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THE NEED FOR DESALINATION IN HUMANITARIAN CRISES

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ABSTRACT

Humanitarian crises ranging from political unrest to natural disasters are becoming increasingly prevalent with global climate change. Correspondingly, there are an increasing number of regions that consist both of high crises risk and saline water contamination. Such regions include the Middle East, Subsaharan Africa (particularly along the Great Rift Valley), Southeast Asia (including the Mekong Delta and Pacific Islands), and coastal regions. However, there is a lack of robust, deployable desalination technologies for humanitarian crises. This is mainly attributed to the highly-constrained environment which necessitate: minimization of consumables, rapid speed of deployment and simplification of operation and maintenance. Such constraints are often secondary thoughts, are difficult to traditionally quantify, and differ from stable commercial situations where operations are supported by an accessible supply chain and network of technicians. These barriers have particularly hindered the adoption of membrane technology and thus, high volume desalination and chemical contaminant removal. This work justifies the need for desalination technology in humanitarian crises via geospatial analysis of saline water databases and exploration of regional case studies, formulates design requirements for an emergency-use desalination system based on needs extracted from open-interviews of stakeholders and literature review, evaluates some of the gaps within currently employed deployable desalination systems and explores the potential opportunities of other desalination technology.

1 INTRODUCTION

The usage of desalination and chemical treatment in the context of humanitarian crises is a fairly unexplored space. There are some technologies adopted from use in other contexts such as military water treatment units that are periodically deployed in emergencies. However, the importance of desalination in humanitarian emergencies is not well understood. Furthermore, the existing solutions and decision making processes that practitioners and humanitarian aid organizations utilize are not designed for desalination and chemical treatment. Finally, the design requirements and an investigation of potentially viable desalination and chemical treatment technologies for usage in humanitarian emergencies has not been explored in depth.

Through literature review, geospatial data analysis, technoeconomic analysis, and through semi-structured interviews of practitioners, this work aims to:

1. Explore the need space for desalination in humanitarian crises.
2. Review the currently employed solutions and decision making processes.
3. Characterize a generalized set of design requirements for a desalination system designed specifically for humanitarian deployment.
4. Briefly examine the trade-offs and potential of existing desalination technology in the context of these requirements.

2 METHODS

To understand if there is a need for desalination in humanitarian emergencies, what the current solutions are, and what potential solutions may exist, non-systematic literature review and technoeconomic analysis was conducted. For understanding the geographic need for desalination in humanitarian emergencies in particular, geospatial data analysis and correlation was conducted between metrics for groundwater salinization and the prevalence of natural disasters and/or conflict.

This exploratory research involved a focused literature review conducted by the researchers using a number of water, sanitation and hygiene (WASH) cluster databases with keywords including items that pertained to the general topics of bulk water treatment, WASH interventions, chemical treatment and desalination. Some of database and publishers the authors found had high relevance include Relief Web, Joint Monitoring Programme, Practical Action Publishing's Waterlines, Assessment Capacities Project (ACAPS), United States Agency for International Development (US AID) Humanitarian Library, various NGO databases (ICRC Resource Centre, Oxfam Research and Publications), and various United Nations (UN) databases (WASH UNHCR Database, UNICEF Data and Reports, UN OCHA Center for Humanitarian Data, UNDRR Prevention Web - many of these organizations' acronyms will be defined in practical context in later sections of this work). Additional gray and unpublished literature from experts and practitioners were also incorporated and considered. In future work, rigorous systematic review protocol would be more comprehensive in identifying literature that was absent from this initial study.

To determine a generalized set of design requirements for potential desalination systems in humanitarian crises, interviews with WASH experts and practitioners were conducted. The interviews were in a semi-structured format with a list of general guiding questions designed to elucidate needs of the practitioner, the overarching organization, and beneficiaries. However, while these questions formed the basis for beginning the interview, the interviews were allowed to digress into detail on the practitioners' areas of concern or interest. Notes and quotations from the interviews were coded using a quick and simple, flat inductive coding frame. The overarching themes that arose were divided into requirements categories and subcategories. Generalized metrics were determined and assigned with the assistance of literature, guidelines, and these interviews. It should be noted that a larger interview sample size and other coding methods such as with automated natural language processing tools could be explored in later work - this design requirements explication is rather preliminary but creates a foundation for future investigation.

3 HUMANITARIAN CRISES

3.1 Water in humanitarian response

In emergencies, a minimum of 7.5 liters of water per person per day is recommended [1], with 3-4 liters per day necessary for survival depending on climate conditions [2]. A natural disaster, political instability and many other types of emergencies can cause immediate disruption of water supply and treatment. Hurricanes destroy infrastructure, warring parties pollute drinking wells of the opposition, persecution can push migrants to unfamiliar territory with a lack of accessible and potable water. One reference of widely agreed upon standards for humanitarian response is the Sphere Handbook [3].

International organizations, local non-governmental organizations (NGOs), and individual governments are a few significant stakeholders which provide monetary and physical aid [4]. Some prominent examples of aid organizations and stakeholders involved in WASH include the United Nations International Children's Emergency Fund (UNICEF), Oxfam, Médecins Sans Frontières (MSF) and the International Federation/Committee of the Red Cross and Red Crescent (IFRC/ICRC).

Crises with multiple agency involvement are typically coordinated by the Inter-Agency Standing Committee (IASC), a forum under the United Nations Office for the Coordination of Humanitarian Affairs (UN OCHA). While forecasts anticipating natural disasters exist, immediate responses to large crises that warrant international coordination are initiated based on rapid needs assessment (e.g. Flash Appeals) within 3-5 days. These reports incorporate metrics such as predicted amount of beneficiaries [5, 6]. Responses later shift to increased specificity of strategy and monitoring. In general, phases of a crisis include emergency/acute response ($<$ 3 months), protracted crisis ($>$ 3 months to years) and long-term/development interventions (multiple years) [7]. The IASC delegates projects and specific targets for involved organizations, which flow down into various aid subsectors referred to as United Nations clusters [8]. These clusters are overseen by various UN organizations (e.g. the Water, Sanitation and Hygiene (WASH) cluster is supervised by UNICEF, the Health cluster by the World Health Organization (WHO), and Food Security by the World Food Programme (WFP) and Food and Agriculture Organization (FAO)). Acute intervention strategies within the WASH cluster commonly include rapid distribution (e.g. tanker truck, bladders, bottled), rudimentary treatment of water, and packaged kits. Targeted interventions to rehabilitate and provide sustainable sources, distribution, and treatment are developed over time based on context (examples of recent intervention plans include [9–11]). The general process for contemporary United Nations crisis response architecture and actions are well-detailed in [12].

