopolitical unrests (e.g., the Ukraine war), and financial crises as the global recession further diversify the classic ECD spectrum.

Classic ECD management relies on singular disciplinary and domain-specific studies and methods for prevention, early warning, mitigation, preparedness, response, and recovery [1]. Disciplinary and domain-specific studies involve environmental science, meteorology, climate science, health science, infectious disease management, epidemiology, and sustainability studies. However, they lack proactive, adaptive, generalized, and end-to-end foundations and capacities for full-spectrum, full-cycle, large-scale, uncertain, and evolving multi-hazard ECD resilience. These areas also face significant capability limitations and gaps in understanding, quantifying, and managing the increasingly complex, uncertain, large-scale, and evolving natural, man-made, technological, and political crises and disasters.

Accordingly, transformative *smart digital ECD resilience* (SDR) has emerged as a critical everyday matter for most people. SDR is essential for managing the full ECD spectrum, from natural and infectious disasters to biosecurity, cybersecurity and machine disasters. SDR is also an imperative and overwhelming challenge and priority in the daily agenda of business, local-regional-global governments, intergovernmental organizations, and the United Nations. It is also critical for effectively addressing UN Sustainable Development Goals. For these, AI for SDR (AISDR) plays a foundational role in enabling SDR.

In this article, we present a comprehensive overview of the broad spectrum of ECDs, the area of AISDR, and their challenges and data. A research landscape of AISDR is dis-

[1] See more from the United Nations Office for Disaster Risk Reduction and "United nations office for disaster risk reduction" (https://www.undrr.org/).

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[1] See more from the United Nations Office for Disaster Risk Reduction and "United nations office for disaster risk reduction" (https://www.undrr.org/).

cussed for AI and data science (AIDS) to address ECDs and develop ECD-oriented AIDS, i.e., creating *disaster AI*, or *disaster data science*.

2 The ECD landscape

Several important terms: emergency (E), crisis (C), disaster (D), and risk (R), are interrelated but also differ from each other in their terminology.[2]

- *Emergency* individual or a series of critical threats to a community or society in terms of their significant health, social, economic, financial or environmental consequences or impacts, requiring urgent actions.
- *Crisis* individual or series of extraordinary threats to a community or society in terms of their large health, social, economic, financial or environmental consequences or impacts, requiring urgent actions.
- *Disaster* 'a serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources'.[3]
- *Risk* the likelihood and consequences of an E/C/D event, which may expose to E/C/D-specific harm, damage or loss, and operational or systemic adverse effects or impacts.

Other relevant terminologies relating to ECDs are hazard, catastrophe, security, and safety. Hazard and catastrophe are often interchangeably used with disaster, where *catastrophe* refers to those hazards and disasters with their scale, coverage and severity being large or extreme and beyond the coping ability of the affected entity (usually a community-level entity). *Security* and *safety* have a broader meaning and coverage than ECDs, while ECDs may cause security and safety concerns or consequences.

All E, C and D events cause serious consequences and impacts, requiring immediate actions. They share wide similarity, and an emergency or crisis may escalate into a disaster. We thus combine them, ECDs, in this article to discuss their processing and management beyond the existing body of knowledge and by advanced AIDS.

Here, the *risks* and *impacts* of ECDs refer to the significant consequences and outcomes caused by ECD accidents.

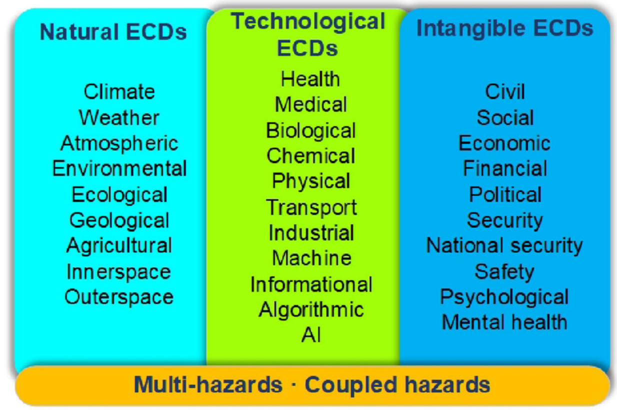

Fig. 1 The landscape of emergencies, crises, and disasters (ECD)

Examples include significant losses of lives, livelihoods, services, and economic benefits; significant harm or injury to health, or humans; significant damages to property, asset, infrastructure, or environment; or significant dysfunctions, disinformation, etc.

Furthermore, generally speaking, ECDs can be categorized into natural ECDs and human-made ECDs. *Natural hazards and disasters* are caused by natural processes or phenomena, such as environmental, physical and climate changes, and geological emergencies. They have been extensively studied and are mostly concerned by governments, intergovernmental organizations, private and professional communities, and the United Nations. In recent years, *human-made crises and disasters* have been diversified and concerning, such as civil wars, invasion wars, cyberattacks, refugee crises, machine failures, technological misuses, and AI weapons. They have become increasingly uncertain, frequent, and devastating, forming a serious threat or concern in contemporary societies.

As a result, today's spectrum of ECDs goes beyond the classic focus on isolated natural hazards and their management. The ECD landscape overspread a very wide range of E, C, and D events, forming open complex systems with significant system complexities [2]. Examples are climate change, weather, hydrometeorological, atmospheric, environmental, geological, biological, chemical, physical, agricultural, transport, civil, social, economic, financial, political, national, security-related, safety-related, technological, machinery, AIDS-related, and health, medical, psychological, and mental health related emergencies, crises or disasters. Often, *multi-hazards* couple, co-exist and co-evolve, resulting in *coupled hazards*, making things very challenging to handle. Figure 1 categorizes ECDs into natural, technological, intangible, and coupled families.

Climate and weather ECDs sometimes clihazards for short, including climate and weather-caused long- or short-term events and consequences. They are the mainly con-

[2] For the UNDRR terminology on disaster risk reduction, refer to "2009 UNISDR Terminology on Disaster Risk Reduction" at https://www.undrr.org/terminology or https://www.undrr.org/publication/2009-unisdr-terminology-disaster-risk-reduction.

[3] https://www.undrr.org/publication/2009-unisdr-terminology-disaster-risk-reduction.

cerned disasters, may cause other disasters, such as meteorological, hydrological, and hydrometeorological consequences. Examples are extreme temperature, heat waves, drought, heavy rainfalls, heavy snowfalls, flood/flash floods, convection-hail, windstorm, thunderstorm, hailstorms, hurricanes (cyclones and typhoons), tornados, blizzards, or cold spells.

Atmospheric ECDs sometimes air hazards alternatively, causing poor atmospheric quality threatening or toxicological to human body. Atmospheric disasters may be caused by natural hazards or man-made accidents, leading to the deficiency, concentration or displacement of gases, chemicals or chemical disasters. Typical atmospheric hazards include oxygen deficiency, dusts, welding fumes, fogs, mists, and chemical vapors.

Environmental ECDs or ecological disasters, referring to damages to natural environments. Environmental disasters may be caused by natural hazards and human activities, which may further cause other disasters such as biological or agricultural disasters. Examples are greenhouse gases, air pollution, water pollution, land pollution, environmental and ecological damage or degradation, fire, and wildfire.

Geological ECDs geohazards for short, including adverse geological conditions, processes or consequences, damages or losses caused by or relating to significant inner-earth processes such as earthquakes and volcanic emissions; significant oceanic processes such as tsunamis; or mass land movements such as rockslides, landslides, avalanche, and surface collapses. Geological hazards relate to environmental ECDs.

