Why "improved" water sources are not always safe

Ameer Shaheed,[a] Jennifer Orgill,[b] Maggie A Montgomery,[c] Marc A Jeuland[b] & Joe Brown[d]

Abstract Existing and proposed metrics for household drinking-water services are intended to measure the availability, safety and accessibility of water sources. However, these attributes can be highly variable over time and space and this variation complicates the task of creating and implementing simple and scalable metrics. In this paper, we highlight those factors – especially those that relate to so-called improved water sources – that contribute to variability in water safety but may not be generally recognized as important by non-experts. Problems in the provision of water in adequate quantities and of adequate quality – interrelated problems that are often influenced by human behaviour – may contribute to an increased risk of poor health. Such risk may be masked by global water metrics that indicate that we are on the way to meeting the world's drinking-water needs. Given the complexity of the topic and current knowledge gaps, international metrics for access to drinking water should be interpreted with great caution. We need further targeted research on the health impacts associated with improvements in drinking-water supplies.

Abstracts in عربي, 中文, Français, Русский and Español at the end of each article.

Introduction

Although all of the world's population has access to water, in many places the water that is available is often not safe, sufficiently affordable or available in adequate quantities to meet basic health needs. In 2010, the United Nations General Assembly declared "safe and clean drinking water and sanitation as a human right that is essential for the full enjoyment of life and all human rights".[1] The General Assembly explicitly called for actions leading to the provision of "safe, clean, accessible and affordable drinking water and sanitation for all".[1] This recognition of access to safe water as a human right came at the mid-point of the International Decade for Action "Water for Life".[2] This Decade, which began in 2005, was intended to generate momentum in meeting various international water and sanitation targets. The aim of one such target, Millennium Development Goal (MDG) target 7c, was to halve – from the value for the year 1990 – the proportion of people without sustainable access to safe drinking water by 2015.[2]

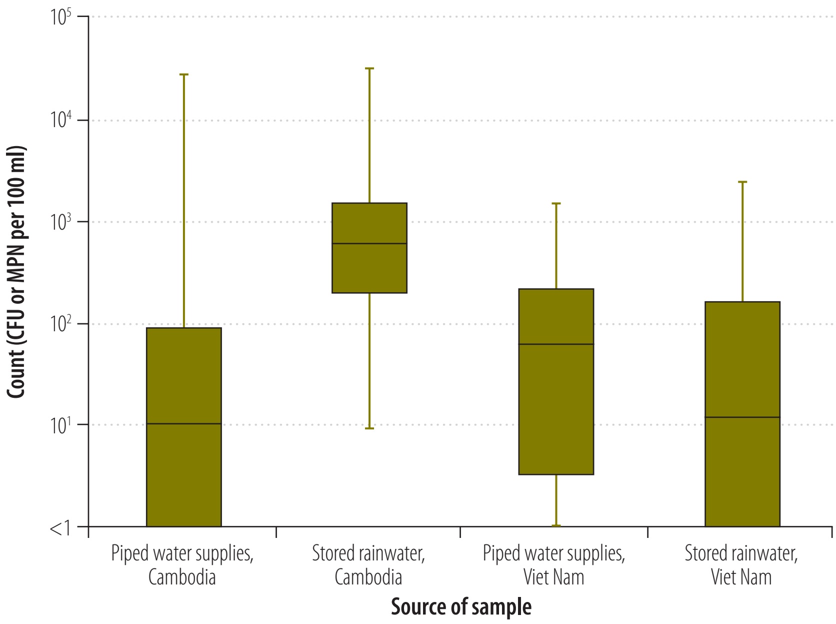
The World Health Organization/United Nations Children's Fund Joint Monitoring Programme for Water Supply and Sanitation (JMP) is charged with tracking progress in meeting global targets set for water and sanitation coverage, including the relevant MDGs. The JMP's current metrics are useful tools for those who are attempting to examine, encourage and direct national and global progress in access to safe drinking water and adequate sanitation. In its *Progress on drinking-water and sanitation: 2012 update*, the JMP indicated that MDG target 7c had been met in 2010, when an estimated 89% of the world's population had access to "improved" water sources.[2] Despite this encouraging claim, significant challenges remain in ensuring that safe water is consistently accessible to all.[3,4] Current JMP metrics do not directly measure two explicit goals of MDG target 7c – water safety and water sustainability – partly because there is no consensus on the definitions and measurement of these concepts. Recently, the JMP has assigned a Post 2015 Water Monitoring Working Group to draft new measures for post-2015 monitoring. Key outputs from this Group's work are available on line.[5]