3.2 Archetypes and intervention structure

Crises are generally categorized, but not limited to, the ontology seen in Fig. 1 [13]. However, humanitarian responses are

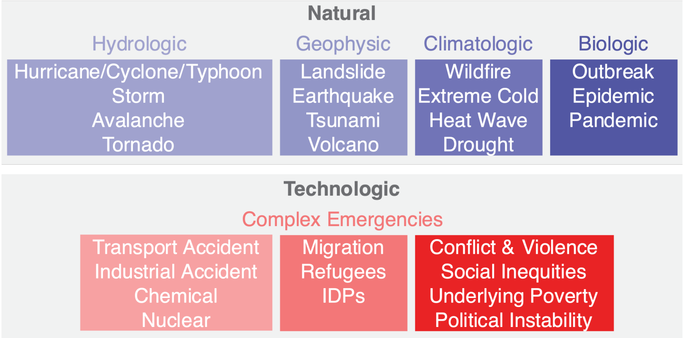


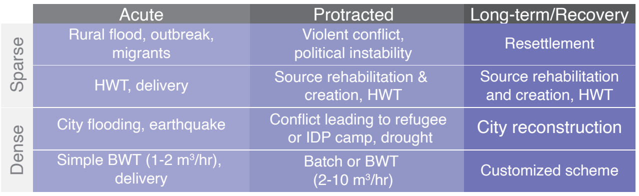
FIGURE 1. ONTOLOGY OF EMERGENCIES

often broken down into three colloquial categories: (1) natural disasters, (2) outbreaks and (3) complex emergencies. Complex emergencies often encompass conflict regions and lead to migration of refugees or internally displaced persons (IDPs) but also may refer to situations where multiple emergencies are ongoing; for instance, the 2010 earthquake in Haiti which eventually was coupled with a Cholera outbreak.

Note, a refugee is defined as an individual that has crossed an international borders to flee persecution, war, violence, or conflict. An internally displaced person is an individual displaced within their own country. A migrant is an ill-defined umbrella term that refers to individuals travelling from their origin country for any other reason, such as fleeing poverty for employment.

WASH emergency response is highly specific to situational context. In an ideal setting, water treatment is tuned specific contaminants, knowledge of source locations, specific populations who require intervention, the distribution of these populations, local supply chain and accessible infrastructure. In acute emergencies, this knowledge is highly-constrained. Thus, it is fundamental for WASH interventions to be flexible to a wide array of contexts.

Despite contextual limitations, the geographic distribution and quantity of the population affected are one of a number of metrics often estimated in early response reporting. From this, general WASH archetypes somewhat agnostic to the category of emergency can be created (Fig. 2). General guidelines for developing needs assessments include [14, 15] as well as exist within organizations such as the Assessment Capacities Project.



	Acute	Protracted	Long-term/Recovery
Sparse	Rural flood, outbreak, migrants	Violent conflict, political instability	Resettlement
	HWT, delivery	Source rehabilitation & creation, HWT	Source rehabilitation and creation, HWT
Dense	City flooding, earthquake	Conflict leading to refugee or IDP camp, drought	City reconstruction
	Simple BWT (1-2 m^3/hr), delivery	Batch or BWT (2-10 m^3/hr)	Customized scheme

FIGURE 2. WASH ARCHETYPES AND COMMON INTERVENTIONS

Emergencies with sparse populations are characterized by a geographically-widespread population distribution in groupings that are less than the thousands. These may involve disasters or crises occurring in rural settings or can involve small mobile populations. For instance, refugees, IDPs, or migrants fleeing regions of political instability or poverty. In acute-sparse emergencies, it is often challenging to logistically provide resources and interventions due to unreliable supply chains and damaged or nonexistent infrastructure to access dispersed populations. If existing sources are damaged, water delivery most commonly via trucking initially occurs, infrastructure permitting. Delivery of household water treatment (HWT) interventions, such as coagulant-flocculant sachets, chlorine tablets, and small filters is also considered, typically delivered as WASH packages which may include items such as soap, buckets, flashlights, cloth, sanitary pads, detergent, educational guides, etc. [16]. HWTs are particularly effective in rural scenarios in low and middle income countries [17]. As the emergency continues over time, rehabilitation of preexisting water sources or creation of new sources often occurs (such as via bore well drilling) [7, 18].

Groupings of population densities of 300 inhabitants per km^2 with a population of at least 5,000 in the cluster are considered an urban cluster by the UN Statistical Commission [19]. Interventions for these relatively dense clusters again include transporting water and/or a range of bulk water treatment (BWT) schemes which systems that produce relatively high volumes of water (approximately $> 1\ m^3/hr$). Natural disasters such as hurricanes, tsunamis, and typhoons often cause rapid flooding and create acute emergencies in population dense regions. Examples of acute, population dense emergencies include flooding in Pakistan in 2010 and the tsunami in Indonesia 2009 where both bulk and small-scale water treatment units were employed [2]. Earthquakes, such as in Haiti 2010 or conflict such as the bombing of Aleppo, Syria in 2012 involved protracted (11 months and 19 months respectively) interventions where sedimentation tank water treatment systems were employed, alongside WASH packages, water trucking, well restoration and local wastewater treatment plant (WWTP) and drinking water treatment plant (DWTP) reconstruction [20]. Over time, rehabilitation-focused interventions become more important and may range from fuel distribution, solarization, well digging and drilling, and operational support of water facilities [10]. While capacity building is an increasingly advocated facet in emergency response, it is not always an aim. Responding NGOs often leave recovery to beneficiaries once a state of stability has been reached [21–23].

Detailed decision making trees for water treatment interventions are outlined differently depending on the intervening organization, but have commonality in two major aims (1) removal of turbidity, and (2) biological disinfection. Turbidity is a measurement of suspended and dissolved matter and is used to assess the health of water bodies [24]. It is most commonly measured in units of nephrological turbidity units (NTU) and is detected via nephelometry or light scattering (USEPA Method 180.1 or ISO 7027). High turbidity hinders the effectiveness of the most common disinfection method in crises: chlorination [25, 26].