Agricultural ECDs damages to critical agricultural infrastructure, assets and their functioning, production, recovery or resilience and losses caused in crops, livestock or fisheries. Agricultural disasters may be caused by extreme climate, extreme weather, environmental disasters, biological infections, plant plagues, or man-made accidents.

Biological ECDs biohazards for short, including biosecurity, genomic and pathological crises and events. Biological disasters may be caused by pathogenic microorganisms like bacteria or viruses, toxins, pests or insects, bioactive substances, infectious or epidemic diseases, animal plagues or infestations, or plant/animal contagion.

Chemical ECDs adverse events and hazards caused by toxic, deadly or environmentally unfriendly chemicals, chemical spills, or chemical weapons. Examples include damages caused by carbon monoxide, hydrogen sulfide, combustible gas, chlorine, or sulfur dioxide.

Physical ECDs damages and losses caused by deadly or environmentally unfriendly physical factors, conditions or processes, such as electricity, heat, heights, noise, vibration, or stressing. Examples include nuclear radiation, electromagnetic radiation (the radiation of electric and magnetic fields), noise pollution, and pressure extremes.

Health and medical ECDs ECDs relating to healthcare services, medical services, or medicine. Health and medical ECDs may be caused by or relate to health emergencies; public health crises, vector borne diseases, or infectious diseases epidemics; hospital incidents like misdiagnosis and mistreatment, virus spread, surgical infections, musculoskeletal injuries, or chronic diseases; natural hazards; technological hazards; and social or transport disasters.

Transport ECDs damages or losses to transportation infrastructure, assets, properties or humans during transportation. Transport accidents or disasters may happen during intense air, sea, ferry, road, rail or underwater transportation.

Civil ECDs intensive or substantial accidents with or damages to civil infrastructure, utilities or services. Civil disasters may relate to the supplies, transmission, or security of civil utilities, facilities and services, such as power, gas, water, sewage, or other types of energy or utilities.

Social ECDs social crisis (or societal crisis), serious social problems or challenges to a society or community. Social crises may be caused by humanitarian, societal, cultural, religious, ethical or ideological challenges, or social policy deficits. Natural disasters or economic crises may also cause social crises. Examples of social crises include civil disorder caused by mass protests or military conflict, illegal immigration, border conflict, violence, terrorist activities, terrorist attacks, or crimes against humanity.

Economic or financial crisis major shocks, dysfunction, or breakdown in economic or financial systems. Examples include economic recession or depression, financial bubbles, financial contagion, regulatory failures, currency crises, banking panics, market crashes, speculative crashes, and sovereign defaults. Emergent crises include 'black swan' and 'gray rhino' events in capital markets, non-fungible crypto markets, digital finance, Internet finance, supply chain, logistics, or trade facilitation, and those relating to energy market, utility market, trade war, or extreme poverty.

Political ECDs disasters or losses caused by political factors or events. Examples include constitutional crisis, policy deficit, political radicalism, nationalism, polarization, instability or change; government mistrust, regulations, shutdown or atrocity; geopolitical conflict, military violence; unlawful protests, revolution, religious violence, extremism, or inequality. Political crises may also be caused by civil crises, financial crises, or natural hazards.

Security-related ECDs damages or losses caused by events or incidents relating to security. Types of security include national security, homeland security, human security, financial security, environmental security, energy security, food security, cybersecurity, transport security, and information security.

National security the non-military security and defense of a sovereign country or region or relating to national interests.

Examples of national security include national border security, extreme social or community events, terrorist activities, and political unrest.

Safety-related ECDs damages, harms or losses relating to safety. Examples of safety include human safety, public safety, work safety, and health safety. Ergonomic safety is a particular safety type, relating to the harm of workstations, malfunctions or breakdowns to human health.

Technological ECDs damages or losses caused by or relating to technology. Technological disasters may be caused by scientific, technical, informational, engineering or industrial accidents, failures, attacks, or manipulations. Technological disasters include *informational hazards* such as cyberattacks, information disorder, infodemic, or fake news [3]; *technical facility disasters* such as machine disasters, information infrastructure attacks, critical infrastructure failures, network and communication failures, robotic attacks, or ergonomic hazards; *industrial hazards* such as industrial pollution, or factory explosions; and *scientific hazards* such as chemical or physical hazards.

AI ECDs damages, harms or losses caused by misdesign, misrepresentation, misoperation, misbehaving, miscommunication, or misuse of AI technology or systems. Examples of AI disasters include misprogrammed devices, programming failures, incorrectly trained machines, biased, unfair, vulnerable or faulty AI designs or algorithms, or the misuse of robotics or unmanned aerial vehicles (UAVs). AI disasters may be due to unethical, irresponsible, untrustworthy immoral, or anti-humanity AI designs or applications.

Psychological and mental health ECDs harm or injuries relating to psychological disorder or mental health. Examples include mental and cognitive disorders such as anxiety, stress, or depression; and psychological or mental problems caused by chronic diseases, fatigue, trauma, sleep disorder, work pressure, workplace discrimination, violence, or harassment.

Coupled ECDs two to multiple ECDs that co-occur and are coupled. In reality, some hazards or disasters may be coupled or associated with each other, forming multi-hazards or coupled hazards. Examples are socio-technical hazards, human-technical hazards, socio-economic hazards, and socio-natural hazards (e.g., of flooding and mud flows). Multiple disasters may present sequentially under certain conditions. For example, flood may be followed by animal plagues and then by infectious diseases epidemics.

3 From ECD management to resilience

3.1 Classic ECD management

ECD management has been widely explored in various specific domains and disciplines where emergencies, crises or disasters are of particular concern. The related scientific research on ECD management has involved many disciplines and techniques. Typical areas include environmental science, climate change studies, biological science, biomedical engineering, sustainability studies, health and medical science, complexity science, economic and financial crisis management, and general and specific emergency and disaster management in management science or business.

- *Environmental science* ECD-related areas include green recovery, land protection, oceanic pollution management, land pollution management, air pollution management, air quality management, nuclear and chemical explosion management, waste management, and carbon emission control.
- *Climate change studies* including extreme weather management, hydrometeorological event management, and managing climate change-derived effects such as on human, health, land, ocean, air, living, or the economy.
- *Biological and biomedical engineering* such as biosecurity management, infectious disease management, biological weapon management, and biological waste management.
- *Health and medical science* such as emergency management, emergency risk reduction, instant emergency treatment, epidemiological modeling, and public health crisis management.
- *Complexity science* such as complex system modeling of dynamic ECD events or systems; simulation of ECD formation, evolution, replay, and consequence; and simulation and optimization of intervention strategies and effects.
- *Economics and finance* such as economic uncertainty modeling, financial crisis analysis, cross-market crisis contagion, cross-sector crisis contagion, and insurance for ECD risk reduction and risk transfer.
- *Sustainability studies* including environmental sustainability studies, climate change management, food management, poverty management, water quality management, energy management, and urban planning.
- *Emergency and disaster management* such as creating policies, specifications, techniques and tools for identifying, assessing, preparing, responding, and intervening emergencies, disasters, or catastrophes.