The "service-ladder" approach to water monitoring after 2015[5] is intended to be realistic, achievable, ambitious and compatible with previous targets and metrics. In this approach, the proposed post-2015 metrics for water access will take account of both "basic" and "intermediate" levels of access. A household with basic access has no water service within the household, but a household member can reach a water supply, queue for water, if necessary, and return with water within 30 minutes. A household with intermediate access has an "on-premises" or "on-plot" water service that fails, on average, for less than 2 days in every fortnight and supplies water that has less than 10 colony-forming units of *Escherichia coli* per 100 ml.[6] The latter definition incorporates metrics for safety and reliability that were not included in the pre-2015 standard metrics for water access. Practical considerations related to the frequency and methods of testing and to who should perform the tests have not yet been decided and the metrics themselves have not been finalized.

The proposed service-ladder approach is meant to be consistent with the progressive realization of the human right to safe water. It is designed to encourage incremental gains, extend them beyond households to schools and health facilities and promote equitable access. In developing new metrics, the members of the Post 2015 Water Monitoring Working Group made a compromise between what is ideal in terms of water quality and service reliability and what is practically achievable and measurable.[6] By incorporating measures of reliability, quality and accessibility into the proposed post-2015 framework, future monitoring methods could lead to a more sophisticated understanding of the progress being made towards meeting the world's needs for safe drinking water. The same framework may also allow for a more accurate assessment of the changes in health risks that are associated with such progress.

[a] Department of Disease Control, London School of Hygiene & Tropical Medicine, London, England.
[b] Sanford School of Public Policy, Duke University, Durham, United States of America (USA).
[c] Water, Sanitation and Health Unit, World Health Organization, Geneva, Switzerland.
[d] School of Civil and Environmental Engineering, Georgia Institute of Technology, Mason Building, 790 Atlantic Drive, Atlanta, GA 30332-0355, USA.
Correspondence to Joe Brown (email: joe.brown@ce.gatech.edu).
(*Submitted: 18 February 2013 – Revised version received: 26 November 2013 – Accepted: 28 November 2013 – Published online: 10 January 2014*)

Fig. 1. ***Escherichia coli* counts in water samples from "improved" sources, Cambodia and Viet Nam**



CFU, colony-forming units; MPN, most probable number.
Note: The data are presented as "box-and-whisker" plots. The bottom and top of each box indicate the 25th and 75th percentiles, with the height of the box therefore indicating the interquartile range. The line dissecting the box is the median value. The "whiskers" indicate the range of values.
Piped water ($n = 142$) and rainwater supplies ($n = 1166$) in Cambodia were studied in 2011[7] and 2006,[8] respectively, while the piped water ($n = 553$) and rainwater supplies ($n = 126$) from Viet Nam were all investigated in 2009.[9,10] In each case, the piped water supplies were on-plot and the rainwater samples came from dedicated rainwater-storage containers.

Our work on the microbial quality of "improved" drinking-water sources in south-eastern Asia (Fig. 1)[7–10] and other related research[11,12] show that the current definition of "improved" does not reliably predict microbial safety – a fact that is widely acknowledged in the water sector. In this paper, we briefly discuss three interrelated factors that contribute to the sources of microbiological risk among households with access to "improved" water sources: water storage; risks specific to piped water supplies; and household water management practices. A critical examination of these factors reveals key priorities for further research on drinking-water safety and health. Most importantly, it indicates the need to place greater emphasis on the provision of microbiologically safe water at both community and household levels.