There is generally agreement amongst most water quality thresholds and decision making processes within WASH organizations, however some include more or less detail with less common scenarios such as chemical contamination. Fig. 3 details water treatment strategies in crises which the authors developed based on coalescing decision making processes from a number of guidelines and handbooks [3, 27–34].

While this decision tree describes multiple strategies for removing physical particulate and disinfecting biological contaminants, there are currently no commonly employed, standardized, or well-agreed upon methodologies for treating chemical contaminants including salinity [35]. Operators are instructed to avoid sources contaminated with high salinity or unacceptable levels of chemicals such as nitrates, heavy metals, arsenic. Relatively low concentration of chemical contaminants can cause long-term health issues and thus are not of principal concern in emergency water treatment but are growing factors of importance in long-term development. Drinking saline water over a period of time is linked to numerous adverse health effects including cardiovascular diseases, gastrointestinal disease, dermatological disease, acute respiratory infections, and miscarriages [36, 37]. However even in acute emergencies, salinity can cause operators to avoid and beneficiaries to reject otherwise satisfactory water sources.

4 SALINITY IN EMERGENCIES

Desalination is a relatively unexplored element of humanitarian emergencies. When dealing with the treatment of saline waters in emergencies, current procedures for prominent international agencies such as MSF [33], UNICEF [34], and Oxfam [28] simply instruct aid workers to avoid saline sources. Lack of saline water treatment protocol is prevalent not only in acute emergencies (3-6 weeks) but also exists even in protracted emergencies (months) and into long-term recovery and development periods. It also is more broadly, a growing chronic issue as a form of groundwater contamination.

Crises where saline contaminants may become prevalent water sources include tsunamis, flooding (about 42% of natural disasters), seawater intrusion [7], desertification, drought, and chemical contaminants are often used in conflict driven sabotage of water bodies. With approximately 40% of the world population living within 150 km of the coast [38] and high frequency of flooding, drought, extreme weather, and sea-level events affecting this population (relative to other natural disasters) [39, 40], these regions are increasingly susceptible to saline water intrusion and saline water treatment will become increasingly relevant in response and in global health development. Unfortunately, little if any data or literature currently exists on understanding the prevalence of salinity in different crisis archetypes, so forecasting the scale of the problem is non-trivial. Nevertheless, there have been a number of calls for desalination systems from humanitarian groups, including Oxfam [41–43] and a recent discussion of treatment systems for desalination in emergencies hosted by the Red Cross [44].

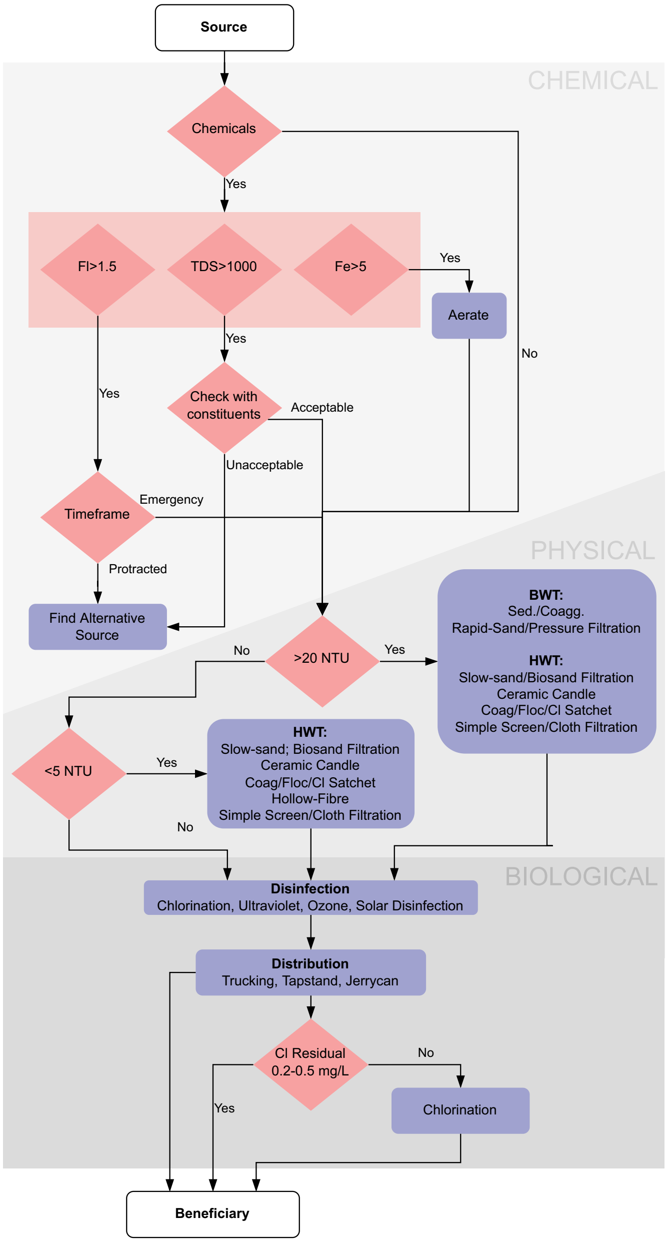


FIGURE 3. GENERALIZED WASH INTERVENTION DECISION-TREE IN EMERGENCIES

To understand the potential scope of salinity in humanitarian crises, the authors examined known databases of high salinity groundwater aquifers [45–48]. It is noted that multiple regions