From operational perspectives, ECD management has involved broad-reaching communities, authorities, practitioners, and the public. Examples are global and hierarchical efforts made by agencies or focus groups of United Nations, governmental agencies, intergovernmental institutions, non-governmental organizations (NGOs), research institutions, and domain-specific private and professional institutions and service providers. They commit to various developments of ECD management standardization (e.g., codes, standards, and specifications), ECD data processing and management, ECD research and innovation, and ECD management solutions and tools.

A typical ECD management framework for managing natural hazards and health emergencies consists of four phases: mitigation, preparedness, response, and recovery (MPRR) [4].[4]

- *Mitigation* develops structural and nonstructural disaster management measures and resources, preventive regulations and strategies, advanced codes and standards to prevent and contain ECD consequences and impacts.
- *Preparedness* makes all-round personnel and their skills, facilities, supplies, other relevant resources, action plans, procedures, and specifications ready, including making them planned, organized, exercised, and evaluated, for ECD incident and consequence management.
- *Response* reacts to emergencies and consequences by taking appropriate resource coordination, responsive actions, safety measures, damage assessment, humanitarian assistance, and consequence management.
- *Recovery* takes actions to rehabilitate functions, stabilization, and normalcy such as by undertaking damage assessment, infrastructure reconstruction, livelihood restoration, and community development.

This MPRR framework has also been widely applied in non-health disaster management, in particular, natural disaster management. However, MPRR are problem-specific, process-focused, passive, and coarse, and lack intelligence. Its high-level methodological roles do not adapt to the expected objectives and performance for smart ECD resilience.

3.2 Smart ECD resilience—SDR landscape

Smart ECD resilience aims for a thinking and methodological paradigm shift from passive, reactive, discipline- and domain-specific ECD management to intelligent, hierarchical (strategic, tactical to operational), all-round (full spectrum of ECDs), full-cycle (from ex ante to ex post ECD events), proactive, and adaptive end-to-end digital ECD resilience. With advanced AIDS (including shallow and deep machine learning and analytics), the MPRR framework can be further personalized, strengthened and upgraded with intelligence toward more proactive, active, fine-grained, tailored, and full life span-oriented ECD resilience. Taking the lessons learned from successful AIDS applications in other domains [5, 6], a new-generation smart ECD resilience framework emerges. Smart ECD resilience enables proactive and early contingency planning, prevention, prediction and warning during normal time and prior to ECD events; active and online real-time and evolving detection, identification, recognition, planning, and management; and strategic and next-best action and strategy recommendation and decision-making. These provide the capability and capacity building, enhancement and optimization of historical, present and future ECD events, risk and impacts for smart ECD resilience.

Figure 2 presents a new framework for smart ECD resilience. The MPRR framework is decomposed and expanded to more fine-grained and collaborative phases for full-cycle, full-spectrum, and full-scale ECD management. We call it smart disaster resilience (SDR) framework. SDR consists of: early warning, forecasting, prevention, identification, assessment, response, mitigation, recovery, evaluation, and optimization.

Early warning alerting on potential ECD accidents. ECD early warning may provide ECD knowledge, monitor and analyze ECD events, predict potentially harmful ECD events, generate and communicate alerts, and respond to early warnings. These aspects form early warning ecosystems, which may be people-centered, human–machine-cooperative, automated, or end-to-end.

Forecasting foretelling a future ECD accident. ECD forecasting includes predicting the occurring likelihood, severity, timing, location, consequence, or impact of a future ECD accident. Forecasting and prediction are often interchangeably, building on domain-specific modeling, mathematical and statistical forecasting, or shallow-to-deep machine learning.

Prevention avoiding ECD events or their impacts. ECD prevention preserves resources and completely avoids prospective ECD events and their adverse effects. Prevention may take place before ECD occurrences, before the exposure to adverse effects, or during the design phase (e.g., of man-made disasters). Forecasting results may inform prevention.

Identification identifying ECD events or their impacts during, before or after their occurrences, typically focusing on the ECD detection at present time and in real time. ECD detection and identification detects, identifies, discovers and recognizes existing, immediate or new ECD events and their risk factors; analyzes and evaluates the risks and impacts of ECD events; and recommends, selects or determines appropriate approaches for instant risk elimination or control. Identification may be undertaken during the design, formation, or implementation of a dangerous event. It may also happen prior to, during or post an ECD occurrence.

Assessment assessing the risks, vulnerability, susceptibility of damage, effects or impacts by ECD events throughout

[4] "Emergency management in the united states," https://training.fema.gov/emiweb/downloads/is111unit%204.pdf.

the ECD cycle.[5] ECD assessment may include: prior to disasters, the risk and vulnerability assessment of potential ECD events; during disasters, the estimation of potential stricken people, location, damages and losses, the potential impacts on stricken people, community, asset and economy, the coping capacity and priority of emergency response; and after the emergency phase, the estimation of the priority of recovery, the demand of recovery resources, and the potential of continuing disasters and secondary threats. Assessment techniques, such as onsite inspection, satellite or UWV aerial inspection, survey, questionnaires, interview, and data analytics, may be used to understand and estimate the nature of an ECD event and its impact.

Response responding to emergencies. ECD response provides emergency and basic resources, facilities and support to affected people or community during or immediately after an ECD occurrence; and takes emergency and essential reactive actions and services to instantly eliminate or control (contain) ECD events and their adverse effects. Response reacts on emergency processing and disaster relief with essential and temporary resource provision, basic and short-term people or community support, and immediate effect removal or containment.

Mitigation mitigating the long-term risks of ECD events or their impacts. ECD mitigation makes strategic, local-to-global mitigation planning, and takes sustained actions to acknowledge, avoid, eliminate, reduce, control or transfer the long-term risks, effects, or impacts of ECD events. Strategic, administrative, regulatory, preventive or educational mitigation plans and actions may be made before or after an ECD event.

Recovery reacting to ECD accidents after their emergency phase. ECD recovery takes recovery actions such as rehabilitation, restoration, or reconstruction immediately after the emergency response to resume damaged functions, facilities and services to normalcy; improves the public awareness of risks and risk factors, understand risk contexts and complexities; enhances community participation and collaboration; strengthens resilient capacities and capabilities; and eliminates or reduces risk factors and impacts.

Evaluation assessing and reviewing the ECD management program and results. ECD evaluation defines criteria, standards, and measurement of ECD resilience quality, performance and outcome; develops performance indicators; specifies questions to be answered or surveyed; collects and analyzes ECD management-related quantitative and/or qualitative data; and quantifies ECD management performance and outcomes. An ECD evaluation plan is required, then an ECD evaluation report is generated as the result of ECD evaluation. Examples of evaluation criteria and performance indicators are the effectiveness and efficiency of response and recovery; the appropriateness of prevention and recovery procedures, actions and resources; the reliability, survivability and connectivity of critical infrastructure and services; the sufficiency of capacity and capability; and the utility, success rate, costs and savings of implemented strategies and activities.

Optimization optimizing the methodologies, approaches, resources, and performance for ensuring ECD resilience. ECD optimization optimizes the performance of forecasting, prevention, identification, assessment, response, mitigation, recovery, evaluation, etc.; enhances ECD resilience through reinforcement, retrofitting or upgrading ECD infrastructures, facilities, resources, technologies, or services; improves the ECD management specifications, standards, criteria, processes, measurement, and evaluation.

4 ECD data and complexities

ECD events and management generate large, and complex data. Different ECD events involve their respective data and data characteristics and complexities. Understanding and quantifying ECD data characteristics and complexities is foundational for enabling smart digital ECD resilience.

4.1 ECD data sources

Hence, we summarize the typical data relating to natural and man-made ECDs below. Both internal and external data are involved, such as workplace data, health and medical data, meteorological data, climatological data, environmental data, oceanic data, water data, space data, GIS data, imagery, GPS data, sensor data, human and community response data, census data, telecommunication data, social media data, cyberspace data, public data, crowdsourcing data, and reflection data.

- *Workplace data* such as infrastructure and building conditions and accidents, working conditions and incidents, fires, violent activities, bullying behaviors, and harassment events.
- *Critical infrastructure data* about the conditions, security, continuity, operations or disruption of building, energy, transportation, information etc. infrastructure.
- *Health and medical data* such as the conditions of health emergencies, emergency management, healthcare transactions, hospitalization, medical activities, and treatments of stricken people.
- Meteorological and climatological data, such as the conditions, events, dynamics, changes, and quality of climate, weather, and atmosphere.

[5] UNDAC: "Un disaster assessment and coordination,"https://www.unocha.org/our-work/coordination/un-disaster-assessment-and-coordination-undac.

- *Environmental data* such as land conditions and incidents, environmental degradation, mass movements, river conditions and incidents, lake conditions and incidents.
- *Oceanic and water data* such as oceanic movement, temperature, activities, and pollution; sea ice conditions and movements; water quality, volume, flow and speed.
- *Space data* such as the conditions, behaviors, activities, and events of the innerspace and outerspace.
- *Geographical information systems (GIS) data* about an ECD accident.
- *Imagery* such as satellite imagery, the aerial imagery captured by UAVs, and data from military or special purpose systems.
- *GPS data* spatial and temporal conditions, activities of ECD ecosystems captured by global positioning systems (GPS).
- *Sensor data* such as from remote sensing devices and networks, wireless sensor networks, CCTV surveillance data, Internet of Things (IoT) networks, industry IoT data, and on-site observation networks.
- *Human and community response data* such as the response behaviors, people's evacuation behaviors, mobility, or routes to an ECD accident.
- *Census data* about the affected society or community.
- *Telecommunication data* such as the mobile phone call reports, call detail data, and messaging data relating to an ECD event.
- *Social media* such as public, community and privacy-preserving communications, discussions, connections, messaging, or sharing.
- *Cyberspace data* such as Internet repositories, infrastructure conditions and activities of wide area networks, infrastructure conditions and activities of local area networks, infrastructure conditions and activities of wireless and wifi networks, and communication and messaging data such as online news, blogs, behaviors, events, networking and communication activities.
- *Public data* data about ECDs, such as the Google mobility data, the Emergency Events Database, and other open data shared by open government, professional or research institutions.
- *Crowdsourcing data* about the crowdsourcing activities relating to ECD events and their resilience management.
- *Reflection data* about the review, feedback, and comments on ECD events, their impacts, response and effects from their affected people and communities and the public.
- *Simulation data* artificial data generated for evaluating the disaster scenarios, impact, and vulnerability of target systems.

There may be other types and sources of data relating to a particular ECD event. Given an ECD event, a fundamental task is to collect its relevant data, understand their characteristics and complexities, and process them for ECD resilience.

4.2 ECD data characteristics and complexities

ECD data present various data characteristics and complexities. Smart ECD resilience must deeply understand and characterize the ECD-specific characteristics and complexities [5]. The random and outlying nature of ECDs makes their data both general and special. In addition, some of the data characteristics and complexities may be related to ECD data quality issues. Below, we discuss general ECD data characteristics and complexities and potential ECD data quality issues, respectively.

On one hand, general ECD data characteristics and complexities include multiplicity, granularity, heterogeneity, interaction and coupling relationships, decentralization, timing, frequency, uncertainty, and dynamics.

- *Multiplicity* ECD data often involve multi-domain, multi-modal, multi-scale, multi-grain, multi-source, or multi-view ECD sources, e.g., data mixing spatio-temporal, imagery, and textual information; an ECD event may be associated with multi-aspects, multi-factors, or multi-effects.
- *Granularity* ECD-sensitive factors and data share multi-scale, hierarchical or multi-grain differences.
- *Heterogeneity* ECD data often involve significant diversity in their types, formats, structures, distributions, or relations; or differences in recording frequency, format, timing, granularity, meaning, semantics, or period.
- *Interaction and coupling* diverse ECD factors, events and objects may interact or couple with each other; they may be associated, correlated, dependent, or causally related.
- *Decentralization* ECD data may be decentralized, or distributed; they may involve distributed or decentralized factors, individuals, or facilities widely spread across the affected regions or communities.
- *Timing* lifelong data about past, present and future ECD activities, or specific data such as with high-frequency and real-time streaming imagery about a landslide.
- *Frequency* ECD factors are associated with different frequencies in recording or acquisition.
- *Uncertainty* ECD events and their factors and effects are often uncertain; showing high randomness, unpredictability, or unreliability.
- *Dynamics* ECD events, effects and impacts are often progressive, evolving, or changing; presenting nonstationarity or variance over time, frequency, or value

domain.

Interested readers may also refer to many other data characteristics and complexities [5]. All aspects of ECD data characteristics and complexities should be deeply explored in both general and ECD-specific perspectives.

On the other hand, real-world ECD events and their associated entities are often rare, random, and outlying, which present specific outlying data characteristics and complexities. The ECD nature further involves various data quality issues in data acquisition. First, ECD events may be blind, unknown, or novel. Second, unusual ECDs may involve changing, outlying, sparse, infrequent, insufficient, incomplete, inconsistent, or irregular properties in their systems and data. Lastly, ECD data may also involve quality issues, such as bias, error, or missing values.

- *Blindness* ECD events may present little to no forewarning signals or indications, and are unable to be perceived or forecasted; resulting in lack of awareness or judgment.
- *Unknownness* ECD factors, events or effects may be unseen, unknown, unrecognizable, open, invisible, or hidden; resulting in no, hidden, or unknown observations or no sensors capable to monitor or detect them.
- *Novelty* ECD data may involve cold-start, emergent, new, or unannotated ECD events, conditions, and activities, affected people or community, effects, and impacts; resulting in unsupervised, no-ground-truth, cold-start or novel scenarios.
- *Change* ECD events may present light drift (shift) or significant changes or movements from time to time; presenting unstable or unpatternable outlying and evolving characteristics and complexities.
- *Outlierness* outlying values, features, or objects in the ECD data.
- *Sparsity* a small amount of ECD-sensitive data, or the rareness of ECD events.
- *Infrequency* i.e., rareness, consisting of infrequent, rare, or scarce values, entities, etc.
- *Insufficiency* or incompleteness, ECD data are insufficient, partial, incomplete or limited to capture the lifespan, target, environment or effect of an ECD event.
- *Inconsistency* ECD data are inconsistent, e.g., mixing large vs small scale, static vs dynamic features, high vs low granularity, or high vs low frequency.
- *Irregularity* ECD data consist of irregular values, factors, or entities in terms of their range, distribution, or dynamics.
- *Bias* inappropriately, unreasonably, unfairly or illegally sampled or extracted data about ECD events, which may be caused by biased sampling, collection, or manipulation.
- *Error* ECD data are incorporated with typos or errors, which may be caused by machine, human, process, etc., failures.
- *Missingness* values of ECD factors are missing.

In reality, ECDs often are not independent of their ecosystems. ECD ecosystem data and resources may come from all-round systems, sources, and entities relating to an ECD event. The mixture of the above ECD data characteristics and complexities makes ECD ecosystem data even more complex to explore.

5 AISDR research landscape

Smart ECD resilience and the ECD data characteristics and complexities challenge the existing domain-specific and disciplinary ECD management and methods. The widely available ECD data further inspire and support data-driven, and evidence-based digital ECD resilience. From the AIDS perspective, *AI for smart emergency, crisis and disaster resilience* (AIECD), or simply, *AI for smart disaster resilience* (AISDR) and *AI for Natural Disaster Management* (AI4NDM),[6] emerges as a critical AI application and a new AI area, enabling to transform ECD management to SDR.

5.1 AISDR research map

AISDR[7] emerges as a critical and foundational area to develop translational AIDS theories and tools to deeply understand, quantify and manage ECD challenges and complexities. Such translational AISDR theories, approaches, and capacities will enable transformative cross-disciplinary and cross-domain ECD resilience.

Translational AISDR research will enable transformative smart ECD resilience by:

- Catering for the paradigm shift in disaster management;
- Addressing the gaps in existing ECD management approaches by advanced AIDS;
- Enabling proactive data-driven and evidence-based digital ECD resilience;
- Developing the area of 'disaster AI' for ECD-oriented AIDS theories and approaches.

[6] The International Telecommunication Union initiated a focus group on AI for natural disaster management: AI4NDM, https://www.itu.int/en/ITU-T/focusgroups/ai4ndm/.

[7] Smart disaster resilience and AISDR may not be effective for some ECDs, in particular, political crises, cultural or religious crises, and military disasters. Their resolution may highly depend on non-technical approaches.

First, crisis and disaster management is experiencing significant paradigm shifts

- From natural hazards and disasters to broad-reaching emergencies, crises and disasters in various domains and areas, including urban, environmental, social and economic domains.
- From ECD management to ECD risk reduction and risk management.[8]
- From people-centered to comprehensive loss-oriented management.
- From domain and discipline-specific approaches and studies to cross-domain, and cross-disciplinary approaches and studies.
- From consequence and impact-oriented mitigation to early forecasting, warning, prevention, preparation, and intervention.

These paradigm shifts inspire and request new SDR theories and approaches.

Second, AISDR addresses various gaps and limitations in existing ECD management with and without using advanced AIDS.

- Disciplinary ECD management focuses on domain-specific problems and their challenges and resolution, while is incapable of satisfying the goals for smart ECD resilience and lacks intelligence and data-driven discovery.
- AIDS, including shallow machine learning and deep learning, have been increasingly applied to ECD management, which focus on simple applications without a deep understanding and characterization of ECD characteristics and complexities.

Third, digital ECD resilience, or *digital disaster*, presents new opportunities for intelligent ECD management. This may be achieved by

- Converting a physical ECD space to its digital ECD space, by digitizing ECD events, processes, management, data, and systems; and
- Developing physical-digital ECD solutions integrating domain-specific, data-driven, and AIDS-empowered thinking, methodologies, and techniques.

[8] Refer to the "Sendai Framework for Disaster Risk Reduction 2015–2030" at https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030 for disaster risk reduction, the "UNDRR Strategic Framework 2022–2025" at https://www.undrr.org/publication/undrr-strategic-framework-2022-2025, and "Global Assessment Report on Disaster Risk Reduction 2022: Our World at Risk: Transforming Governance for a Resilient Future" at www.undrr.org/GAR2022.

Lastly, *disaster AI* and *disaster data science* (*disaster AIDS* for short) emerge as a new AIDS area and a new generation of ECD management,

- Covering the full ECD landscape over domains, cycles, and types;
- Addressing the full landscape of smart ECD resilience;
- Utilizing the full body of knowledge in AIDS;
- Understanding the problems and challenges in the digital ECD space, by data-driven thinking, methodologies, and discovery;
- Customizing AIDS thinking, theories and tools to address their specific characteristics and complexities; and
- Developing unique and specific disaster AIDS theories and methods for the spectrum and nature of ECDs.

As a result, on one hand, AISDR aims for a full body of capability and capacity of understanding, quantification, representation, monitoring, analysis, discovery, intervention, management, optimization, evaluation and reflection of historical, present and future ECD events and their risks and impacts. It enables

- proactive and early contingency planning, prevention, prediction and warning during normal time and prior to ECD events;
- active and online real-time and evolving detection, identification, recognition, planning, and management; and
- next-best action and strategy recommendation and decision-making.

On the other hand, AISDR cultivates a full body of knowledge for smart ECD resilience, which

- consolidates and promotes cross-disciplinary research capacity and leadership for the CD resilience across natural, technological and socio-economic domains and cyberspaces.
- fosters a cross-disciplinary, one-stop and general knowledge base and solution repositories to address complex multi-hazard needs and challenges in one go.
- provides general AISDR knowledge, theories and approaches across the relevant disciplines and fusing their knowledge and methods for ECD problem characterization, data processing, problem modeling, and ECD-oriented AIDS developments and applications.
- is developed by concerted efforts made by a critical mass of the relevant research excellence across disciplines and domains.

Accordingly, Fig. 2 presents a landscape of AISDR builtin the above thinking. The research map of AISDR may consist of multiple layers to cover

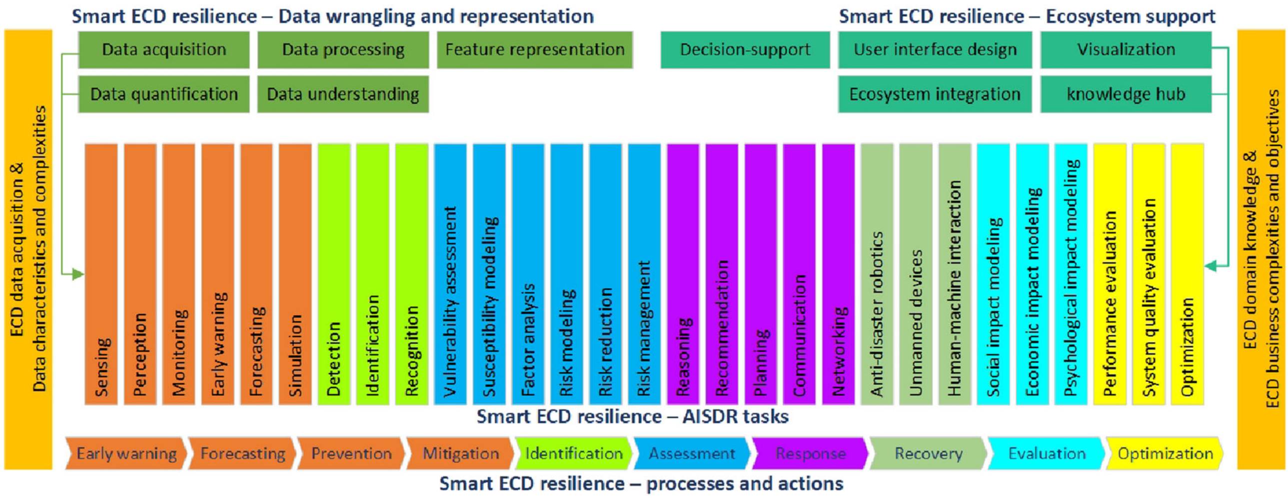

Fig. 2 The research landscape of translational *disaster AI* for smart ECD resilience (AISDR). *E* emergency, *C* crisis, *D* disaster

- the wide spectrum of domain-specific ECD landscape, spreading from natural hazards to man-made disasters and emergent ones including AI, information and machine disasters;
- the wide spectrum of phase and task-specific SDR landscape, spreading from early warning, prevention and intervention to evaluation, optimization and reflection;
- the wide spectrum of ECD-specific data and repositories; and
- the wide spectrum of AISDR research areas and tasks.

5.2 AISDR research tasks

AISDR can benefit from the practice and lessons learned from the successful AIDS applications in other domains such as AI in finance [6]. Below, we discuss a few cross-disciplinary, transformative, and interconnected research tasks for AISDR.

ECD sensing, perception and monitoring perceiving, monitoring, acquiring, collecting, communicating, transporting and storing the conditions, characteristics, changes of potentially affected or affected ECD-interested objects, areas, infrastructure, facilities, people or communities. This may combine techniques including for remote sensing, computer vision, image processing, wide area networking, data communication, cloud computing, and personal digital assistants. Remote sensing devices include satellites, aircraft, UAVs, ground-based systems, acoustic systems, or near-acoustic systems may be used for ECD sensing, monitoring, and data acquisition.

ECD data understanding and quantification developing a deep understanding and quantification of ECD problems, systems and data; and characterizing their complexities in and across domains and cycles. Effective ECD-related data quantification theories, models and methods may be created in statistics, environment science, climate change studies, health science, medical science, epidemiology, chemical analysis, biomedical engineering, or AIDS to characterize ECD events.

ECD feature representation characterising data complexities and challenges across ECD spaces; and creating representations of ECD events, factors and effects. ECD representations may be created by statistical/mathematical methods, shallow and deep learning methods, etc., specific to environmental, climate, epidemic, biosecurity, cybersecurity, and fake news oriented ECDs. These methods extract, select, and integrate cross-ECD, multi-model, -aspect, -granularity, -distribution, and -relation, static-dynamic, and explicit-hidden factors, structures, relations, interactions, and dynamics.

ECD identification and recognition developing translational ECD-oriented theories and methods for detecting, identifying, recognizing or measuring interested ECD objects, events, factors, or effects. They detect, recognize and measure the stricken people, location, object, etc., in satellite and sensor imagery, text, or spatial and temporal signals over time, building on AIDS advances and disciplinary foundations. Examples are to develop end-to-end scalable, multi-grain and federated deep transfer learning systems across ECD domains.

ECD vulnerability assessment analyzing, assessing and estimating the characteristics or conditions vulnerable to potential hazards or adverse and damaging effects of a disaster. Vulnerability may be measured or caused by low quality (e.g., of an infrastructure), insufficient adequacy (e.g., of preparedness, protection or supplies), lack knowledge (e.g., of public awareness), limited recognition (e.g., of poor sensing and communication devices), or poor management (e.g., of risks).

ECD susceptibility modeling estimating and forecasting the likelihood, intensity, coverage, timing, location, and duration of population, assets, or facilities susceptible to ECD effects, potential losses, damage or risks. This may integrate domain models with data-driven methods, e.g., environmental models with deep neural networks for potential environmental damage, or epidemic models with variational statistical inference for susceptible population to infectious diseases.

ECD early warning perceiving, recognizing, identifying, analyzing, and forecasting the likelihood, severity, coverage, intensity, and changes of potential ECD events or their adverse effects; the causal and risk factors, patterns, location, timing, duration, or frequency of potential ECD events; risky, adverse or impactful effects; evolution and change of ECD events or their effects; recommending and disseminating alerts or warnings for the public awareness and preparation; and estimating and evaluating the response and effect of early warnings.

ECD forecasting analyzing, estimating and predicting various aspects of an ECD condition or event, such as (1) their occurrence likelihood, frequency, duration, intensity, severity, timing, and location; (2) the susceptible and vulnerable population or area of potential affection; (3) the risks to lives, livelihood, community services, infrastructure, social functions, and economic losses; and (4) the severity and coverage of damages or adverse effects.

ECD risk factor analysis and assessment developing translational ECD-oriented theories and methods for analyzing and assessing risk factors sensitive to specific ECD events and effects. They estimate the probability, severity, and risk factors of ECD events and damages, and the losses before, during and post events. Examples include developing evolving cross-domain and multi-scale federated transfer learning systems across ECD domains.

ECD risk reduction analyzing, identifying, improving, or optimizing risk factors, preventive timing and measures, intervention timing, strategies and actions to lessen exposure likelihood and degree, vulnerability, and adversity of ECD events and impacts. Techniques including complex system dynamics, interaction modeling, next-best action recommendation, behavior informatics, and simulation systems may be used.

ECD risk modeling analyzing, assessing, estimating and forecasting the potential likelihood, severity, intensity, losses and adverse effects of continued ECD conditions, events and outcomes in health, livelihood, environment, society, culture, the economy, or technical aspects; the vulnerability of community or society; the frequency, recurrence and persistence of ECD conditions or cumulative impacts; and the sufficiency and performance of preventive, prepared and mitigating measures and arrangements. This may involve various techniques, such as risk factor analysis, risk rating, impact modeling, influence modeling, and simulation systems.

ECD impact modeling assessing, estimating and predicting the consequence and adverse coverage and severity causing (1) life loss, physical injury, health, disease or mental problems, or social well-being; (2) damage to infrastructure or facilities; (3) failure of social or community functions and services; (4) economic and financial losses, hardship or disruption; or (5) environmental degradation or atmospheric influence. Techniques in health science, medical science, social science, economics and finance, and management science may be combined with data-driven modeling and discovery approaches.

ECD risk management developing cost-effective plans, measures and activities for ECD prevention, mitigation and preparedness to avoid, reduce or transfer potential or future disaster risks. This may include identifying and recognizing hazard incidents; identifying, discriminating and evaluating risk factors causing or driving hazards; conducting risk analysis and risk evaluation to assess the risk of hazards; and selecting, evaluating and recommending appropriate measures and methods to remove risks or contain risks. This may involve mixed techniques from risk analysis and event detection to recommender systems and management science.

ECD robotics constructing robots to perceive, monitor, recognize, identify, or detect objects affected in ECDs; investigate ECD sites, infrastructure, or facilities; assess damages or injuries; rescue stricken objects; distribute resources; or evaluate response and recovery performance; etc. Disaster robotics involve various techniques, including autonomous systems, AI techniques and algorithms for perception, vision, reasoning, search, communication, planning, or recommendation.

ECD reasoning developing reasoning methods and tools to reason about, conclude, predict and explain ECD cases, scenarios, contexts, etc., by involving ECD knowledge. ECD reasoning enables case-based or context- and situation-aware perception, comprehension, recommendation, decision-mak ing, planning, replanning, or projection. ECD reasoning may be undertaken in distributed, decentralized, cloud, or edge environments.

ECD recommendation identifying, selecting, forecasting, evaluating or suggesting the timing, location, actions, next actions, next-best action, alternatives, or options for ECD prevention, intervention, response, or recovery. This may involve various recommendation techniques for ECD events, processes, interactions, or interventions.

ECD planning developing intelligent planning methods and tools to represent, analyze, synthesize, reason, decompose, learn, merge, monitor, execute, reuse, or evaluate plans, policies, actions to investigate, prevent, intervene, or manage ECD events, or impacts. ECD planning methods may involve both traditional AI planning, data-driven planning, prediction, recommendation, behavior analysis and reasoning, interaction modeling, etc. ECD reasoning and planning must involve the knowledge, contexts, constraints, etc. relating to specific ECD accidents and resilience objectives.

Post ECD management identifying and assessing infrastructure failures, communication disruption, power, communication or network outages, ICT infrastructure damages, or transport infrastructure damages; evaluating post-event recovery requirements on time, resources, priority, or costs; estimating resource supply or availability; and recommending demand-supply prioritization, matching or scheduling for rescue or recovery operations.

Cross-ECD socio-economic effect and impact estimation developing translational ECD-oriented theories and methods for estimating social and economic effects and impacts of ECD accidents. They estimate ECD socio-economic impacts on functions and services of affected community, infrastructure, facilities, or transport. Examples are developing integrative domain-driven, and utility-oriented deep statistical neural models.

ECD simulation developing simulation methods and systems to imitate, replicate, or replay ECD events, processes, or effects; assess strategies and performance of ECD preparation, prevention, response, or recovery; evaluate plans, policies, processes, or resources for ECD management; etc. ECD simulation techniques include simulation systems, complex systems, visualization, etc.

ECD management performance evaluation quantifying, assessing or analyzing the sufficiency, effectiveness and gaps of ECD management capabilities, capacities in terms of ECD conditions, scenarios, or consequences;

AISDR system quality The criticality of AISDR in saving lives and losses requires its high system usability and actionability. It is essential to develop ethical, safe and secure AISDR systems during understanding and managing the complexities of ECDs; making their operations and results validated, trustworthy, acceptable, explainable and actionable to domain experts, end users, local communities, or emergency system managers. Usable and actionable AISDR systems should avoid 'black box' predicament, and be easy to understand, trust and use by non-subject matter experts.

AISDR ecosystems developing AI-driven ECD ecosystems, consolidating infrastructures, functions, resources, and services for (1) various ECD aims and objectives over the life span of ECD events; (2) respective stakeholders in ECD ecosystems; and (3) historical-present-future, and proactive-active-prospective ECD processes from planning, prevention, early warning, mitigation, response, recovery to evaluation, reinforcement, and optimization. An AISDR ecosystem customized for a specific ECD disaster may be composed of most of the above technical and non-technical, functional and nonfunctional, structural and nonstructural AISDR modules or subsystems.

AISDR knowledge hub with illustrative ECD early warning, prediction, and recommendation. An open AISDR knowledge hub may consist of ECD knowledge, resilience approaches, guideline, modelling tools, and showcases. It may support effective analysis, prediction, and recommendation of AISDR events, knowledge sharing, training and external engagement.

6 AI and data science in COVID-19

COVID-19 have been not only a global health emergency, crisis and disaster [7, 8], it has also overwhelmingly caused, intensified and created other ECD events, such as supply chain disconnection, misinformation, conspiracy [9], and geopolitical crises [10]. AI and data science have played a profound role in fighting COVID-19 disasters.

The roles of AI and data science in COVID-19 are multi-aspect and substantial. Examples include [10]:

- diagnosis and treatment of COVID-19 diseases and its SARS-CoV-2 viruses, including through medical imaging analysis [11];
- quantification and understanding of the COVID-19 disease complexities, virus mutations, and disease resurgences [12];
- efficacy modeling of COVID-19 medical treatment, vaccinations and pharmaceutical interventions [13];
- discovery of drugs, vaccines, and biomedical products [14];
- effectiveness modeling of non-pharmaceutical interventions and policies [15];
- characterization of social, economic and political impact of COVID-19 [16].

In the massive literature on modeling COVID-19 [10] and the global scientific response to COVID-19 [17], we can find that comprehensive AI and data science technologies have been applied to address the above COVID-19 issues. Examples include

- mathematical and statistical methods and models, such as time series analysis, Bayesian models, and stochastic compartmental models [18];
- data-driven methods and models, including classic (such as kernel methods and text mining) and modern (such as large language models, deep neural networks, and deep reinforcement learning) technologies [19];
- domain-driven methods and models, such as epidemiological compartmental models, medical analysis, biomedical analysis, and social inference analysis;

- event and behavior modeling methods, such as behavior informatics, historical event analysis, and collective and coupled behavior analysis;
- simulation methods and models, such as theories of complex systems, multiagent systems, game theories, and evolutionary learning;
- influence and impact modeling methods, such as social network analysis, social media analysis, and social science methods; and
- hybrid methods and models, such as ensemble methods, and probabilistic compartmental models.

7 Related work and gaps

We summarize the related work on applying AIDS and quantification methods to disaster management.

7.1 Research review

Domain-specific and disciplinary methods have been widely applied to disaster management [1], which are not focused in this article. In AIDS, all-round AI techniques, in particular, modeling, simulation and deep learning methods, have been widely applied to all phases of the MPRR framework for disaster management [20, 21]:

- mitigation: e.g., for assessing vulnerability, forecast risks, estimating impacts, and analyzing strategies;
- preparedness: e.g., for the early warning, detection and prediction of hazards, or evacuation planning;
- response: e.g., for assessing damage, mapping events, allocating resources, rescue and relief, and analyzing sentiment;
- recovery: e.g., for assessing impact, planning recovery, and evaluating recovery performance.

Model- and data-driven disaster management techniques can be categorized into (1) unsupervised settings without pre-annotation: such as detecting and identifying damages in infrastructure, properties, or environment; detecting, identifying or recognizing injuries and life losses in debris; and identifying affected objects, people, areas, or communities; (2) supervised settings with prior knowledge: such as segmenting struck objects in images; detecting outages or flooded areas; and evaluating damage levels and severity from aerial images; and (3) semi-supervised settings mixing partial knowledge with unknowns: such as early warning based on past ECD events.

Domain-, model- and data-driven ECD quantification methods integrate a broad disciplinary body of knowledge. Examples of modeling and learning techniques for SDR include:

- Statistical and mathematical modeling: such as regression models, change or movement detection, factor analysis, risk modeling, time series analysis, spatial signal processing, and Wavelet transform.
- Classic machine learning methods: almost all methods have been applied to ECD domains. Examples are K-means, spectral clustering, hierarchical clustering, representation learning, dimensionality reduction, K nearest neighbor, support vector machine, decision tree, artificial neural network, and ensemble methods; and statistical machine learning models such as latent Dirichlet allocation, Naive Bayes model, and random forest.
- Deep neural learning methods: including basic convolutional neural networks, various image nets, long short-term memory networks, recurrent neural networks, gated recurrent unit, and attention networks for various vision tasks, such as people identification, action recognition, and flood, fire or damage detection on remote sensing images.
- Text analysis methods: including bag of words, search and retrieval methods, neural language networks such as Transformer and BERT, and sentiment analysis methods like topic models.
- Other AI techniques: including computational intelligence methods, such as evolutionary learning methods genetic algorithms, transfer learning, and (deep) reinforcement learning.

The applications of the above methods can be seen in various ECD problems, objectives, and developments over the lifespan of ECD [20–22]. Examples of AISDR applications include:

- *Unsupervised learning* applied to assess and detect damages, damage areas or damage severity; event or subevent detection [23] in disaster.
- *Supervised learning* applied to categorize, identify, reidentify, or recognize damage types and severity; estimate disaster relief population based on crowdsourcing, web mapping and social media data; score rescue priority for immediate or low-priority aid, search or rescue of affected population; allocate demand resources, or match rescue teams with affected people by involving medical features and classify severity.
- *Robotics and unmanned intelligent devices* such as UAVs applied to aerial monitoring, rescue planning, or resource allocation.
- *Image processing and computer vision methods* applied to recognize the status of disaster struck people, e.g., differentiating possibly death or survivals in debris; and identify standing, laying, or sitting conditions with video action recognition.

- *Natural language processing techniques* applied to disaster monitoring through online news or social media posts [24]; sentiment analysis by classifying sentiment into positive, neutral or negative; estimating socio-economic disaster impact from social media data; and crisis mapping in real-time social media.
- *Multimedia and multi-modal modeling* applied to multimodal disaster classification by combining satellite images with news or social media text or image posts; and multimedia sentiment analysis [25].
- *Spatio-temporal signal analysis* applied to estimate crowd dynamics in spatio-temporal data by DNNs [26]; and financial crisis contagion by cross-market couplings and interactions [27].
- *Decentralized and edge AI* with autonomous drones empowered by edge AI and computing for real-time emergency situation detection, navigation, or surveillance.
- *Simulation* of evacuation behaviors, routes, mobility, scheduling, or prioritization; resource logistics, supply, or distribution; rescue resource demand, prioritization, or dispatching during disaster events, such as earthquakes, hurricanes, or flooding.
- *Evaluation* applied to creating a monitoring and evaluation framework for disaster recovery [28].
- *Contrastive analysis* of pre-disaster, disaster-hit, and post-disaster data, such as aerial area images, traffic signals, communication throughput, for changes and variations associated with different disaster types and conditions, such as by earthquake, hurricane or flood, by classifiers and change detection methods.

7.2 Gap analysis

AIDS is playing an increasing important role in mitigating the domain-specific knowledge and capability gaps and complementing the domain-specific disciplinary sciences for smart ECD resilience. The existing AISDR research presents various imbalances: AIDS research area imbalance, ECD type imbalance, ECD phase imbalance, ECD data imbalance, and ECD method imbalance.

First, there is an *AIDS research area imbalance*. No ECD-oriented systematic AIDS theories and tools are available. The existing work only focuses on simple applications concentrated on analytical and machine learning methods. AIDS techniques are not limited to shallow and deep analytics and learning. Their full landscape from deep perception, representation, analytics, search, learning, recognition, vision, conversation, and communication to informative and actionable planning, recommendation, and decision [29] are essential for AISDR enabling digital smart ECD resilience.

Second, there is an *ECD type imbalance*. In the broad spectrum of ECDs, intensive research has been on floods, earthquakes, hurricanes, and landslides. Much less and insufficient research is available on wildfire, avalanche, and tsunami.

Third, there is an *ECD phase imbalance*. Intensive research capabilities and knowledge are on post-disaster response modeling, damage assessment, risk assessment, and disaster prediction. Much less efforts are on early warning, disaster detection, and disaster monitoring.

Fourth, there is an *ECD data imbalance*. Intensive research has been on structured and annotated ECD data. In cases with limited structured data, shallow machine learning methods report better prediction accuracy; while deep neural networks report high performance on images, videos, and texts with annotated samples. Insufficient research is on emergent ECD events such as wildfire forecasting, AI disasters, machine failures, and cyberattacks.

Last but not least, there is an *ECD method imbalance*. Shallow machine learning methods are widely used for outlier detection, clustering, and classification of disaster early warning, risk and vulnerability assessment, and disaster monitoring on sensor data. Deep neural networks dominate disaster detection, sentiment analysis, damage assessment, and response evaluation on video, aerial imagery, online news, social media posts, and spatio-temporal signals.

8 Ways forward

The aforementioned broad ECD landscape, AISDR research map, and the various imbalances in existing work inspire various opportunities. Both general and specific tasks are demanding in creating translational AISDR body of knowledge and transforming ECD management.

ECD complexities developing a deep understanding of diverse system complexities in ECD ecosystems from human, natural, physical, social, cyber and mental perspectives [2]; and deeply quantifying diverse data characteristics and complexities in ECD data systems [5].

Full-cycle resilience covering and connecting full-phases from forecasting, early warning, prevention to detection, response, recovery, and secondary threats for long-term resilience; all-round vulnerability and risk assessment including for critical infrastructure of power, transportation, communication, ICT, utilities, community services, and living resources; and quantifying, forecasting and managing systemic risks across all cycles.

Full-space management fusing physical, social and cyber ECD-related systems and resources; integrating climate, weather, environmental, civil, living, and community information; integrating factor, event, behavior, interaction, and effect; and fusing temporal, spatial and multi-modal systems and data for a full-spectrum view of ECD problems and their evolution.

ECD data intelligence enabling quality and usable ECD data with sufficient timeliness, completeness, accessibility and computability; augmenting data quality, mitigating noise in online and social media texts, background noise in spatio-temporal signals, and complex background information such as complex weather and illumination conditions in satellite and drone imagery; collecting and integrating high-resolution private data with privacy preservation and in edge and cloud environments; and annotating critical yet rare disaster types, damages, effects, and impacts.

Prioritized AISDR research focused studies on rarely studied and hard questions; studying highly uncertain disaster events, including earthquakes, wildfires, and avalanches; enhancing disaster recovery operations and post-disaster resilience and management; conducting evacuation, rescue and search simulation, including mobility, routing, and planning; enhancing post-disaster management, such as secondary disasters, infectious diseases, animal plague, land movements, water pollution, and air pollution; advancing stream online identification and extraction of useful information in social media and instant messaging apps for disaster mitigation and response; and identifying harmful information to avoid fake news in massive online texts, real-time rumor and fake new detection in instant messaging.

Precision resilience management developing disaster event-specific assessment and management methods and processes; enabling personalized rescue, recovery and treatments to affected people or communities; developing tailored detection of specific disaster events or objects; and enabling timely and factor-sensitive intervention.

Autonomous resilience management developing autonom ous monitoring, investigation, planning and recommendation systems and automated learning and analytics [30]; enabling autonomous sample collection and detection of water and air pollution; and enabling real-time outlier detection and behavior recognition from satellite imagery by autonomous AI into satellites, UAVs, or drones.

Impact and influence modeling, monitoring and intervention evaluating damages, injuries, or losses on multi-levels, -scales, or -occasions for struck individuals (people, objects or buildings), communities, areas or regions; and assessing economic losses and costs for recovery; evaluating social, psychological or mental health impact during and post disasters, particularly on children, disadvantaged people or communities.

Quantifiable resilience measurement developing quantitative measurement of phase-specific and full-cycle resilience across different stages of ECD management; and developing measures or metrics required for each phase or objective, such as vulnerability, survivability, robustness, reliability, and recovery speed.

Actionable AISDR systems developing configurable, modular intelligent subsystems and modules capable of instant setup into disaster emergency ecosystems; enabling essential functions and services required for emergency requirements, such as ICT infrastructure with sensor networks for data collection, 5 G devices for communications and networks, crowd intelligence (by crowdsourcing platforms and resources), cloud intelligence (by cloud infrastructure and computing), edge intelligence (by edge devices including UAVs and smart phones, apps), or replay systems; providing one-stop resource dispatching with healthcare, medicine, utility, food, water, living materials, and transport; and capabilities of identifying, predicting, recommending next-best points, actions, or strategies for risk mitigation.

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