A holistic reliability system approach of a water distribution network in Saudi Arabia
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ABSTRACT

Saudi Arabia, with no perennial rivers, is considered to be an arid land where water losses in the Water Distribution Network (WDN) supply increase the need for sea water desalination. This paper provides a reliability model to enhance the WDN for a water pumping station in Saudi Arabia. The paper utilizes the Fault Tree Analysis (FTA) reliability tool to mitigate water supply stoppages. In the case under study, the pump station utilizes two groundwater aquifers in the eastern part of Saudi Arabia to meet the raw water demand through a water distribution network (28 km long pipelines). Data has been gathered from the maintenance history to estimate the system reliability based on the loss of water by which each component of the system is assessed on its contribution to the overall system reliability and water supply. The findings revealed that system availability can be improved by adding a new pump in the booster station which further enhances the availability of the system to 99.99% and saves the WDN more than 740,974.60 gallons of water loss per year. It is hoped that the paper’s recommendations will enhance the reliability practices in similar water network stations.

Key words | availability, failure tree analysis, reliability, Saudi Arabia, water distribution system, water loss

HIGHLIGHTS

- The reliability of a community raw water distribution system in Saudi Arabia is assessed.
- A reliability tool based on fault tree analysis is utilized to mitigate water supply stoppage.
- Real data are collected to estimate the system reliability.
- The water distribution system availability is analyzed and improved.

INTRODUCTION

A water system is a hydrologically and hydraulically engineered system consisting of many components and parts with various rates of failure (Laucelli & Giustolisi 2015). These components are utilized together to supply water to end users. The system can be highly sophisticated and automated. It normally includes a raw water source, a production water plant, water storage, and water treatment facilities. In addition, it contains pressurizing equipment such as booster and transfer pumps, a piping network, and a drainage system (Alegre et al. 2016). The water supply system is the most costly urban system. Moreover, leakage and failures significantly contribute to an increase in the water supply and distribution network cost Giustolisi et al. (2006). The expenses of this network are more than 85% of the whole water supply system. In 2012, the maintenance of aging and deteriorating components of water supply systems cost $25.9 billion in Canada (The Canadian Infrastructure Report Card 2012). Furthermore, in 2013, a
low grade was assigned to the water supply system in the United States ASCE (2015). In the Middle East, many regions are facing major problems regarding their water supply. Qatar, for instance, has the highest rate of evaporation and the lowest rate of precipitation (approximately 82 mm/year) in the world. The water distribution network in the country loses around 33% of its water as a result of failures Scott (2013). Likewise, Saudi Arabia is one of the driest desert regions in the world and relies heavily on sea water desalination. Hence, water treatment and distribution is an essential source to satisfy the water demand for around 30 million people living in Saudi Arabia.

Saudi Arabia used a government agency known as the presidency of meteorology, in addition to local departments, to look after the fresh water supply in the country. Reliability and availability are important measures for the quality of water supply. However, these measures have not been linked with the amount of supplied water. A lack of such measures may have a severe effect on the water supply which is usually caused by frequent failure breakdowns of the systems and poor reliability studies. The estimation of system reliability has a great impact on the quantity of the produced supply which greatly concerns the decision makers who strive to predict the expected supply capacity by assessing reliability. (Kawas et al. 2013) developed a robust optimization model to enhance the reliability of production system in satisfying demand and in terms of providing guarantees on profits. Kanakoudis & Tolikas (2001) introduced an approach to compute the optimal time of replacement for the water system pipes. The approach is based on the technico-economic analysis. In addition, Kanakoudis & Tolikas (2004) and Kanakoudis & Tolikas (2002a) evaluated the water network performance by analyzing the possible actions of preventive maintenance in water network. The authors utilized technico-economic analysis to accomplish the work. Similar work was conducted by Kanakoudis (2004) to determine the optimal schedule of the preventive maintenance. The author compared the optimal obtained schedule with empirical schedule. (Tsitsifili et al. 2021) utilized the discriminant analysis and classification approach to assess and forecast the behavior of the water system pipes. The results of this work were very promising. The authors used the DAC method to classify the pipes into success and failure pipes. Alternatively, overestimating a system’s reliability is usually an issue in large capacity production supply systems. Thus, more resources, such as over-time and raw materials, are required to obtain the expected revenue Huang (2012).