Water safety compromised by storage

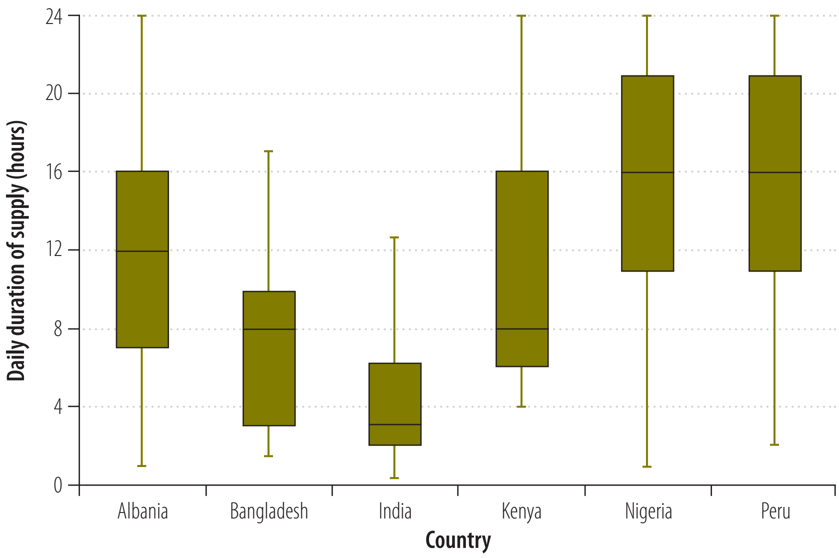
Water must be available throughout the day to meet basic health needs for drinking, cooking and hygiene. A quantity of approximately 50 litres per person per day is recommended to minimize the health risks associated with poor hygiene.[13] For those using "improved sources" other than on-plot piped water, such as protected wells, springs, public standpipes or stored rainwater, water collection and storage are typically required. Where on-plot piped water is intermittent, storage may still be required. In 2010, over 40% of the world's population – including many users of "improved" sources – fetched water from outside the home.[2] The distance to the water source used by a household has been found to be a robust independent predictor of disease risk in that household.[14] In most countries, the burden of water collection is primarily borne by women and children and that burden is associated with a loss of household productivity, reduced school attendance and physical injury, particularly when water has to be carried over long distances.[15]

If properly protected from the reintroduction of microbes, stored water will generally improve in microbial quality because of the settling and natural die-off of pathogens. Safe storage can therefore maintain or even improve the quality of drinking water and thereby reduce exposure to waterborne pathogens even without other treatment. Often, however, water is stored in open containers where it may be exposed to faecally contaminated hands, utensils and insects. There is a close relationship between hygiene, water safety and health, yet the dynamics of this relationship are not well understood. In several studies, unsafe water storage and water handling practices have been associated with elevated counts of "faecal indicator" bacteria in water collected at the point of consumption.[16–18] The health risks associated with water storage have been investigated in studies that have relied primarily on simple counts of *E. coli* – or of coliform bacteria in general – to evaluate water quality. In our study of the quality of household water from "improved" sources in Cambodia, we observed substantial and statistically significant contamination of drinking water during storage.[19] Arithmetic mean counts of *E. coli* in stored household tap water were significantly higher than those in samples taken directly from the tap.[19]

Despite a wealth of evidence indicating that safe storage of water lowers the risk of exposure to waterborne microbes associated with diarrhoea, there have been few epidemiological studies of safe water storage with health measures as outcomes. While several trials of household water treatment have included interventions that included safe storage,[20,21] only two published unblinded studies have attempted to measure a reduction in diarrhoea as the result of safe storage alone.[22,23] In one of these, Günther and Schipper found that improved methods of water storage were associated with both a reduction in detectable *E. coli* in the water and a significantly lower risk of self-reported diarrhoea.[22] In the other study, which was based in a refugee camp in Malawi, Roberts et al. found that, compared with the other households in the camp, households with an improved water-storage container had 69% lower mean counts of coliform bacteria in their stored water and a 31% lower incidence of reported diarrhoea among children aged less than 5 years.[23] In another investigation, unsafe storage of water in the home was thought to have contributed to high prevalences of dengue and chikungunya fever.[24] