Technical Report

Waterborne Antimicrobial Resistance in India: Strategies to Address the Key Challenges and Gaps Through a One Health Approach

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The science program envisions improving the lives and well-being of people in low- and middle-income countries by sustainably transforming animal and aquatic food systems, so they foster inclusive, healthy, and nutrient-dense food supply chains that are climate- and environmentally- friendly in Kenya, Ethiopia, Mali, Tanzania, Uganda, Vietnam, Bangladesh, India, Nepal, Colombia, Guatemala, Senegal, Tunisia, Cambodia, Ghana, Nigeria, Timor Leste, Zambia, Malaysia and Egypt.

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Summary

Antimicrobial Resistance (AMR) has become the “silent pandemic,” threatening health and environmental sustainability on a global scale. By 2050, AMR is projected to be the leading cause of global deaths, more than cancer. India is among the nations with the highest death rates attributed to AMR. The Ministry of Health and Family Welfare (MoH&FW) of India identified AMR as among the top 10 priorities to act upon in collaboration with the World Health Organization (WHO). Overuse and irrational misuse of antibiotics for human consumption, livestock, agriculture, plants and aquaculture have contributed to environmental contamination by antibiotic residues and AMR pathogens. Inappropriate waste disposal coupled with inadequate treatment of effluents from various anthropogenic sources such as healthcare facilities, pharmaceutical industries, aquaculture, agriculture, and households, has substantially contaminated the receiving water bodies with antibiotics and waterborne AMR. Antimicrobial resistance bacteria (e.g., *Escherichia coli*, *Klebsiella pneumoniae,* and *Pseudomonas aeruginosa*) and resistance genes (e.g., $bla_{NDM\text{-}1}$ and $bla_{OXA\text{-}48}$) were found in the contaminated surface and groundwater bodies in India, posing a serious risk to the aquatic environments, food systems, human and animal health.

Since the Government of India identified AMR as a national priority, several concerted efforts were taken for AMR containment such as the launch National Policy for AMR containment (2011), National Program for AMR containment (2013), National Action Plan for AMR (NAP-AMR) in 2017 and initiated NAP-AMR 2 in 2022, National AMR Surveillance Network covering 33 states and Union territories, and schedule H and H1 policies that regulates the sale of certain drugs thereby restricting the easy access to over the counter (OTC) antibiotics. The state action plan to contain AMR was formally launched by a few states: Kerala, Madhya Pradesh, New Delhi, Karnataka, Gujarat, and Telangana. In the environment, water and waterbodies are important carriers and storehouses for AMR. However, only a few states' action plans, such as those from Delhi and Gujarat, emphasized water components for AMR control. In 2022, the country launched the ambitious National One Health Mission (NOHM), which recognizes the multidisciplinary approach to combat the infectious disease outbreak, including zoonotic disease and AMR, integrating human, animal, and environmental health. Nevertheless, the relevant water departments dealing with water bodies, distribution and supply still need to be recognized as the key stakeholders in the NOHM for a targeted intervention to curb the waterborne AMR.

This technical report assessed the current situation of waterborne AMR in India, key challenges and gaps to address the spread and transmission of AMR through water pathways and proposed the short and long-term strategies/interventions at the national and local level in alignment with the NOHM and NAP-AMR from a One Health perspective.

India would benefit from building on current efforts to urgently contain the spread and transmission of waterborne AMR across different sectors through a focused One Health approach targeting water as an important environmental pathway for contamination and disease transmission. In particular, we recommend the following strategies/interventions to address the key challenges and gaps in tackling waterborne AMR:

- The inclusion of key water stakeholders in the National One Health Mission steering committee;
- Recognize and champion water and One Health in national policies and action plans for AMR;
- Targeted interventions and nature-based solutions as a barrier for waterborne AMR dissemination;
- Integrated AMR surveillance and modelling for AMR environmental pathways;
- Identify and target the key waterborne AMR organisms for reduction strategies;
- Promote sustainable “Best Buy” technologies and best practices for water pollution control and health risk mitigation;
- Encourage research funding and the National One Health Data Archive on waterborne AMR;
- Enhance Awareness Generation, Capacity Building and Policy Measures on waterborne AMR.

Purpose of this Report

The report aims to assess the current status of waterborne Antimicrobial Resistance (AMR) in India. Identify the barriers and gaps in addressing the spread and transmission of waterborne AMR through water pathways in the country. The water and environmental pathways are important and often overlooked pathways in tackling the spread of AMR. It emphasizes the urgent need for targeted interventions and a focused One Health approach to contain the spread of waterborne AMR across different sectors. The report further aims to strengthen the AMR response by concerned authorities and stakeholders at the local (watershed-scale) and national level to mitigate the health risk associated with waterborne AMR exposure in India.

1. Antimicrobial Resistance (AMR) – A global health threat with major impacts in India

AMR occurs when bacteria, viruses, protozoa, and other microbes develop resistance to treatments, which increases the risk of infectious diseases. Exposure to antibiotics, heavy metals, and disinfectants eliminates susceptible microbes while allowing resistant strains to survive and proliferate in the environment (Murray et al. 2022). Human activities, along with the overuse of antimicrobial drugs, are fueling the rise of drug-resistant strains, known as "superbugs," which make infections increasingly difficult—or even impossible—to treat (UNEP 2023, Knapp et al. 2010).

In 2021, bacterial AMR contributed to 4.7 million deaths and directly caused 1.27 million deaths (Murray et al. 2022). Children are especially vulnerable, with one in five AMR-related deaths occurring in those under five years old. By 2050, AMR could directly cause 1.91 million deaths and be associated with 8.22 million globally (Naghavi et al. 2024). If left unaddressed, AMR could result in economic losses of up to USD 1 trillion in additional healthcare costs by 2050 and Gross Domestic Product (GDP) losses of USD 1–3.4 trillion annually by 2030 (WHO/FAO/WOAH 2020; Murray et al. 2022). Since 1970, no new class of antibiotics has been developed, further worsening the crisis (World Bank, 2019). AMR has become the "silent pandemic," threatening health and environmental sustainability on a global scale.

While AMR is a worldwide issue, low- and middle-income countries (LMICs) are particularly vulnerable due to higher levels and diversity of infectious diseases, inadequate disease diagnostics and infection control, inappropriate antibiotic use, and overburdened healthcare systems (Kaur et al. 2024). India has a rapidly expanding economy, but still has the 60th highest age-standardized mortality rate per 100,000 population associated with AMR among 204 countries (IHME 2022). More importantly, it has the highest AMR rate across multiple pathogens, contributing to a mortality rate of 417 per 100,000 people from infectious diseases (Singh et al. 2024; Taneja and Sharma 2019), and was responsible for 297,000 and 1,042,500 direct and associated deaths, respectively, in India in 2019 (IHME 2022).

As such, addressing AMR in India requires urgent action to address the key barriers, including prevention and surveillance across the human and animal health, agricultural, and environmental sectors adherent to One Health principles (UNEP 2023), especially an increased focus on environmental pathways of spread to reduce the recirculation of AMR back to human and animal systems due to water and other pollution (Figure 1).

In this report, the current situation of waterborne AMR in India was assessed and key challenges were highlighted to curb the AMR spread and transmission through water and environmental pathways following the proposed One Health strategies/interventions at local and national level. The proposed strategies further aim to address the key challenges and gaps, strengthen the AMR response and health risk mitigation from waterborne AMR exposure.