Water supply is a vital resource for the population, general welfare, and community health (Alegre et al. 2016). Water is normally obtained from four sources, namely, non-renewable groundwater from the deep aquifers, desalinated water, surface water such as rivers, and renewable groundwater from shallow aquifers. A part of the master plan of any community is the water distribution network, which has to be planned and designed by expert engineers. Critical factors such as the proper location, current demand, future anticipated growth, pressure, pipe size, required firefighting flow, etc. must be considered while planning and designing water distribution networks. Designing such systems without failures is hard, if not impossible, because of technological concerns and higher cost. Consequently, the reliability and availability concepts need to be taken into account at the early design stage for production performance.

Reliability improvements in water supply networks can be reached by reducing failures in the future. Several studies have been conducted to evaluate the water distribution network reliability. (Tabesh et al. 2009) addressed three techniques for forecasting the failure rate of pipe. The developed methods are fuzzy approach, artificial neural network, and regression. A real case study involving a big network for water distribution in Iran are used an application of the proposed model models. Model predictions outcomes are compared to the data calculated for pipe failure. The findings showed that the neural network outperforms the other developed techniques. Kanakoudis & Tsitsifili (2011) applied the discriminant analysis and classification approach to assess and predict the reliability of water pipe system. The results indicated the ability of the applied method for forecasting the reliability of urban water pipe network. Another work was conducted by the same authors Tsitsifili & Kanakoudis (2010). They discussed the reliability evaluation of pipes in two pipe networks using the DAC approach. Each network piping is divided into two groups on the basis of whether or not it failed at least once (failures group) (successes group). The ‘critical Z-score’ criterion is utilized as a measure of the potential pipe status. Moreover, (Piadeh et al. 2018) developed a hybrid model based on the
combination of fault tree analysis and event tree analysis for the reliability assessment of water treatment systems.

Gheisi & Naser (2014) applied a multi-criteria decision analysis approach for ranking some alternative distribution layouts of a WDN employing statistical flow entropy and considering various states of reliability (the probability that a WDN satisfies water demands during different states of simultaneous pipe failures). In addition, Ataoui & Ermini (2014) developed an approach for evaluating the overall reliability of WDNs in terms of nodal pressures and the quantity and quality of nodal available discharges using a fuzzy technique. They applied demand-driven analysis (DDA) which is the disadvantage of their work. Pressure-driven analysis (PDA) that considers the pressure dependency of nodal discharges provides more realistic results than the DDA (Shirzad et al. 2015). (Liu et al. 2017) considered surrogated metrics to take reliability in water distribution networks into account under normal working conditions. Furthermore, Chengchao & Goulter (1999) proposed a novel method for optimizing the reliability of water distribution network under uncertainty of pipe capacity and nodal demand. The model included a strategy to identify significant nodes that are subject to reliability constraints in the cost minimization step. A sensitivity analysis was conducted to evaluate the efficiency of the proposed model. Other studies that considered reliability assessment in water distribution systems have been conducted by Ataoui & Ermini (2014). Shirzad & Safari (2019) compared random forest and multivariate regression methods for predicting failures in a WDN.

This paper aims to improve the reliability of the current community raw WDN systems by estimating the failure probability, availability, and unavailability indices for WDN system components to determine the reliability of the current system. The contribution of this study is to link developed reliability measures with the water supply loss in the WDN by applying sensitivity analysis at the component level to understand their influences on the system reliability as a whole, in addition to modeling the faults using fault tree analysis.

MATERIALS AND METHODS

The aim of Water Distribution Network (WDN) is to supply water to the consumers with sufficient pressure (2.75 bar to 5.5 bar at the household supply) (Alina et al. 2010). The WDN must be reliable and maintained at a positive pressure at all times. It must also prevent leakages which should be tackled immediately. WDNs usually have a designed pumping station with storage tanks and pumps. Although there is an agreement that reliability is an important trait of any distribution system, there is no universally recognized definition for ‘reliability’.