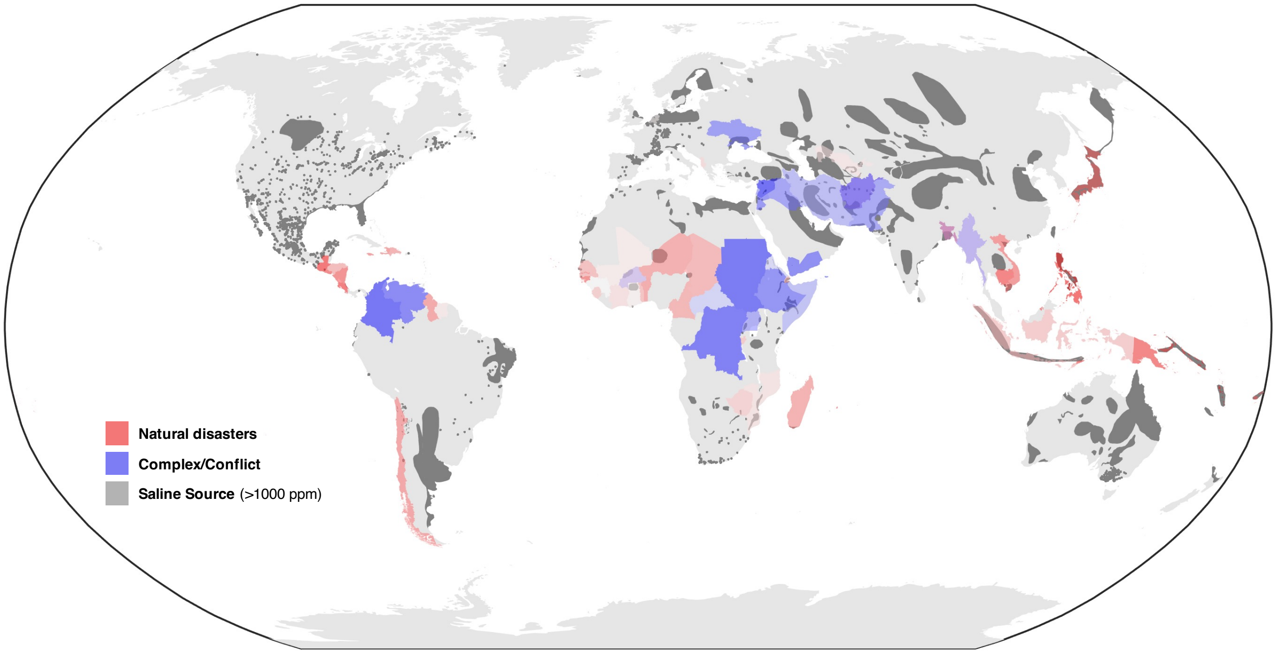


FIGURE 4. GLOBAL CRISES AND SALINITY MAP

high groundwater salinity overlap with areas that are susceptible to disasters [49–51] and have history of conflict [52, 53] (Fig. 4). This indicates that many of their potential water sources may already have saline contaminants. These regions also correspond to regions projected to experience decreases in precipitation as a result of climate change, which will exacerbate the lack of non-saline surface and groundwater [54–56]. There are noticeable gaps in water salinity and composition data due to cost; some groups are attempting to alleviate this issue by developing low cost conductivity sensors [57].

These regions of note can be generalized into the Middle East, Sub-Saharan Africa, and Southeast Asia, and these regions have also been noted as regions of concern in literature [58]. However, it should be noted as far as inland Southeast and Western United States there are increasing cases of saline aquifers. There are some naturally occurring saline aquifers due to geologic formation (connate) but many aquifers are experiencing rapid increases in rates of salinization due to rising sea levels and withdrawal from wells; Overdrawing groundwater from wells can intensify saline intrusion by exacerbating the pressure differential between seawater and lower water tables [59–61]. The USGS published a comprehensive report which outlines the scope of brackish groundwater in the United States [62].

In the Middle East, some specific cases where desalination has becoming increasingly prevalent include Palestine. Palestine is one example within the Middle East where a reliance on desalination has developed due to its supply chain isolation [63]. Nitrates, heavy-metals and other chemicals are also present due to wastewater leeching, unreliable power, and excess pumping [64]. Syria, Lebanon, and Jordan experience high salinity in both surface water and aquifers linked to over exploitation from irrigation [65] and an influx of water demand from refugees [66–68]. Yemen experiences extremely high salinity surface water (up to deciSiemens [69]) and saline groundwater again due to seawater intrusion and its arid climate [70]. Many of these regions unfortunately have been historically subject to conflict and are ranked high risk in terms of political instability [71]. Refugee camps including Zaatari in Jordan [72] and Domiz in Iraq [73] have reported saline water contamination. Beneficiaries have been reported to avoid treated water and seek other nearby surface water sources which are untreated and often contaminated with harmful organisms and bacteria (e.g. Escherichia coli) due to taste preferences [3]; such practices have been observed across agencies with some beneficiaries even rejecting food [74]. UNICEF constructed a partially solar powered reverse osmosis plant (producing 20,000 m^3/day) in Palestine to mitigate these water shortages and compensate for unreliable grid power [75].

In Southeast Asia and the Indo-West Pacific, increasing amounts of seawater intrusion are present in soil and drinking water. In Bangladesh average tubewell salinities of 915 mg/L have been reported [76] and have been shown to cause severe illness [36]. The Mekong Delta including Vietnam has become increasingly prone to saline intrusion due to drought and seasonal water shortages [77, 78], which have also caused agricultural losses affecting upwards of 1 million people [79]. Indonesia [80], the Philippines [81] and Papua New Guinea all [82] report saline groundwater aquifers and an increased reliance on bottled water and rainwater catchment; a supply chain interruption due to disaster or conflict would create a major disruption to this drinking water supply. Rainwater catchment in general is quite common in island nations [83], however cases exist where brackish groundwater is desalinated using membrane processes (e.g. Canary Islands [84]).

In Africa, there have been an influx of reports of saline groundwater in multiple areas of the continent. In East Africa, groundwater scarcity and saline intrusion are exacerbated by a deep water table, the arid climate, volcanic and geothermal activity [85, 86]. Some specific examples of countries with recent conflict and reports of a need for saline and chemical treatment include Somalia [87] and Sudan [88]. They report surface water higher in salt concentration than groundwater; some suggest drilling deeper for less saline water in this region [89]. One instance of acute response noted the potential need for saline water treatment in Mozambique in the aftermath of Cyclone Idai [90] and subsequent efforts have been made to map seawater intrusion [91, 92]. At the Kakuma and Dadaab refugee camps in Kenya, increasing groundwater salinity has been noticed, especially over periods of drought [93, 94]. Similarly, reverse osmosis plants have been recommended for use at Sahrawi in Algeria [95]. Coastal regions of Kenya including Kwale County have had increasing desire for community scale desalination systems for water security and economic development [96]. Other prominent issues of broader chemical contamination include fluoride in Tanzania and heavy metals that leech from mines in the Democratic Republic of the Congo.

Central and Latin America have some reports of brackish water concerns, including the countries of Belize, Nicaragua, and Peru [97].

These are just some of the many regions that are currently affected, and could be affected by the need for desalination in humanitarian crises and development. When a region's nominal water sources experience shortages or damage from natural disasters such as drought or storms, or even isolation due to conflict, saline water bodies will more frequently become the only available source of water.