2. One Health and Waterborne AMR in India

One Health is a multisectoral, multidisciplinary, and collaborative approach aimed at establishing a sustainable health delivery system that encompasses human, animal, and environmental health (OPSA 2024). It is an integrated and unified approach that aims to improve human, animal, and environmental health (WHO 2017). It recognizes the interconnectedness of these sectors and emphasizes a holistic strategy to prevent the spread and transmission of AMR and infectious zoonotic diseases (**Figure 1**). The development, selection, transmission, and spread of diverse AMR strains occur simultaneously across the One Health spectrum (Graham et al. 2019; OHHLEP 2022, 2023).

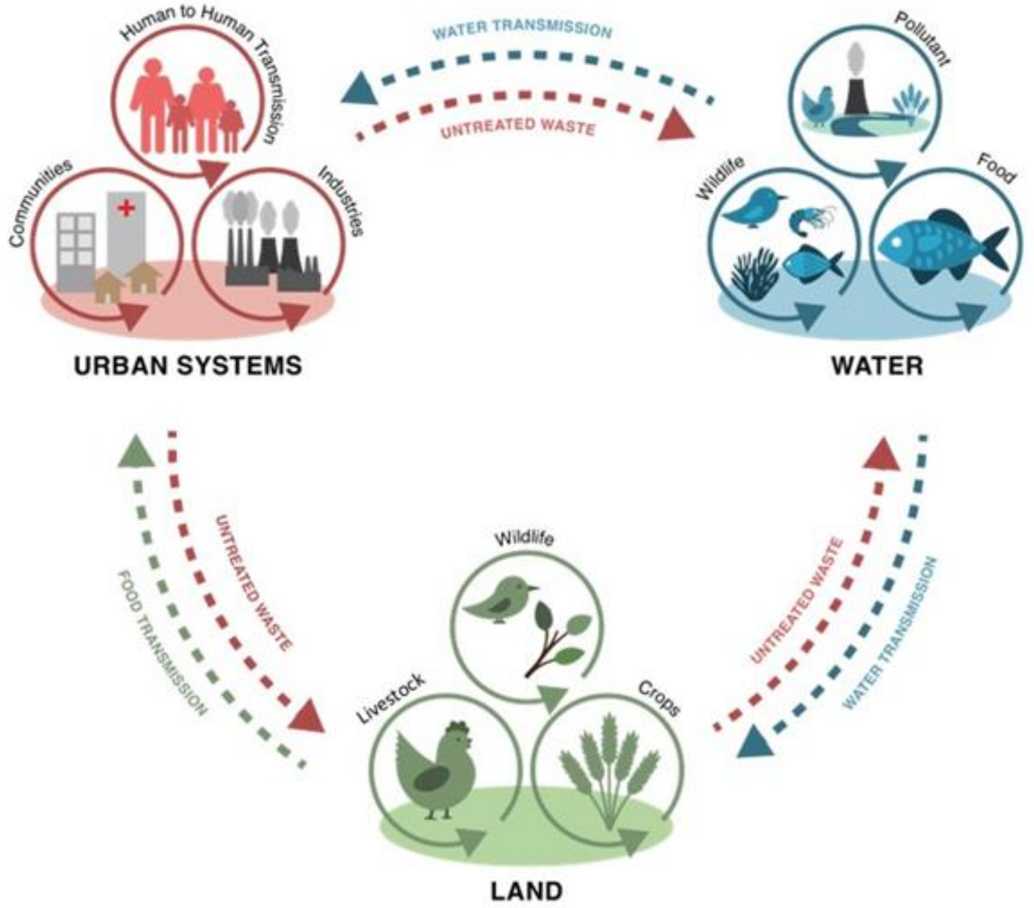

Figure 1. AMR sources and sinks are highly interconnected, often linked by environmental pathways (Graham et al. 2024).

These processes involve AMR pathogens, non-pathogenic microorganisms, the genes that encode and transmit resistance, and environmental constituents that can exacerbate the AMR problem (**Figure 2**). Clearly, exposures and infections by resistant pathogens are of greatest immediate health concern but continued inappropriate antibiotic use and inadequate pollution prevention have expanded the microbial and resistance gene pools across natural environments, increasing the likelihood of even more untreatable, resistant pathogens emerging within the microbial world.

Water readily moves and bridges all components of the One Health spectrum, as it is essential to all life. Reducing antimicrobial use, controlling water pollution, and improving water quality are therefore central to all solutions that aspire to mitigate AMR (Jampani et al. 2022). In India, the discharge of inadequately treated waste and wastewater into waterways is the major source of waterborne AMR. India treats only 28% of its urban wastewater, while a staggering 72% flows untreated into water bodies (CPCB 2024), resulting in massive amounts of resistant organisms and resistance genes entering the environment.

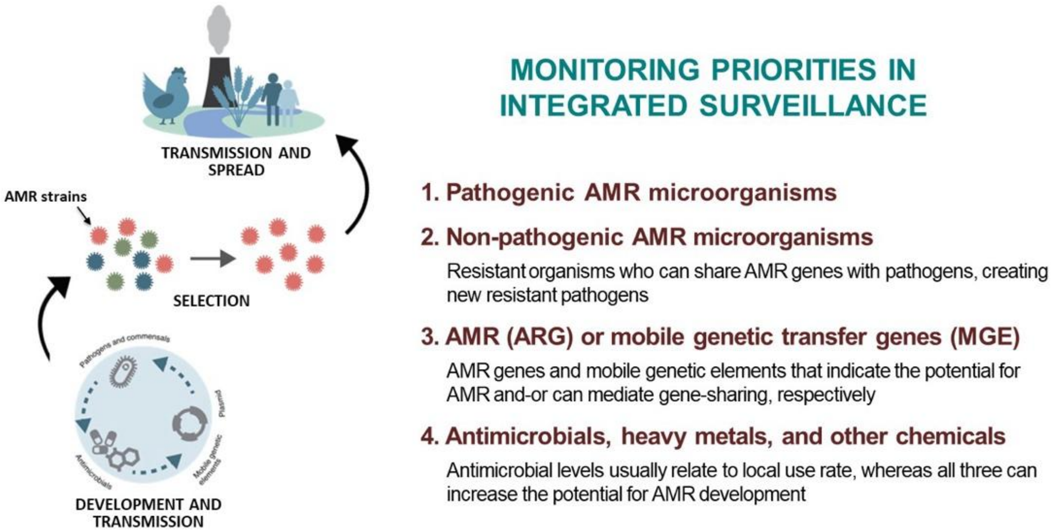

Figure 2. How AMR is developed and selected, and monitoring priorities in order of importance, in integrated surveillance studies aimed at reducing the transmission and waterborne spread of AMR (Graham et al. 2024).

Further, India is among the world's largest producers of antibiotics, accounting for 80% of the global supply (Gandra et al. 2017), which in turn influences the local use, resistance development, and environmental impacts. For example, depending on the antibiotics, about 30–90% of antibiotics consumed by humans are excreted in their active form, entering waterways through untreated discharges resulting from community waste releases. Similarly, 90% of antibiotics administered to animals are excreted in their active form, ultimately reaching water bodies through surface runoff (Gandra et al. 2017). Inappropriate disposal of expired and unused drugs/ antibiotics in urban drains (nallahs), along with other household waste, also finds its way into waterbodies. **A recent study estimated that 80% length of India's rivers (677 *10^3 km) falls under the high to very high environmental risk category due to antibiotic pollution (Figure 3), posing health risk to 315 million people in the country (Macedo et al. 2025)**. In Delhi, wastewater from farms containing antibiotic-laden animal manures and unused antibiotics often finds its way into the Yamuna River system. This contaminated river water is also used for irrigation in the agricultural fields, potentially contaminating the food crops with resistant bacteria or their residues (SAP-CARD 2020).

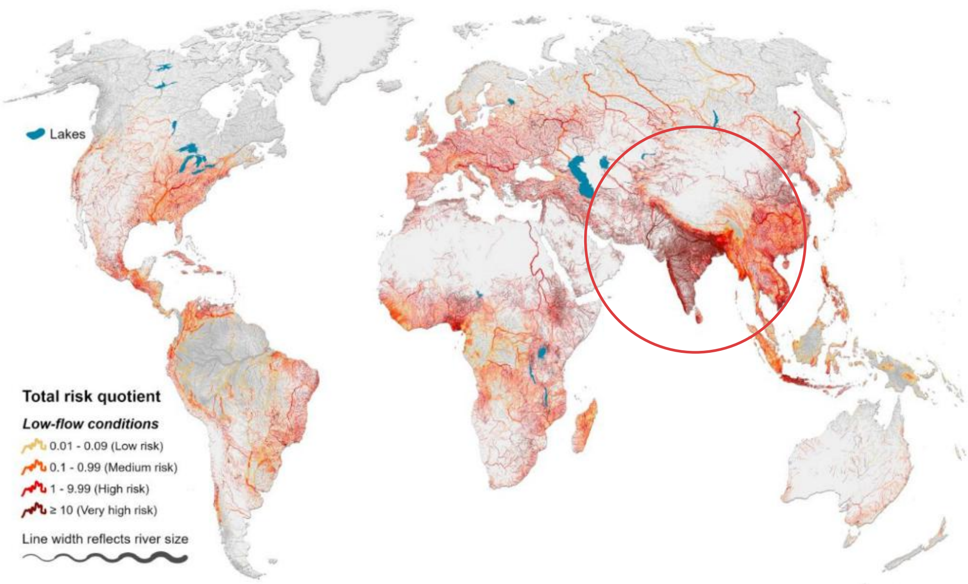

Figure 3. Environmental exposure levels of antibiotics in global rivers; high risk in Indian rivers (Macedo et al. 2025).

Consequently, waterborne antimicrobial-resistant bacteria (ARB), including *Escherichia coli, Klebsiella* species, *Salmonella* species, and antimicrobial resistance genes (ARG) such as ***bla***$_{NDM-1}$, ***bla***$_{OXA-48}$ and ***mcr-1*** are easily found in river and groundwater bodies receiving untreated sewage in India (Gandra et al. 2017), including among the most sacred sites in the country (Ahammad et al. 2014). Elevated levels of waterborne resistant bacteria, particularly those resistant to broad-spectrum antibiotics such as cephalosporins, have been found in major Indian rivers, including the Yamuna and Ganga in the north and the Cauvery in the south (Akiba et al. 2015). In 2013–2014, 40% (169 out of 446) of *E. coli* isolates from rivers in five Indian states were resistant to extended-spectrum cephalosporins (Akiba et al. 2015). In the state of Bihar, India, sulfonamide resistance genes were found in both deep groundwater and surface water, including the sacred Ganges River, where wastewater from urban drains containing hospital wastes and domestic wastes was considered as the major source of contamination (Wilson et al. 2024).

Because of all these integrated factors, India faces among the highest risks of waterborne AMR in the world (**Figure 4**), and urgent integrated action is needed in the country. To address this threat, a multisectoral and integrated One Health approach is essential to enhance surveillance and prevent the spread of AMR through water and waterways.

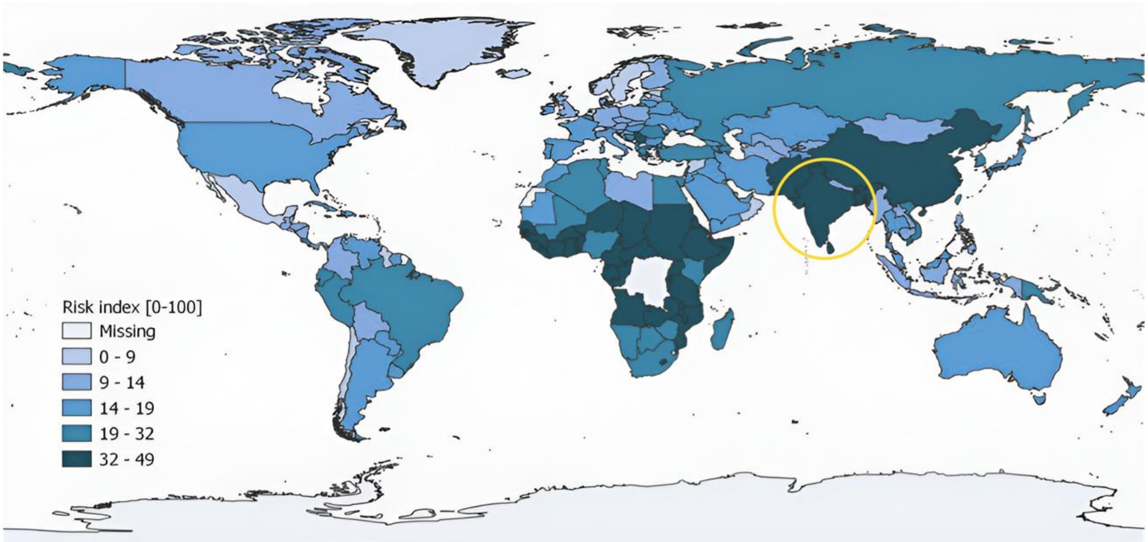

Figure 4. Predicted waterborne AMR exposure risk around the world in 2030. India is among the countries with the highest risk. Adapted from the World Economic Forum (WEF 2021).

3. What has been done to tackle waterborne AMR in India? Initial One Health steps

India has initiated several crucial steps to combat AMR, increasingly recognizing its One Health dimensions, though with varying degrees of integration for waterborne AMR:

- **Wastewater and waste management programs:** India's wastewater and waste management efforts are primarily spearheaded by the Swachh Bharat Abhiyan (SBM), launched in 2014. This extensive campaign focuses on achieving open defecation-free status and progressively moving towards advanced sanitation and waste processing. The Solid Waste Management Rules, 2016, provide a regulatory framework for handling municipal solid waste. Additionally, programs such as the National River Conservation Plan (NRCP) and the Namami Gange Programme specifically target river pollution through the development of Sewage Treatment Plants (STPs) and sewerage infrastructure. The Atal Mission for Rejuvenation and Urban Transformation (AMRUT) also supports urban wastewater management, while the GOBAR-Dhan Scheme launched in 2018 promotes converting organic waste into useful resources like biogas and organic compost. While waste and wastewater management are essential to prevent the spread and transmission of waterborne AMR, inadequate wastewater treatment and waste disposal are still major challenges.

- **National Action Plan on AMR (NAP-AMR)** within a Global One Health Context: Developed in alignment with the Global Action Plan on AMR (GAP-AMR), India's NAP-AMR (2017-2021) outlined six priority areas. While not explicitly detailed for water, its overarching goals, like "Strengthening Surveillance" and "Optimizing Antimicrobial Use" implicitly touch upon One Health aspects, aiming to reduce the overall AMR burden that would eventually lessen environmental release. Current efforts to develop NAP-AMR-2.0 specifically aim to incorporate identified gaps under the broader One Health umbrella, signaling a more explicit integration of environmental pathways.

- **National One Health Mission (NOHM)** India launched the National One Health Mission (NOHM) in 2022 to tackle human, animal and environmental health in a holistic way with a focus on the rising antimicrobial resistance (AMR) and other zoonotic diseases (OPSA 2024). NOHM brings together government ministries, academic institutions, NGOs, and industry partners to build an integrated disease control system spanning human, animal, and plant health sectors. Its three primary goals are: establishing a unified disease surveillance system, implementing environmental monitoring, and developing a strong outbreak investigation mechanism. Despite the involvement of 13 government agencies in launching NOHM, the Ministry of Jal Shakti (Department of Water Resources, River Development, and Ganga Rejuvenation) still needs to be recognized as one of the stakeholders. This is a significant oversight, as the ministry is responsible for water resources and water bodies in India and is well-positioned to lead waterborne AMR surveillance. Waterborne AMR is fundamentally a water quality issue. Reducing AMR transmission across One Health sectors requires a functional surveillance system in aquatic ecosystems (UNEP 2023).

- **National AMR surveillance network** (NARS-Net): Established in 2013 under the National Program on AMR Containment, NARS-Net monitors AMR magnitude and trends through medical college laboratories. It is recognized that the practice of self-medication and open accessibility of antibiotics is common in India (estimated to be >73% in humans and animals; Singh et al. 2024). Nevertheless, the lack of integrated and harmonized AMR surveillance data from across health, food safety, livestock, and environmental sectors makes it difficult to allocate responsibility for increasing AMR and develop appropriate technical and behavioral interventions across the sectors (Taneja and Sharma, 2019; NCDC 2024). As an example, there is no specific surveillance system for antibiotic residue or gene monitoring for rivers, lakes, and soils, except in states like Gujarat, where environmental surveillance includes surveillance of river water and sewage (Kaur et al. 2024; NAP-AMR 2017; Singh et al. 2024; Taneja & Sharma 2019). There is still also limited data on antimicrobial use in human and animal healthcare systems, which is yet a key driver of AMR occurrence in Indian waters.

- **State-level action plans with growing water emphasis**: Several states, including Kerala, Madhya Pradesh, New Delhi, Karnataka, Gujarat, and Telangana, have launched state-specific action plans, many explicitly incorporating a One Health approach (KARSAP 2018; MP-SAPCAR 2019; SAP-CARD 2020). Crucially, the action plans for New Delhi and Gujarat have directly integrated water-related aspects into their strategies for AMR spread and control, demonstrating a nascent recognition of the environmental component of One Health at the sub-national level.

- **New indigenous antibiotics in India:** The rapid emergence of resistance, coupled with financial and regulatory challenges, has reduced new antimicrobial development in the country. After three decades of research, the country has developed a new indigenous macrolide antibiotic known as Nafithromycin. Nafithromycin was launched in November 2024 to combat the multidrug-resistant pathogen, a step towards the fight against AMR. (MoST 2025). However, waterborne-AMR still needs to be addressed through research and development.

- **Regulatory efforts for antimicrobial use**: Regulatory measures like Schedule H and H1 policies, which mandate prescription-based sales, aim to optimize antimicrobial use in human health, thereby indirectly reducing the flow of active compounds into the environment. Schedule H involves the sale of the prescription-only drugs which cannot be sold without the doctor's prescription, it involves broad range of drugs including antibiotics listed in the Drugs and Cosmetic Rules 1945. Whereas schedule H1 policy is strictly controlling the over the counter sale of third and fourth generation antibiotics, psychotropic drugs including anti-TB drug The H1 drugs can only be sold by a pharmacist on producing a valid prescription from a registered medicine practitioner and doctors, also their records are maintained separately. However, strict enforcement and implementation of these regulations (Schedule H1 policy) are still required.

These initiatives represent India's foundational commitment to addressing AMR through a more integrated, One Health lens. However, as the subsequent section highlights, significant steps are still required to fully operationalize this approach, especially concerning the critical waterborne transmission pathways.

The main gaps in current Indian action that are preventing progress towards the control of waterborne AMR are summarized in **Figure 5**.

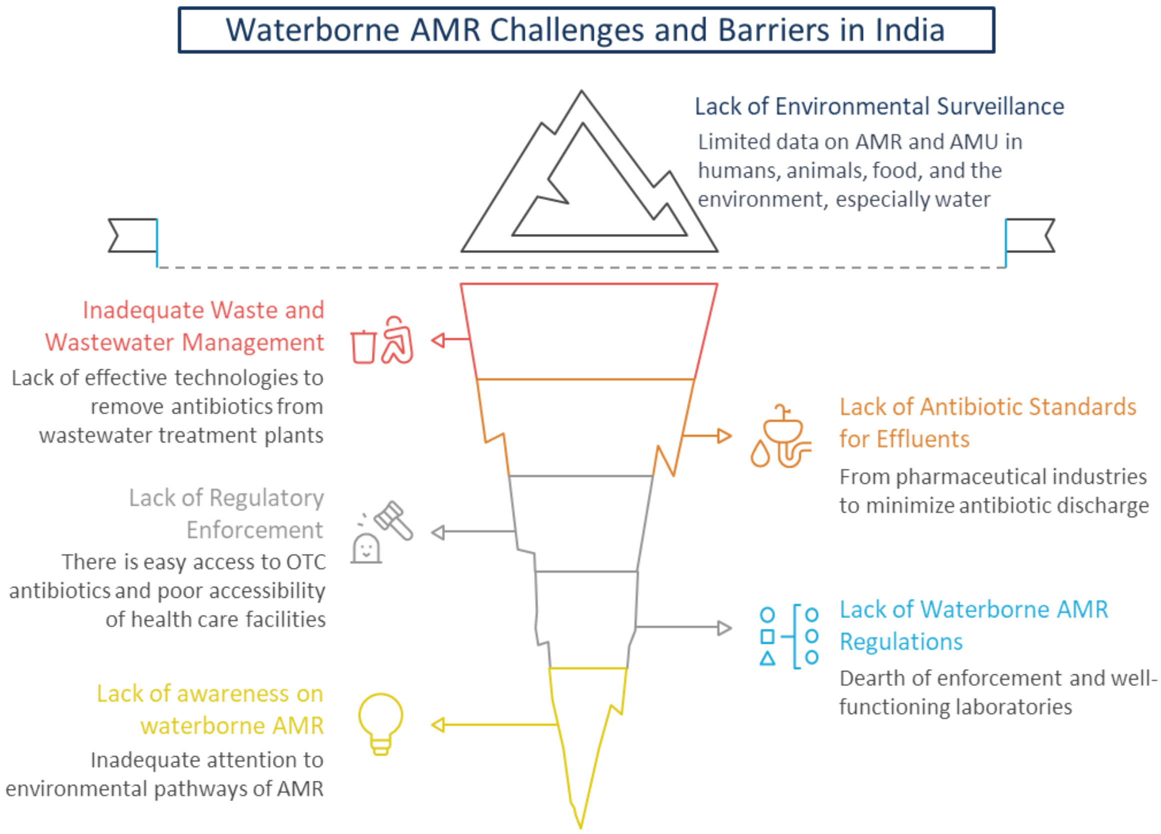

Figure 5. Gaps and challenges in preventing waterborne AMR transmission and spread in India. (IHME 2022; Kaur et al. 2024; NAP-AMR 2017; Singh et al. 2024)

4. What still could be done to tackle Waterborne AMR in India: Deepening the One Health Approach

India requires a series of multifaceted actions, such as inclusion of water and One Health in AMR policy measures, integrated multisectoral waterborne AMR surveillance, data archive for waterborne AMR, strict enforcement of the regulations and policies, technologies, and increased awareness of environmental AMR in the country. The proposed strategies are provided in **Table 1**.

Table 1: Short-term and long-term strategies for waterborne AMR containment (Water and Environment).

Indicators	Short-Term Strategies (<1 year)	Long-Term Strategies (>1 year to 5 years)
1. Policy & Schemes	• Recognize and champion water, environment, and One Health in national policies and action plans for AMR. Designate a technical committee and focal point for AMR in the environment and associated sectors to formulate and guide the action plan for waterborne AMR. • Ensure adequate budget allocation and annual performance assessment of the AMR action plan at the state level.	• Inclusion of the relevant water department in the National One Health Mission (NOHM) steering committee and operationalising environmental AMR surveillance that includes water systems. • Develop an ecosystem for multisectoral collaboration among relevant government agencies using a One Health approach.
2. Regulations & Implementation	• Implementing effective treatment and disposal of sewage and wastewater, aligning with the environmental standards, guidelines, and incentivising the best practices. • Strict regulations are needed to control and monitor the OTC use of antibiotics. • Implement a ban on the unsolicited use of antimicrobials as growth promoters in animal farms and animal feed products, aligning with WHO recommendations for targeted antimicrobials. • Incentivise farmers to reduce the environmental impact of intensive farming practices relying on antimicrobial usage.	• Improve infrastructure for safe access to water and sanitation in health care facilities. • Improving waste management practices in different sectors, including agriculture and aquaculture production/processing. • Improving safe disposal of unused antimicrobials and implementing Extended Producers Responsibility (EPR) for pharmaceutical waste management.
3. Surveillance & Monitoring	• Integrate environmental surveillance of AMR (soil and water) into the state surveillance network of every state using existing microbiology laboratories. • Establish a public and private network of AMR surveillance focusing on environmental pathways statewide. • Create an AMR database for key pathogens in the environment and use the surveillance data to identify local hotspots and critical control points for AMR and AMU, enabling targeted interventions. • Utilize waterborne AMR or microbial source tracking to identify various point and non-point sources of pollution and biobanking of the samples from the environmental compartments.	• Watershed-specific integrated AMR surveillance and modelling for AMR environmental pathways. • One Health surveillance to identify the key waterborne AMR pathogens across the human, animal, and environmental sectors (e.g., ESBL producing E-Coli). • State to develop water and environment-specific surveillance networks, including rivers, lakes, and aquifers, and share the data with the national surveillance network. • Ensure the collection of ARGs, ARB, AMU, AMC, and other quality data at the local level across all sectors contributing to the waterborne AMR and pollution.
4. Tools & Technologies	• Promote sustainable “best buy” technologies and best practices for water pollution control and health risk mitigation. Targeted interventions and	• Improve infrastructure for safe access to water and sanitation in health care facilities.

	nature-based solutions as a barrier for waterborne AMR dissemination. • Combining Artificial Intelligence (AI) and quick diagnostics with ecological and regulatory tools, to curtail the spread of AMR from environmental reservoirs. • Identify and target the key AMR organisms for prioritizing the reduction strategies.	• Upgrading wastewater or Sewage treatment technologies to remove antibiotics, AMR, and ARGs from wastewater. • Develop indicators to assess the drivers of waterborne AMR.
5. Investment & Fundings	• Support identified agencies and institutions focusing on environment and waterborne AMR research, and conduct innovative research. • Encourage public and private investments to curtail waterborne AMR.	• Ensure the sustained investment in strengthening microbiology laboratory infrastructure for environmental, veterinary, and human health, with advanced facilities, and quick diagnostics. • Encourage research funding and the One Health data archive on waterborne AMR.
6. Awareness Generation	• Community-level education regarding AMR and its impact on humans, animals, and the environment needs to be conducted effectively. • Promote the rational use of antimicrobials through antimicrobial stewardship activities and broadcast media across various sectors. • Improve awareness among patients and doctors regarding the guidelines and protocols for antibiotic use. • Sharing the best practices across the states. • Improve the awareness through schools, universities, and research activities. • Enhance awareness generation, capacity building, and policy measures	• Create an equitable partnership with the community for knowledge exchange through (a) communicating good practices & Science, and (b) adapting the local solutions generated by the community. • State to launch an antibiotic awareness campaign and antibiotic literacy program based on the One Health approach, introducing best practices of WASH, and antibiotic use and disposal. • Piloting the curriculum change in medical and nursing universities targeting the infection control and environmental pathways of AMR.
7. Capacity Building	• Improve stakeholder engagement and community participation for waterborne AMR surveillance and data sharing across sectors. • Waterborne AMR-specific training and capacity building of the relevant stakeholders and agencies, for surveillance, infection prevention and control in the environment.	• Training for healthcare providers in public and private sectors on AMR and AMU: Training of the Trainers. • Piloting integrated surveillance programs with local stakeholders in high-risk regions.

The following section provides a detailed discussion of various short-term and long-term strategies.

- **National One Health Mission steering committee to include key water stakeholders:**
  India's National One Health Mission (NOHM) includes water and AMR pathways within its "Sentinel Environmental Surveillance System". The environment component in NOHM is primarily led by the Ministry of Environment, Forest and Climate Change (MoEF&CC). In India, the planning, development, conservation, and management of water as a national resource falls under the purview of the Ministry of Jal Shakti/ Department of Drinking Water and Sanitation and the Department of Water Resources, River Development and Ganga Rejuvenation (MoJS). However, the department was not represented on the initial steering committee of the NOHM, which implies water engineering and existing environmental surveillance systems were not

represented in planned sentinel systems for AMR. It is proposed that MoJS and the concerned water department be included in the NOHM, whereas the environmental surveillance, including waterborne AMR, will be included in the Mission plan and the NAP against AMR in India.

- **Encourage Research Funding and National One Health Data Archive on Waterborne AMR:** Surveillance receives low research funding in India; waterborne AMR monitoring has been primarily performed in largely unconnected academic studies. Indian rivers have among the highest levels of antimicrobials in the world (Wilkinson et al. 2022), yet studies that link in situ waterborne antimicrobials, AMR genes, microbes, and their human or animal health consequences do not exist. This is partly because of limited cooperation from health care sectors, but also because no centralized One Health data archive exists for AMR in India, which is urgently needed. Therefore, greater centralized government initiatives are needed to harmonize and integrate studies, and greater domestic funding for academic studies that specifically integrate their monitoring results across sectors is required. Additionally, improving modelling of AMR transport and fate in water bodies is also crucial, as calibrated models can extrapolate predicted AMR to areas where no sampling data exists (Jampani et al. 2024).

- **Watershed-Specific Integrated AMR Surveillance and Modelling for AMR Environmental Pathways:** Valuable work related to surveillance and modelling in India is possible because it has massive technical capacity, but actions must include environmental factors, as recommended in UN guidance (UNEP 2023). Laxminarayan and Chaudhury (2016) suggest that over 50% of AMR infections in India may result from food or waterborne transmission.

  Watershed-specific integrated surveillance studies are needed in India to identify dominant AMR transmission pathways to guide national policy (OPSA 2024). The AMR surveillance network is established in several Indian states, including Kerala, Delhi, Tamil Nadu, Gujarat, Maharashtra, Rajasthan, Karnataka, Madhya Pradesh, Telangana, and Assam. Further to understand the role of water in the spread and transmission of AMR in Indian watersheds, modelling the fate and transport of AMR is essential (Jampani et al. 2024, Jampani et al. 2022). Mathematical and other simulation-based models can be used to evaluate the potential mitigation measures, identify point and non-point sources of pollution, predict the long-term health and economic risks associated with AMR, provide specific policy guidance, and inform priority interventions in the country at the watershed scale. By combining Artificial Intelligence (AI), quick diagnostics with ecological and regulatory tools, the spread of AMR from environmental reservoirs can be curtailed.

  The identification of critical control points enables targeted interventions, optimizing resource allocation and enhancing the effectiveness of AMR mitigation efforts at local, regional, and global scales. Point sources can be directly identified and tracked, including wastewater treatment plant outflows, pharmaceutical production discharges, and hospital effluents. Non-point sources, such as urban stormwater, animal manure application, and agricultural runoff, are diffuse and episodic, making them difficult to detect and manage. A strategic approach to identifying these sources involves integrated surveillance using microbial source tracking (MST) markers, metagenomic analysis, Antibiotic resistant bacteria (ARB) and antibiotic resistance gene (ARG) profiling across environmental matrices like water, soil, and sediments (Hendriksen et al. 2019; Ott et al. 2021). Next Generation Sequencing (NGS) and high-throughput PCR targeting resistance genes (e.g., bla, tet, sul) and mobile genetic elements (MGEs) can provide a link between pollution sources and specific anthropogenic activities or land uses. In India, advanced technical capacity exists for using most microbial culturing and genetic surveillance methods; however, this capacity tends to be based at centers of expertise and the National One Health Mission aspires to make such capacity universal across the country.

- **Champion Water and One Health in National Policies and Action Plans for AMR:** For AMR control, India has developed several regulatory measures, including the National policy on AMR containment (2011), National AMR surveillance Network (2013), and National action plan for containment of AMR and the Delhi declaration (2017). However, environmental factors such as waste management, water quality, and pollution, which were stated as important to AMR, were only minimally described in AMR policies, surveillance, and action plans. This could be attributed to the fact that water professionals and experts who plan and operationalize environmental monitoring were not adequately represented in the policy formulation and action plan development.

  Prevention of AMR at the point of use is critical, including better diagnostics and more informed antimicrobial use (AMU), as well as improving waste management and water quality. *One Health*, encompassing the environment, must be a cross-cutting approach. However, value from environmental monitoring will only be gained by integrating AMR monitoring with other One Health sectors (human and animal health systems), taking a holistic approach. The inclusion of experts on water and environmental AMR is urgently needed in future action plan development and its implementation, especially those involved with existing environmental monitoring programs (Mateo-Sagasta et al. 2024).

- **Promote Sustainable "Best Buy" Technologies and Best Practices for Water Pollution Control and Health Risk Mitigation:**
  Implementing prevention and containment measures across sectors using a One Health approach will progressively enhance environmental water quality, thereby reducing the broader spread of AMR. However, creating new technologies is not necessarily the best or only solution for reducing AMR in India. The World Health Organization (WHO) promotes the "best buy" principle in employing technological solutions, i.e., choosing the most appropriate technology for each location, rather than the most expensive (WHO/FAO/WOAH 2020).

  Decentralized fecal sludge management, waste treatment facilities, and wastewater treatment plants can be implemented to treat the wastewater from human settlements and livestock farms in densely populated countries like India. This approach encourages technologies that provide the optimal cost-benefit given existing conditions and available resources (Graham et al. 2019). This means that technology applications, such as for waste treatment, might be improved in small steps as more resources become available. AMR can consequently be reduced by simply implementing Water, Sanitation and Hygiene (WASH), i.e., improving water quality and managing fecal wastes, which can then be extended to include decentralized and full-scale waste treatment plants, which then must be operated correctly (Graham et al. 2024). Co-selecting and co-developing business models with the local stakeholders can facilitate the adoption of proven technologies to treat wastewater, solid waste from cities, livestock farms (Sathiskumar et al. 2024), and industries. It is also important to assess the risk downstream where the contaminated water from upstream is being used for various purposes (Yadav et al. 2019). **Figure 6** illustrates how AMR can spread in dysfunctional watersheds and pathways to transition to cleaner and safer watersheds.

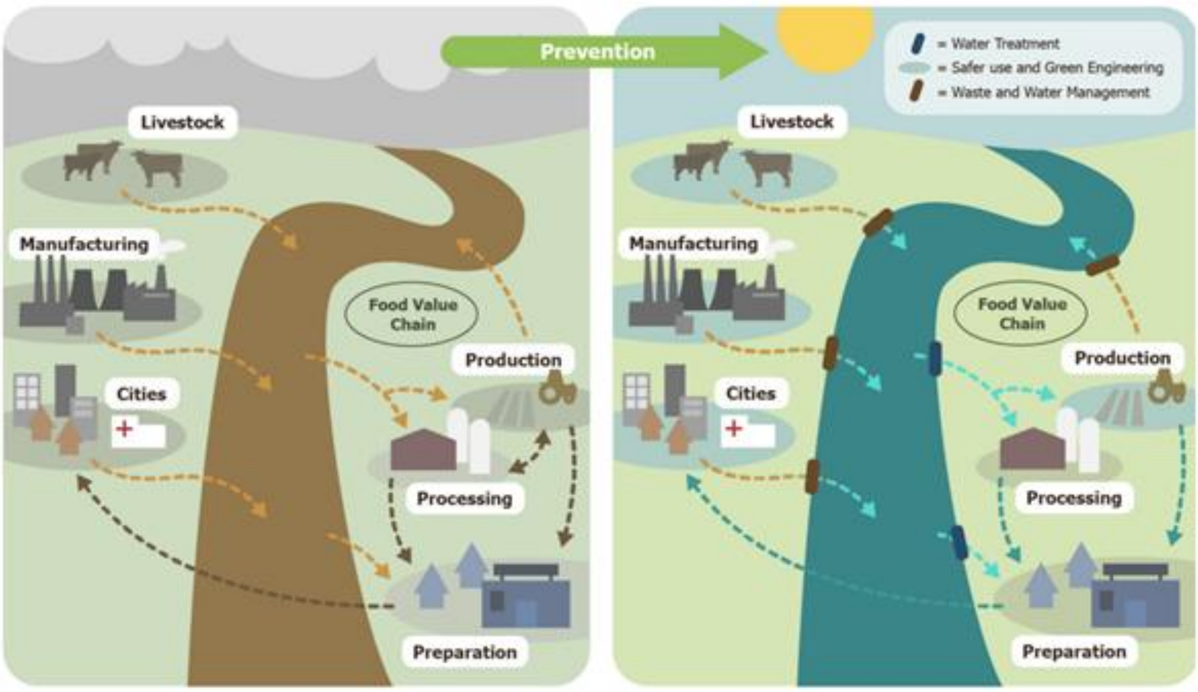

Figure 6. What a One Health approach to preventing AMR transmission and spread across the environment would look like in India. (Source: Graham et al. 2024).

- **Enhance Awareness Generation, Capacity Building and Policy Measures:**
  Greater awareness of the impact of waste releases into water courses, whether through direct discharges or runoff, is crucial. Community-level education regarding AMR and its impact on humans, animals, and the environment needs to be conducted effectively. Training for healthcare providers on AMU or piloting integrated surveillance programs in high-risk regions is essential. With public awareness campaigns and international collaboration, these measures can reduce the burden of AMR and safeguard public health, the environment, and economic stability. Importantly, the formulation of government, non-government and academic institutions for AMR information dissemination and outreach is essential.

  An enabling environment for the effective implementation of the AMR action plan and policy measures is crucial. Policy interventions like antibiotic stewardship programs in agriculture and environmental regulations on antibiotic disposal might also play an important role in curtailing waterborne AMR in India. Regulating the wastewater discharge from the pharmaceutical industries by setting the effluent discharge standards for antibiotics. Regular monitoring of the effluent for antimicrobial residue and appropriate legislative support to penalize the offenders. Hospitals and industries should be mandated to pre-treat effluents for antibiotics and other contaminants before discharge into water sinks. However, training does not only include techniques, but also educational initiatives and increased awareness campaigns of waterborne AMR and other environmental quality factors. Government awareness must be informed, for example, to trigger political action.

- **Targeted Interventions and Nature-Based Solutions as a Barrier for Waterborne AMR Dissemination**
  To tackle the waterborne AMR at the watershed scale, interventions should be targeted and source specific. For nonpoint sources, best management practices (BMPs) at the source, such as vegetative buffer strips, controlled manure application, and reasoned antibiotic use in livestock, can limit runoff and prevent the leaching of resistant bacteria into the environment. For point sources, upgrading wastewater or sewage treatment technologies to include advanced oxidation, membrane filtration, or UV disinfection can significantly reduce bio-contaminant loads, such as bacteria, viruses, and fungi.

  Nature-based Solutions (NbS) are sustainable and cost-effective interventions widely used as secondary and tertiary treatment systems at the source to reduce sediment, nutrients, and emerging contaminants such as antibiotics, AMR, and ARG entering the stream, lakes, and groundwater (Borsetto et al. 2025). Constructed wetlands as an NbS play a critical role in reducing the antibiotics and AMR load from both point and non-point sources of pollution in a watershed. Constructed wetlands are an engineering system that uses natural processes involving plants, substrates, and microbes to degrade a variety of pollutants from wastewater, thus reducing the overall contaminant load to the receiving water bodies (Yadav et al. 2024). Sabri et al. (2021) found the removal efficiency between 28% and 100% for 54 antibiotics, including sulphonamides, quinolones, and tetracyclines, from wastewater treatment plants using constructed wetlands. They also act as a nature-based barrier against the dissemination of AMR in river basins. It can potentially reduce pathogenic bacteria *E. coli resistant to last resort antibiotics such as colistin and carbapenems through adsorption, plant uptake, and microbial degradation in substrate (Borsetto et al.* 2025*).*

- **Identify and Target the Key AMR Organisms for Reduction Strategies:**
  In 2019, 1.27 million AMR-associated deaths were reported, among which 0.92 million died because of six pathogens: *E coli, Staphylococcus aureus, Klebsiella pneumoniae, Streptococcus pneumoniae, Acinetobacter baumannii,* and *Pseudomonas aeruginosa* (Murray et al. 2022). While *Staphylococcus aureus, Streptococcus pneumoniae,* and *Acinetobacter baumannii* can be detected in the aquatic environment, *Escherichia coli* (*E. coli*), *Klebsiella pneumonia*e, and *Pseudomonas aeruginosa are* primarily waterborne pathogens. Hospital-originated nosocomial transmission of these organisms can be limited through various prevention measures, such as judicious use of last resort antibiotics and the utilization of rapid diagnostic techniques. In parallel, infection prevention and control (IPC) measures—such as hand hygiene, surface disinfection, and patient isolation—are crucial in preventing nosocomial transmission, particularly of multidrug-resistant (MDR) and extensively drug-resistant (XDR) strains. Vaccination also plays a critical role; while pneumococcal vaccines are already effective in reducing *S. pneumoniae* infections, ongoing efforts aim to develop vaccines against other resistant waterborne pathogens such as *E. coli* and *K. pneumoniae*. Furthermore, alternative therapies, including bacteriophages, antimicrobial peptides, and probiotics, offer promising adjuncts, particularly for pathogens such as *A. baumannii* and *P. aeruginosa*, where treatment options are limited. The outcomes of these interventions are significant. A reduction in infection rates and antibiotic usage translates into decreased selection pressure, limiting the emergence and dissemination of resistance genes. Improved clinical outcomes, reduced healthcare costs, and preserved efficacy of existing antibiotics are direct benefits.

A success story for containment of AMR from Kerala is given in **Box 1**, indicating a successful multisectoral approach to curb AMR; however, the focus on the waterborne AMR and environmental pathways is limited.

Box 1. Success Story: Case Study for Containment of AMR in Kerala, India

Kerala was the first state in India to formulate the Kerala Antibiotic Resistance Strategic Action Plan (KARSAP), incorporating the One Health approach in 2018. The plan was initiated in 2013, led by a public private partnership (PPP), supported by professional bodies, and delivered through local initiatives, champions, nodal officers, and PPP representatives. It operates through block and district AMR committees. The objectives were achieved through seven years of stakeholders' engagement, both through formal and informal networks. Major steps taken by the state include the State government's initiative of good antibiotic prescription practice with PPP in most of the medical colleges and hospitals. The robust surveillance network includes 56 tertiary centers, 22 satellite labs, and 14 district AMR labs. The state task force engaged with the major stakeholders, 14 professional bodies of the state and societies. Sensitization workshops were conducted with public/private hospitals and medical colleges, emphasizing public engagement. AMR surveillance was established for the priority pathogens. Health organizations adopted the PPP identified state action plan. The curriculum of undergraduate, post-graduate, and trainees was revised as per the recommendation in collaboration with Kerala University of Health Sciences for antibiotic prescribing and infection prevention at all levels, focusing on state-wide education and training. Strategies were developed across the One Health spectrum, giving equal emphasis on human, animal, environment, and food safety sectors. Capacity building focuses on the practical and local solutions for AMR control. Furthermore, efforts were taken to implement and enforce the AMR laws and policy (KARSAP 2018; Singh et al. 2021).

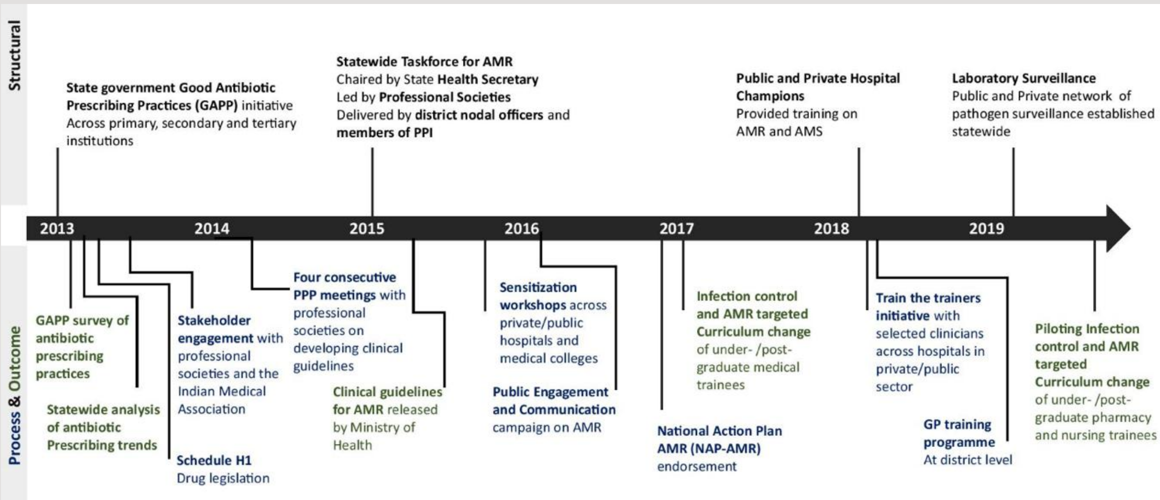

Figure: Box 1.1 Kerala roadmap to tackle antimicrobial resistance (Singh et al. 2021)

Conclusions

Waterborne Antimicrobial Resistance (AMR) is a growing threat in India posing serious health risks to human, livestock and environment. The country has the highest risk of waterborne AMR in the world with high risk of antibiotic pollution in the majority of Indian rivers. Overuse and misuse of antibiotics, together with inappropriate waste and wastewater management from various anthropogenic sources, exacerbated the spread and transmission of waterborne AMR in the country. The fragmented approach confined to human health is ineffective in dealing with the complex web of AMR transmission through water and environmental pathways. A multisectoral and multi-disciplinary One Health approach, which integrates human, animal, and environmental health, is essential to combat the spread and transmission of waterborne AMR holistically.

Multiple challenges and gaps were identified in the efforts towards tackling the AMR, specifically waterborne-AMR in the country, such as a lack of environmental surveillance focusing on water, lack of antibiotic standards for effluents, insufficient regulation for waterborne AMR, along with improper waste and wastewater management. The limited data on antimicrobial use in human and animal healthcare systems and their impact on the environment is one of the identified drivers of AMR occurrence in Indian waters. Dedicated programs and strategies are in place in the country such as the National Action Plan for AMR (NAP-AMR) and the National One Health Mission (NOHM). To transition from assessment to action, the role of concerned water departments and authorities needs to be recognized for a holistic approach to combat waterborne AMR through a **"One Health" approach**. This requires not only policy adjustments but also dedicated stakeholder engagement, financial allocation, and robust regulatory frameworks with stringent enforcement mechanisms.

To address the identified gaps, multi-pronged strategies at the local and national levels are suggested following One Health principle. Recognizing water and the One Health in national policies and action plans for AMR together with the inclusion of key water stakeholders in the National One Health Mission steering committee is important step for addressing identified policy gaps. Upgrading the wastewater treatment technology to remove antibiotics and AMR is required. Nature-based solutions (NBS) can act as a natural barrier to reduce the waterborne AMR dissemination in the environment. Furthermore, the establishment of a comprehensive surveillance system for environmental AMR is also paramount to address the data gap. The goal is to move beyond passive monitoring to proactive, watershed-scale interventions informed by real-time data. The waterborne AMR challenges in India demand a holistic and technologically informed strategy that addresses the problem at its environmental source. By implementing these recommendations, the country can build a robust system to curb the spread of waterborne AMR, and mitigate the health risk in humans, animals, and the environment.

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Glossary

Antibiotic Resistance Gene (ARG) – An antibiotic resistance gene (ARG) is a segment of DNA that encodes for traits that allow microorganisms to withstand the effects of specific antibiotics, reducing or eliminating the drugs' effectiveness in treating infections caused by those organisms.

Antimicrobial Resistance (AMR) – Antimicrobial resistance (AMR) develops when bacteria, viruses, fungi and parasites develop a resistance to the effects of antimicrobial drugs. AMR renders antibiotics and other antimicrobial medications ineffective, making infections challenging or even impossible to manage.

Antimicrobial Use (AMU) – Antimicrobial use (AMU) involves using medicines like antibiotics, antivirals, antifungals and antiparasitics to prevent and treat infections in humans, animals and plants. AMU also includes use for other purposes, such as growth promotion in food animal production.

Antimicrobials – Medications used to address infectious ailments across humans, animals and plants. They encompass a range of therapeutic agents, including antibiotics, antivirals, antifungals, and antiparasitics. Antibiotics are drugs specific to bacterial infections.

Best-buy Technologies – The most cost-effective and efficient technologies or solutions available in a particular resource context, emphasizing value for money and optimal performance.

Exposure Risk – Exposure risk is the probability that individuals or populations will encounter potential AMR microorganisms. Characterizing AMR exposures (ARGs and AMR microbes) identifies possible health risks that depend on the pathways of exposure. Not all exposures pose consequential health risks.

Gene – A gene is a segment of DNA that contains the instructions for building and maintaining living organisms. Genes serve as the basic units of heredity, carrying genetic information from one generation to the next, including resistance genes (ARGs) that can confer AMR in microorganisms.

Growth P-promoters – Growth promoters are substances or agents administered to enhance the growth and productivity of animals, often in the context of animal farming or agriculture. These can include antibiotics or other compounds that stimulate growth.

Health Risk – The health risk of AMR depends on the duration and concentration of exposures to AMR microorganisms and the pathways of exposure. Pathways range from direct ingestion to proximal exposures. The risk of acquiring AMR pathogens varies based on available pathways and local behavior.

Infrastructure – Physical resources and nonphysical systems that underpin civil existence, such as sewer lines, wastewater treatment plants, roads and other urban and rural systems.

Integrated AMR surveillance – This type of integrated surveillance is the coordinated monitoring and data collection on AMR organisms, genes, antimicrobial use, and metadata, spanning humans, animals and the environment. This approach recognizes the interconnectedness of health in these domains, aiming to provide a comprehensive understanding and address AMR collectively.

Microbial Culturing – Growing microorganisms present in clinical, veterinary and environmental samples on selective solid media. For AMR isolates, selective media contain antimicrobial agents to determine microbial susceptibility to those agents and their physical AMR traits. Sequencing of an organism's DNA can be used to determine the genetic basis of its observed resistance.

National Action Plans (NAPs) – NAPs are comprehensive strategies developed by governments to address growing challenges, such as AMR. AMR NAPs should outline coordinated efforts and policies involving healthcare, agriculture and other relevant sectors to promote responsible use of antimicrobials, enhance surveillance, raise awareness and implement measures to mitigate and control antimicrobial resistance at the national level.

One Health – One Health is an inclusive strategy that aims to harmonize and enhance the health of people, animals and the environment. It recognizes the interconnectedness of human health, animal health, plant health, and the broader environment, emphasizing that their interdependence must be considered in the overall well-being of all elements.

Pathogen – A pathogen is a microorganism, such as a bacterium, virus, fungus or parasite that causes disease or illness in its host organism.

Resources – Resources are essential elements needed for a system's operation. They encompass three groups: human resources, infrastructure and consumables. Human resources involve the skilled personnel needed for the system, while infrastructure includes the physical components like equipment and facilities. Consumables refer to the supplies required for ongoing activity.

Spread of AMR – The dissemination or proliferation of resistant microorganisms or genes across populations, environments or geographical regions. The spread of AMR extends local transmission events to wider scales and often results from contaminated food and water. Efforts to control and mitigate the spread of AMR often involve creating barriers that block AMR from migrating away from its point of development.

Transmission of AMR – The transfer of resistant microorganisms or genes between individuals, animals or environments. Transmission can occur through various means, such as direct contact, contaminated food and water, or the exchange of genetic material, leading to AMR spread. Understanding and controlling transmission pathways is key to managing and preventing the wider spread of AMR.

WASH – WASH, i.e., water, sanitation and hygiene, is a collective term for practices aimed at ensuring access to clean water, proper sanitation facilities and good hygiene practices. WASH programs address public health concerns by promoting safe water sources, adequate sanitation infrastructure, and hygiene education to prevent waterborne diseases and improve overall well-being.

Zoonotic Disease – A zoonotic disease is an infectious illness caused by pathogens, such as bacteria, viruses or parasites, that can be transmitted between animals and humans, posing a risk of disease transmission at the human-animal interface.


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