An effective analysis of reliability and availability improves the performance of production systems. In this regard, it is essential to understand the relationship between the productivity of a WDN and its reliability to satisfy certain production levels. In general, a water supply has to be reliable and available to all end-users at all times, even during maintenance. The performance level of a water supply system under normal and up normal operating condition can be evaluated using the appropriate indices such as percentage of use, grade and quality of service, reliability, and availability Kanakoudis (1998). Moreover, Kanakoudis & Tolikas (2002b) presented an assessment simulation model for an integrated water supply system in Athens. The objective was to determine the best configuration and the flow through the water system that minimize the total cost. Other related works have been carried out by (Kanakoudis & Tolikas 2002c) and (Kanakoudis & Tolikas 2002d).

In general, reliability can be assessed and measured using different tools including, reliability hazard analysis, failure mode and effects analysis (FMEA), fault tree analysis (FTA), reliability centered maintenance (RCM), and other methods. FMEA is used at the beginning to identify potential failures and the associated impacts. Then an FTA was constructed which could be used to describe all the causes of the events that lead to failure mode. (Stiff et al. 2005) used a HAZID (Hazard Identification) technique to define the differences between turrets and spread mooring systems. Quantitative risk assessment between the turret and spread mooring was calculated using structural reliability analysis.

In this paper, a system reliability analysis for a community raw WDN in Saudi Arabia is analyzed. First, the major input variables (components or equipment) that the system reliability depends on are identified and selected. Then, the failure probabilities of each input variable are calculated. Then, a fault tree analysis diagram is constructed and the system reliability is computed quantitatively using indices.
such as system availability. Lastly, the failure effect of each component is measured in terms of water loss on the system.

**Inputs parameters**

In this study five main input variables are identified as shown in Figure 2, which are:

1. Water wells (11 components)
2. Booster pumps at the source (3 pumps)
3. Network pipelines (2 Pipelines)
4. Booster pumps at destination (4 Pumps)
5. Diesel engine driven pumps (2 Pumps)

These are the main components of the system. Any failure in these components will cause the system to fail. In order to calculate the system reliability, failure probabilities have to be calculated. Table 1 shows the average repair time for each major component in the system.

Other water wells were not included in the study because their components do not contribute much to the operation, i.e., their capacities are small compared to the main water wells. The maintenance history for each component is extracted from the Enterprise Resource Planning (ERP) system. Sometimes the system does not give accurate data. For example, maintenance activity is completed today, while the ERP gets updated after one month. This will cause an offset in the history data and, hence, there will be reasons to take experts' judgments into consideration.

**Reliability analysis**

Reliability can be assessed using various models, including failure rate $\lambda(t)$, Mean Time to Failure (MTTF), Mean Time between Failures (MTBF), Mean Time to Repair (MTTR), and Availability and Unavailability (Duffuaa et al. 2000). In this paper, the following assumptions are used to develop the model:

1. The failure rate is constant during normal operating lifecycle.
2. System study is under the normal operating phase of the system lifecycle.
3. The failures occur independent. The occurrence of one failure does not affect the probability of occurring the second failure.
4. The time between failures is not affected by the repair time.

To calculate these indices, the following equations are used:

$$MTTF = \frac{1}{\lambda}$$

$$MTBF = \frac{\text{total operating hours}}{\text{number of failures}}$$

$$MTTR = \frac{1}{\mu}$$

where $\mu$ is a constant repair rate.

$$Availability Rate = \frac{\mu}{\mu + \lambda}$$

$$MTBF = MTTF + MTTR$$

$$System Availability = \frac{MTBF}{MTBF + MTTR}$$

$$R(T) = e^{-\lambda T}$$

**Fault tree analysis**

FTA is a popular reliability analysis tool used globally. It was introduced in 1962 at Bell Telephone Laboratories, in connection with a safety evaluation of the launching system for the intercontinental Minuteman missile Rausand & Hoyland (2003). FTA depends on identifying failure events that may occur in a system. It graphically represents the interrelationships between potential critical failure events which impact the occurrence of a specific undesirable event that is called 'a top event'. In drawing up the tree we use the so-called

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**Table 1 | Average repair time and rate for each major component in the system**

| No | Equipment                      | Average repair time (days/failure) | Repair Rate ($\mu$) |
|----|--------------------------------|-----------------------------------|---------------------|
| 1  | Water wells pumps             | 60                                | 6.94E-04            |
| 2  | Booster pumps at the source   | 30                                | 1.39E-03            |
| 3  | Network pipelines             | 1                                 | 4.17E-02            |
| 4  | Booster pumps at destination  | 30                                | 1.39E-03            |
| 5  | Diesel engine driven pumps    | 15                                | 2.78E-03            |
functions (logic gates), specifying, among others, the logical product of events and the logical sum of events.