5 SYSTEM DESIGN REQUIREMENTS

5.1 Interviews and requirements extraction

18 practitioners, academics, and engineers from MSF, UNICEF, ICRC, IFRC and with experience in WASH were interviewed in a semi-structured interview format and needs statements and attributes were extracted. These statements were then codified and related to a proposed set of generalized design requirements, discussed in depth below.

Generalized requirements for BWTs are most practically defined for acute emergencies. Protracted emergencies often have more flexible, situation specific design opportunities which are often focused on rehabilitation, sustainability, and capacity building. Requirements for BWTs in acute emergencies can be broken down into the categories listed below. However, many of these requirements for this design scheme are useful to consider in broader applications. The requirements defined in Table 1 reflect constraints and do not show the relative importance of each factor; the prioritization of one criterion over another depends greatly on the operational context and is difficult to generalize, but could be considered in future work or in specific case studies.

5.2 Quantity

In acute emergencies, it is best to maximize quantity of water while preserving a minimum threshold water quality. In other words, it is better to have a high quantity of lower quality water than a low quantity of the highest quality water. Existing BWT system production rates range from 1 m^3 to 10 m^3/hr of treated water [2, 35, 98]. As the emergency extends, this quantity must eventually reach WHO and/or Sphere standards. However, these standards in practice are often adjusted depending on the assessment of the nominal or baseline country state. For instance, a country nominally with a 15 CFU/100 mL of Escherichia Coli concentration is already exceeding the WHO/Sphere standard for drinking water- however, an NGO might aim to reach that nominal state again rather than aim for the standard in an emergency.

To achieve quantity, large sedimentation tanks or bladders are constructed (especially near dense, static populations) with chlorine dosing. Water tankers may transport nearby surface water to refugee camps for the purpose of maximizing quantity initially (often times this surface water may even be contaminated). Trucks may have been previously used for fuel and not properly sanitized. Chlorine dosing might be inconsistent and not well monitored [99]. These examples show prioritization in the acute phase on quantity over quality.

5.3 Quality

However, there are typically minimum thresholds for water quality even in acute emergencies with metrics predominantly associated with health and with user acceptability. The water quality metrics associated with health are most commonly turbidity and free chlorine residual. Typical turbidity targets are $< 5-10$ NTU and targets for free chlorine residual (FCR) are 2.5-5 mg/L in emergencies [3, 33]. As the reader may recall, reducing turbidity is an aim for effective chlorination and thus elimination of biological pathogens which often include but are not limited to Escherichia coli, Cryptosporidium, Salmonella Typhi, and Giardia. Diarrheal disease and malnutrition are the leading causes of death these contexts [100].

Chemical and radiological [101] contaminants such as Arsenic, Fluoride, Lead, and other heavy metals are less commonly tested and almost never treated (simply avoided) in acute emergencies but are still important factors. Other quality metrics typically associated with user acceptance include salinity, color, and smell. A salinity threshold of $< 200-250$ mg/L of sodium and chloride ions is a common health guideline from the WHO [102]. In emergencies, acceptable salinity thresholds are approximately < 1000 mg/L [28] and have even been accepted as standard levels in some regions with chronic saline water problems [103, 104]. However, salinity often follows user taste preferences specific to the geographic area; for instance, some regions of India have taste pallets that are most commonly $< 200-500$ ppm [105] because they are accustomed to reverse osmosis treated water. In some regions of Africa, beneficiaries will resolve the problem of saline taste by diluting water with milk [106].

Color and smell are additional factors which can dissuade user acceptance [107] because beneficiaries believe the water is unclean, or even culturally inappropriate. Users may seek alternative sources which may appear in higher quality but are actually more dangerous in composition.

5.4 Cost

The cost of humanitarian aid ranges greatly, with an example of total annual humanitarian expenditure per capita in 2017 ranging from \$2.5 USD in Burkina Faso to \$75 in Jordan [108]; much of this is attributed to factors such as differences in the number of humanitarian aid organizations in the region, geopolitical importance, and quantity of refugees (Jordan had approximately 33 times the amount of refugees than Burkina Faso). The funding allocated to the WASH cluster in particular also varies greatly depending on the forecasts and situational assessments of demand. A typical cost threshold for bulk water treatment devices is nontrivial and highly dependent on the emergency and purchasing organization or entity. From the perspective of designing a device to be used specifically by international NGOs and operated by deployed practitioners, the cost per m^3/hr of water for historically employed packaged water systems is approximately \$2800-4500 USD. These packaged water systems were designed for the removal of turbidity and chlorination - none of the systems deployed are designed to treat chemicals including salinity. The International Federation of the Red Cross and Red Crescent, as well as the International Committee of the Red Cross/Crescent have historically used LMS, Berkefield, Scan, SETA, and other chlorine dosing systems [109] but many have not been employed in recent history [90]. Oxfam has one generalized water treatment unit in its catalog [110]. UNICEF also has a variety of water purification units, skids, and tanks [111]. MSF uses rapid pressure sand filtration units in two parallel channels which can be easily back washed [106]. Other purchasing perspectives include the potential for local governments and (in rare cases) beneficiaries to pre-purchase systems and use them nominally or store them ”in case of emergency”, however, household scale treatment and supplies are most commonly stored and distributed (rather than large systems). Because of the complexity of operation and high cost, UNICEF claims membrane processes are generally not appropriate for use in developing countries [30]. The current low perceived viability of membrane technology thus drastically reduces the quantity of treatable chemical or salt contaminated water.

5.5 Transport

5.5.1 Weight

Ease of transportation in unreliable supply chains is essential in crises. The weight of the system is one important characteristic, and should be less than 1500 kg to meet European pallet (ISO1) requirements. This requirement is driven by the maximum weight for a single pallet to be air shipped. Air shipment is the fastest and preferred method for immediate response in emergencies. The system weight should also be light enough to fit on a small 4x4 truck/SUV or at the greatest be trailered by such a vehicle [90]. Common vehicles used by the UN include Toyota Land Crusiers, Hilux, Prato, Land Rover Defenders, Nissan Patrol, and at times trucks (e.g., Renault) and busses (e.g., Volvo). Ideally, the system would be light enough to be lifted via a human crew; forklifts and heavy equipment are often unavailable [112]. Low weight caters well to flexibility - transport may need to be via rowboat, bush plane, and many other vehicle forms.

5.5.2 Volume

Similar to the weight requirement, the aim of volume is to be minimal for ease of shipment. However, an upper limit could be the volume and dimensions of a European pallet < 2.09 m^3 or (31.5” x 47.24” x 77”). European pallets are smaller than United States standards and used broadly by the UN. Such a system that met this volume requirement would also fit well in ground and ”last-mile” transit. The system could potentially be shipped as one, or in easy to assemble parts. Hoses are commonly reported as large space issues with high volume to weigh ratios in shipment.

5.5.3 Regulations

In interviews with UNICEF operators, batteries are mentioned to be an issue with shipment, maintenance, and reliability [113]. Lithium ion and energy storage devices in general (such as electric double-layer capacitor banks, which cover super and ultra-capacitors) of > 0.3 watt hours are subject to dangerous goods regulations (regulation UN3499). Depending on the type, weight, dimensions, capacity, and mode of transport, these regulations are more or less stringent [114]. These transportation standards vary depending on the international and/or national organizations involved and but are well outlined [115]. Recommendations against batteries were also found in literature due to their ”high cost and short lifetime” [116]. Other items that historically report difficulty in shipment have included chlorine powder and diesel. There have been additional calls for some level of universal testing by independent organizations on bulk water treatment systems; this testing data could be used for system validation and serve as a metric of comparison for future BWTs [2].

5.6 Operation

While skilled operators are often used in large-scale BWT deployment by international NGOs, the aim of a system should be the simplest operation possible, such that the system can eventually be easily run by local users or technicians with minimal training. The best systems are "plug-and-play" with minimal operator maintenance. Operator training time should be minimal, but at max one day. The set up time for such systems should be on the scale of hours to a maximum of two days for complex surface water treatment and should be a similar level of time and simplicity (if the system is to be repacked) upon departure [90, 117, 118]. Service agreements between the local government and the intervening aid organization are also almost always necessary [112, 119]. Generally, the complexity of the system (i.e., number of components) should be minimized to aid not only in simple operation, but also in maintenance and reliability [2]. The ease of user participation must be high as well - standards exist quantifying the maximum distance from water taps and thus, the product water interface must be accessible and acceptable by users [120]. The system should have an operating time that is maximized throughout the day (8+ hours) with minimal downtime for cleaning and maintenance. Finally, the system should have flexibility; a system may need to be moved rapidly and redeployed to other environments as the situation develops. A system should also be capable of handling a variety of feed water and energetic conditions and still perform within a reasonable range of expectation. Modularity, adjustability, and multifunctionality are all important tenets that allow for the system to be adapted to a variety of scenarios and used for many different purposes by practitioners [90]. Flexibility also applies to a system that is adaptable throughout the timeline of an emergency, and which may even be used for capacity building in long-term scenarios (e.g., renewables for BWTs in the initial phase, and then evolving to street lighting for an IDP camp in the protracted time period).

5.6.1 Maintenance

Maintenance is considered by many practitioners to be "the largest issue" [90]. Another representative from ICRC claimed "the three main challenges are the people, the infrastructure, and the consumables" [118]. Maintenance can be quantified by metrics such as part replacement frequency (or amount of consumables and their lifetime), part availability, backwashing frequency, time, and level of skill required to service. Current systems employed at most rely on chemical consumables including disinfectants (calcium hypochlorite) and coagulants and flocculants (aluminum sulphate or "alum"), which are typically widely available locally [121]. The discharge or brine quantity from these systems are stronger areas of concern in protracted emergencies. However, in initial response brine disposal is not as important.

Finally, a reliance on diesel and oil in general as fuel sources for energy generation and pumping in water treatment is an increasing consumables challenge. Shipment of liquids is costly due to their weight, and despite the relatively high energy density of diesel, there have been increasing shortages which are greatly affecting humanitarian aid capabilities with examples in Syria [122], Venezuela [123], Ethiopia [124], Gaza [125] and more recently due to conflict in Ukraine. Fuel shortages are an important aspect of humanitarian logistics [126]. About 5% of humanitarian aid costs are attributed solely to generator repair and diesel fuel and countries in central Africa and some of the Middle East particularly experience unreliable supply and high diesel cost [108]. Solarization and use of other renewables are some currently explored routes to decrease reliance on diesel in protracted scenarios [127].

5.6.2 Reliability

Maintenance is closely tied to system reliability. The less reliable the system, the more time and resources spent on maintenance. A system's reliability can be quantified using a number of metrics including mean time to failure, mean time between failure, mean time to repair, lifetime, etc. but unfortunately these are not well characterized in currently deployed systems. Systems deployed in acute emergencies must be robust against numerous environmental factors including high wind speeds, variations in humidity (anywhere from arid climates to the saturation of a rain forest), and strong fluctuations in temperatures. Even perceptually warm climates such as Yemen have cold winter nights that may see temperatures below freezing and have caused emergency funding appeals for winterization plans in IDP and refugee populations [128]. Robustness of operation below freezing temperatures can be difficult for water treatment systems. Additionally, the system can be subjected to low temperatures and pressures in cargo holds during air transport. A deployed system may also face issues with security and potential for sabotage; warring parties have historically commandeered humanitarian aid from its original designation and used it as a tool for harm [129, 130] and have threatened the safety of health professionals and operators [131]. The potential for a resourced to be used in an ulterior fashion is a tenet designers of BWTs and humanitarian supplies must consider.

5.7 Risks and Limitations

While these requirements are generalized bulk water treatment system requirements that a desalination system should follow, there are limitations and context specific factors to consider. One important but mercurial requirement is the final product salinity. Acceptable taste preferences may significantly differ between separate social, cultural, and geographic areas; for instance, the acceptable salt threshold based on taste profiles in India differs from that of the United States and Canada (<81-800 ppm) [132]. Additionally, there are cases where these specific transportation metrics including weight and volume limitations may be more or less than the recommended values; in protracted scenarios, items may be shipped to ports where heavy off-loading equipment may exist alleviating the weight requirement. Operationally, there may be operators with the expertise to setup multiple containers and components. However, there are also many scenarios where systems may be setup and operated by local experts or in the long-term, the beneficiaries themselves, and thus simplicity and education is a greater concern. Furthermore, there may be some cases where consumables and maintenance may be more allowable. Deployments in regions that have reliable infrastructure may allow for more international or foreign replacement parts - though, a system could be best suited if it were compatible with locally available suppliers and many different product substitutes. Finally, a common difficulty faced with shipment of goods in humanitarian relief is understanding and adhering to local customs and government protocol; the UN logistics cluster (main affiliation within the WFP and under IASC) is well-suited and informed on current minutia. These rules may change the acceptability of system components. While the authors list ISO and IATA standards in the design requirements, the local considerations often carry equal or greater importance.

CRITERION	REQUIREMENT
	Quantity
Flow Rate	(1 L/hr)/person [127]; typically 1 to 10 m^3/hr [90]
Produced Water	2.5-3 L for survival, 7.5-15 L for total basic per person [3]
	Quality
Biological	$> 0.2 - 0.5$ mg/L FCR, < 10 CFU/100 mL [3, 30, 33]
Physical	< 20 NTU; ideally < 5 NTU [3,27,32, 33]
Chemical	desalinate any input to < 1000 ppm [28, 101, 104]
Radiological	$< 100 mSv$ in acute scenario, <0.1 per year long-term [101]
Color	transmittance < 15 color units [107]
Smell	< 3 TON (threshold odor number) [107]
	Transport
Weight	< 1500 kg for Euro pallet/ISO1; $<8{,}000$ lbs for trailered SUV [90, 113]
Volume	$< 2.09 m^3$ Euro pallet/ISO1
Number of containers	1 to 2 containers [118]
Regulations	hazardous materials adhere to ISO and IATA standards [113]
	Cost
CAPEX	$2800 - 4500$ USD / (m^3/hr) [16, 106, 109, 110]
OPEX	1.25-2.5 USD/m^3 [16, 106, 109, 110]
	Maintenance
Replacement frequency	none within 3 weeks [106]
Waste: brine quantity	$< 40\%$ of the total feed [90]
Back-washing frequency	minimize [106, 133, 134]
Maintenance time	< 3 hrs/day
	Operation
Operator Training	1 day or less [90, 117]
Set-Up	2-3 hrs, maximum 2 days for complex surface water treatment [118]
Flexibility	can be shipped as a unit or taken in parts [90, 118]
User ease of participation	< 500 m from a tap, < 250 people per tap, < 30 mins queue time [3, 120]
Operating time	8+ hours per day
	Reliability
Wind Speed	up to 74 mph
Humidity	$0 - 100\%$
Temperature	$+/-40$ deg. Celsius
Pressure	$69.7 - 108.38$ kPa
Security	avoids sabotage [112, 119]

TABLE 1. Desalination BWT Requirements

6 EXISTING TECHNOLOGY

Existing interventions can be broken down into bulk water treatment (BWT) and household water treatment (HWT) interventions. Literature exists that compares trade-offs between various BWT and HWT technologies; but, focus is primarily on currently employed technology. None of the current interventions cataloged by prominent WASH international aid organizations are able to treat chemical contaminants such as pesticides, heavy metals, or salinity. Generally, BWTs are appropriate for longer term, more permanent displacements and are great for high turbidity and more complex treatment. Often many low-cost units are better than a few high cost units. BWTs often lack independent testing standards, have been historically deployed in unnecessary areas, have high capital cost, require skilled operators, and require significant maintenance and downtime for cleaning [2]. HWTs have greater reach, are lower risk, have low short-term cost (but higher long-term cost), and provide point of consumption protection. However, they have a high risk of low utilization without proper education. Some useful reviews of BWT [135] and HWT methodologies include [7, 136] and a book on low-cost emergency water treatment [137]. While BWT and HWTs are commonly employed, the decision making process for their deployment is not well understood and process selection guidelines are not formulated in detail [138].

Existing technology for desalination most commonly in-

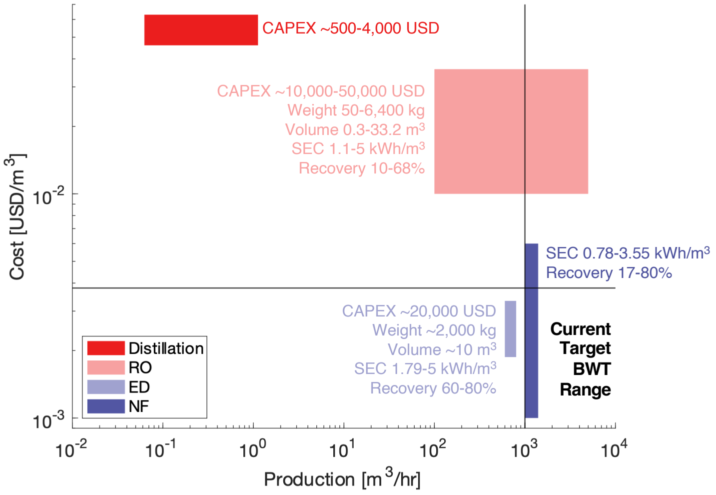


FIGURE 5. EVALUATION OF COST VERSUS PRODUCTION OF DEPLOYABLE DESALINATION SYSTEMS

volves thermal distillation at the home-scale (e.g., boiling water, solar distillation) and reverse osmosis membrane processes in community to large-scale systems. Low-cost home-scale distillation provides little quantity and often does not meet demand [139]. Some cases exist of utilizing forward osmosis for desalination and purification [140] but current solvent packets are typically cost prohibitive. Reverse osmosis processes involve high maintenance, operator knowledge, and require significant pretreatment of feedwater (and thus consumables) - all of which are commonly challenging limitations in emergency response. Point of use reverse osmosis systems have been attempted in Gaza but failed due to rapid membrane clogging and lack of user education [63]. Atmospheric condensation has been implemented by some companies in disasters (e.g., Genaq, Watergen), which boasts the lack of prefiltration and typically includes only air filters as consumables. However, the technology has low production rates relative to its energy consumption, especially in low humidity environments. There are few examples of desalination systems specifically designed for humanitarian relief.

6.1 Nanofiltration

Nanofiltration (NF) is a pressure-driven membrane technology that utilizes pores slightly larger than reverse osmosis membranes, and thus is less prone to clogging (relative to reverse osmosis). It can be utilized for partial desalination (ranging from 20 to 80% [141–143]), and is especially effective against divalent ions and some monovalent ions. The operational cost is approximately 29% less than reverse osmosis (0.001-0.006 USD/L) [144] and has a high water production capabilities for its weight and volume relative to other membrane technologies [145]. For the higher salinity thresholds in emergencies, partial desalination via nanofiltration may be sufficient for some scenarios and could be an interesting area for future exploration.

6.2 Reverse Osmosis

Reverse osmosis (RO) is the most commonly used system and has numerous cases of attempted adaptations to emergency scenarios. Some military equipment (e.g., Reverse Osmosis Water Purification Unit (ROWPU)) has utilized RO for seawater and brackish water desalination, but much of this has high capital costs (approximately 36,000 USD), high operating costs (approximately 16,000 USD every 2000 hours) due to membrane replacement and diesel usage, and requires skilled operators with an average of 4 hours daily maintenance [146–148]. Many of these systems have been infrequently used due to the increased reliance of armies on procured, bottled water, especially in Middle Eastern campaigns where water bottling facilities (often large seawater desalination plants) exist. However, some military RO equipment has been utilized for humanitarian deployments, such as the Canadian Disaster Assistance Response Team (DART) using ROWPUs in Haiti [149] and by the British Army using Stella Meta NBCG units (colloquially within the British Army - Water Purification Unit (WPU)) [150]. Some organizations have explored using deployable RO systems such as Katadyn Spectra Maker models, Aspen 2000DM, Karcher WTC500/700, and other organizations have made containerized systems with some employed in humanitarian scenarios (e.g., Mascara, Yemen Boreal Light, Somaliland RO, Aquasisstance, modified Veolia Aquaforce systems). It is unclear though the length at which these systems are successfully deployed and at what point failure occurs; this would be an interesting area of future investigation. Lastly, RO requires extremely stringent feedwater characteristics and encounters practical issues with fouling and scaling [151–153], which has prevented its broader adoption in emergency scenarios.

6.3 Electrodialysis

Electrodialysis (ED) is a membrane based desalination technique that is not pressure driven, but rather is electrically driven by differential charge on passing salt water. This lends itself well to robustness against turbidity, and has been historically used in harsher applications including wastewater treatment [154]. It is also generally more energy efficient than reverse osmosis in some brackish water conditions (<3000 mg/L) - depending on recovery ratio - and especially when the product salinity does not need to be relatively low; as the product salinity target lowers, the energy required to desalinate increases non-linearly [155]. Lowered specific energy and operational flexibility lends ED well to PV applications and can shift reliance on diesel [156]. Additionally, there is potential for electrodialysis to be utilized for specific ion recovery, as well as the potential for the technology to be coupled with on-site chlorination. Electrochlorination via electrolysis of sodium chloride is utilized in numerous remote field hospitals by MSF and UNICEF (one example company is WATA) and could be well suited for coupling with electrodialysis desalination in emergencies [157]. ED is not effective at removing heavy metals and other compounds with little to no ionic charge. Additionally, ED membranes and membrane technology in general must remain saturated and carefully preserved once wet which may prove difficult for redeployment due to increased weight and maintenance considerations.

Intermittent operation of any of these membrane processes could cause an increased rate of fouling. Membranes are not commonly procurable locally in low and middle income countries, and most guidelines strongly recommend not letting them dry. Shipment of wet materials, including membranes causes a significant increase in system weight. Membrane technologies also often need periodic cleaning with acid - another potential consumeable that hinders fully self-sufficient operation.

7 CONCLUSION

The growing need for desalination in humanitarian emergencies and in international development is increasingly apparent with cases of saline groundwater and intrusion in areas from coastal flooding to IDP and refugee camps. This need is not well quantified, but is inferred through numerous case studies in literature and from interviews with practitioners, and is most obvious in the Middle East, Southeast Asia, and parts of Africa. Much of these regions correspond with high groundwater salinity and high risk of disaster and/or conflict. While NGO operational standards currently lack guidance on saline water treatment, systems for treatment of salinity and chemicals will become increasingly necessary. Some humanitarian BWT requirements including transport regulations, weight, size, simple operation, minimization of consumables, and reliability in extreme weather conditions are not common design requirements for membrane and thermal desalination technologies and thus have historically hindered their adoption and usefulness in the field. RO variants have been attempted in the field, but often fail due to rapid fouling, a lack of a reliable supply chain for replacement cartridges, and the complexity of system operation. NF has not been attempted as frequently in field desalination usage, but could have greater potential as it trades off desalination capability for operational robustness. ED is another technology not attempted to the authors' knowledge in humanitarian deployments, but has great potential for solar deployment, coupled electrochlorination, and other mineral and resource extraction (e.g., hydrogen production in a protracted scenario). Distillation techniques do not appear to be feasible for large scale BWTs at this time due to their lack of production quantity and high energy requirements, but do boast potential simplicity and composition agnostic treatment.

Future work could include exploring the design of NF and ED systems and redesign of RO for these requirements. Higher target salinities could provide opportunities for these technologies to be implemented with membranes that sacrifice some amount of salt cut for robustness to turbidity and a broader range of feedwater compositions. Exploring reverse osmosis techniques that decrease fouling and clogging such as cross (tangential) flow plate and frame reverse osmosis or exploring the usage of hollow-fibre membranes, rather than commonly used spiral wound polyamide based membranes, would be interesting and could show higher potential for the usage of RO in crises scenarios. NF and ED systems have not been designed for this context; exploring the design of a flexible system that can desalinate a variety of feed salinities and turbidities is another area that should be explored, as traditional desalination systems are commonly designed for a highly specific feedwater composition and a specific target composition. A concentrated chlorine stream in electrodialysis could be extracted and utilized for disinfection of water, providing a substitute for another essential consumable; however, a challenge exists in separating this chlorine from other negatively charged ions in this concentrate stream. Another area of significant potential includes exploring minimal consumable prefiltration techniques; identifying and optimizing the architecture and design of low maintenance alternatives to cartridge filters such as disc, sand, and even hydro-cyclones has not been explored in this space. Thermodynamically and technoeconomically comparing these processes within the context of crises would be highly beneficial. Finally, future work should include investigating more social factors (such as distribution practices, taste thresholds, use profiles) that are context specific; neglecting such factors could severely reduce the effectiveness of a system that is designed only for the initial requirements mentioned in this work. A desalination system designed to meet the needs of humanitarian crises would be a substantial step in adopting desalination technology not only for disaster and crisis response, but also for providing water in other highly-constrained communities.

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