There are two basic logic gates, as shown in Figure 1:

‘OR’ gate: an event above the gate occurs if at least one event below the gate occurs

‘AND’ gate: an event above the gate occurs if all the events below the gate occur

**CASE STUDY**

To illustrate the methodology of this work, the case study focuses on a community raw water system located in Saudi Arabia. First, the system inputs are identified. Then, the ERP system is used to find the failure probabilities for each input. Finally, fault tree analysis (FTA) is constructed and reliability analysis is conducted.

**Water distribution network**

The considered community area depends solely on groundwater as the only source of water. There are 18 scattered water wells producing different amounts of water. The majority of these water wells are located in the eastern province of Saudi Arabia (11 water wells) which is around 28 km away from the community area. The water produced from the source of the water system is then transferred through a carbon steel pipe to the community area. The remaining water wells are located in the community area. All of these water wells are connected to the water distribution network. **Table 2** gives information about the main water wells.

| Well No. | Voltage (V) | Motor HP | Capacity GPM | Number of Stages |
|----------|-------------|----------|--------------|------------------|
| 25       | 2,300       | 150      | 540          | 3                |
| 26       | 2,300       | 150      | 1,365        | 6                |
| 27       | 2,300       | 150      | 1,410        | 3                |
| 28       | 2,300       | 150      | 1,485        | 3                |
| 30       | 2,300       | 150      | 672          | 4                |
| 31       | 2,300       | 150      | 753          | 2                |
| 45       | 2,300       | 150      | 901          | 2                |
| 46       | 2,300       | 150      | 731          | 4                |
| 49       | 2,300       | 150      | 563          | 2                |
| 64       | 2,300       | 150      | 1,170        | 5                |
| 71       | 2,300       | 150      | 1,125        | 2                |

The produced water is used for cleaning, showering, drinking, feeding the fire system, irrigation, etc. Hence, the importance and criticality of the water differs from one component to another. The loss of drinking water may not be that important, however, it is crucial to continuously supply the fire hydrants.

The water distribution network consists of pumps, pipes, tanks, valves, fire hydrants, instruments, etc. In order to deliver water to the community, all of these components must operate reliably and be 100% available at all times. **Figure 2** illustrates the water distribution network.

**System input**

A community water distribution system is a sophisticated system with many small and large components. In this
case study the major components are investigated, whereas other components such as valves, instrumentation and small piping branches are not considered. The main components that are included in this study are:

1. Water well pumps and motors (11 components) (1,000 Gallon Per Minute (GPM) each)
2. Booster pumps at the source of a water system (3 pumps) (9,000 GPM each)
3. Network water pipelines (NWP-11 and NWP-12) (6,000 GPM each)
4. Booster pumps at destination (4 pumps) (2,500 GPM each)
5. Diesel engine driven pumps (2 pumps) (2,500 GPM each)

Failure probability

An ERP system is utilized to get the maintenance history of the system inputs identified in the previous section. The number of failures reported for each piece of equipment is shown in Table 3. The failure rate of each system component is calculated on the basis of its lifetime and the number of failures occurring during its life cycle.

FTA analysis

The first step in constructing the FTA diagram is to identify the ‘Top Event’. In this study the ‘Top Event’ is a failure to meet the daily water demand for the community which is 7.26 MMGD (5,000 GPM). After that, the events that lead to the occurrence of the ‘Top Event’ are identified. In this system, the identical components are working in active redundancy. Referring to Figure 3, these events are as follows:

1. Event 1: the failure of more than six water wells simultaneously will cause the system to fail as 5 water wells, at least, must be operational to satisfy the daily water demand for the community. It is assumed that all water wells at the source (WPSs) capacity are similar (1,000 GPM). The probability of this failure can be found based on the binomial distribution (simultaneous failures of more than six water wells) (see Table 4).
2. Event 2: the simultaneous failure of the three booster pumps will cause the system to fail as at least two of them must be operational at the source. The probability
of this failure can be found based on the binomial distribution (simultaneous failures of more than two booster pumps) (see Table 4).

3. Event 3: the failure of the two pipelines will jeopardize the distribution operation. The Network water pipelines transporting water from the source to the community

### Table 3 | Major system’s components failure rates

| Location | Equipment | No. of failures | No. of years | Failure per year | Failure per hour |
|----------|-----------|----------------|--------------|-----------------|-----------------|
| Booster station at the source | WPS-25 | 2 | 10 | 0.200 | 2.28E-05 |
| | WPS-26 | 2 | | 0.200 | 2.28E-05 |
| | WPS-27 | 3 | | 0.300 | 3.42E-05 |
| | WPS-28 | 2 | | 0.200 | 2.28E-05 |
| | WPS-30 | 7 | | 0.700 | 7.99E-05 |
| | WPS-31 | 1 | | 0.100 | 1.14E-05 |
| | WPS-45 | 4 | | 0.400 | 4.57E-05 |
| | WPS-46 | 3 | | 0.300 | 3.42E-05 |
| | WPS-49 | 2 | | 0.200 | 2.28E-05 |
| | WPS-64 | 3 | | 0.300 | 3.42E-05 |
| | WPS-71 | 1 | | 0.100 | 1.14E-05 |
| | Pump L-22 | 8 | 15 | 0.533 | 6.09E-05 |
| | Pump L-23 | 19 | | 1.267 | 1.45E-04 |
| | Pump L-24 | 16 | | 1.067 | 1.22E-04 |
| Network water pipelines (2 pipelines) | Pump 17 A | 5 | 15 | 0.333 | 3.81E-05 |
| | Pump 17 B | 4 | | 0.267 | 3.04E-05 |
| | Pump 17 C | 3 | | 0.200 | 2.28E-05 |
| | Pump 37 | 4 | | 0.267 | 3.04E-05 |
| | Diesel engine driven pump 23 | 8 | 20 | 0.400 | 4.57E-05 |
| | Diesel Engine Driven Pump 24 | 13 | | 0.650 | 7.42E-05 |

### Figure 3 | FTA diagram for the case study.
area must be available all times (simultaneous failures of the two pipelines) (see Table 4).

4. Event 4: The failure of the four booster pumps and one diesel pump will cause the system to fail. At least two booster pumps in the community area must be operational or the two diesel engine driven pumps must be available (simultaneous failures of at least one diesel engine and more than three booster pumps) (see Table 4).

5. Event 5: The failure of three booster pumps and one diesel pump will cause the system to fail (simultaneous failures of two diesel engine and more than two booster pumps) (see Table 4).

RESULTS

In this section, system reliability is assessed utilizing the aforementioned data. In addition, sensitivity analysis is conducted to find which component is more influential on the overall system reliability. Figure 4 presents the mean time to failure and the mean time to repair of the equipment.

Table 4 | Probabilities of system failure

| Scenario | Probability of system failure |
|----------|------------------------------|
| Event 1 The failure of more than six water wells simultaneously | 1E-06 |
| Event 2 The failure of the three booster pumps simultaneously | 3.01E-04 |
| Event 3 The failure of both network water pipelines | 4.76E-06 |
| Event 4 The failure of the four booster pumps and one diesel pump | 4.08E-08 |
| Event 5 the failure of three booster pumps and one diesel pump | 1.54E-08 |

Figure 4 | System’s Components MTTF and MTTR.
system components. Based on MTTF and MTTR of the major system’s components, the availability and unavailability of the main components is computed as shown in Figure 5. As can be seen, the network water pipelines (2 pipelines), WPS-71, booster pump 17 C, and diesel engine driven pump 23 are the most available components.

In order to simplify the calculation process, the average of the unavailability for each similar piece of equipment is taken:

- Water wells (11 components) = \( P_{(WPS)} = 0.040 \)
- Booster pumps at the source (3 pumps) = \( P_{(BPS)} = 0.067 \)
- Network pipelines (2 pipes) = \( P_{(NEP)} = 0.0022 \)
- Booster pumps at the community area (4 pumps) = \( P_{(BPCO)} = 0.021 \)
- Diesel engine driven pumps (2 pumps) = \( P_{(DEDP)} = 0.021 \)

Furthermore, the probabilities of each basic event (scenario) that cause the top event to happen are computed using binomial distribution. Table 4 shows the different scenarios and corresponding probabilities of the system failure.

Then the failure probability of the whole system has been calculated by summing up all of the basic event probabilities:

\[
P_{\text{system}} = P_1 + P_2 + P_3 + P_4 + P_5 = 0.000307 = 0.030686\%
\]

Hence, the system availability is 99.96931%.

Since the minimum required capacity of the system to meet the daily water demand is 5,000 GPM, the minimum water loss due to unavailability is:

Water loss \( \geq 5,000 \times (1 - 0.9996931) \geq 1.5345 \) GPM. This implies that the yearly water loss is more than 806,533 gallons. The water loss is the amount of distributed water that does not reach the end users from water supply system, which will be supplied from other water sources.

Figure 5 | System’s Major Components Availability and Unavailability.
Sensitivity analysis

In this section sensitivity analysis is conducted to evaluate the system reliability by adding an extra unit as a back-up to enhance the overall system reliability. Five scenarios are tested as shown in Table 5. From Table 5 it can be noticed that having an additional booster pump in the source of the water system will enhance and boost the system reliability by around 0.028%, which is the highest among all of the scenarios. In addition, the minimum quantity of water saved is computed to illustrate the effectiveness of enhancing the system reliability. Table 4 shows that it is worthwhile to add an extra unit of BPS as a back up to save more than 740,974.60 gallons per year.

| Table 5 | Sensitivity analysis |
|---------|---------------------|
| 1st Scenario | 2nd Scenario | 3rd Scenario | 4th Scenario | 5th Scenario |
| Additional WPS | Additional BPS | Additional NEP | Additional BPCO | Additional DEDP |
| New Availability | 99.9693 | 99.9975 | 99.9699 | 99.9694 | 99.9694 |
| Minimum Saving of water (gallon per year) | 262.80 | 740,974.60 | 15,346.21 | 2,858.48 | 2,850.59 |

Implications

In many production systems if an unexpected failure happens the failed machines have an impact on the line upstream by causing them to operate without processing material and causing a gap in production downstream of the failure. Furthermore, this may lead to a gap in the production interruption upstream. This is due to the quality problems during the breakdowns that leads to scrapping the material interruption upstream. Therefore, the real production rate is less than the nominal production rate.

Despite the fact that the system availability of 99.97% is considered to be high, there is still a very minimal chance of failure (0.030%) which, if it happens, may be dangerous and will raise safety concerns. This is because of the fact that the community water system feeds different facilities such as residential, offices, plants, labs, recreational facilities, etc. Moreover, it feeds the fire system and the fire hydrants. This is why we cannot tolerate this small percentage occurring. Hence, huge storage tanks in the booster station in community area have been constructed which may last for at least three consecutive days and more than that if we reduce the amount of unnecessary demand such as for irrigation.

Conclusions

The main purpose of this paper is to assess the reliability of a community raw water distribution system in Saudi Arabia and to conduct a sensitivity analysis. The analysis was built on five failure scenarios which, if any one of them occurred, would cause the system to malfunction. These scenarios were used to build and construct the fault tree analysis.

Despite the fact that the system is very complex and sophisticated, the major components are considered, and some logical and legitimate assumptions are made. This is in order to have a more convenient system for analysis and to have a sense of the behavior and characteristics of a real system. The analysis shows that the system availability is around 99.97%. The system availability is improved by adding a new pump in the booster station at the source of the water system, which results in boosting the availability to 99.99%.

This study helps management to be aware of the strengths and weaknesses of the system. Moreover, most of the reliability studies focus only on the system reliability indicators. This study links the reliability indicator with the production output of the plant (in our case, cubic meters of fresh water). This would enable to estimate the service level provided by the plant and also help to justify the maintenance cost as it can be easily translated into cost benefit analysis. Furthermore, the study, in conjunction with the sensitivity analysis, will assist management to make decisions with regards to the feasibility of adding...
extra equipment to the system to enhance its reliability. The method applied in this paper is applicable to other similar water supply systems and can be used in assessing the reliability of these systems. Certain assumptions can be made in order to simplify the calculations. However, we should not ignore any major input to the system so as not to jeopardize the quality of the results.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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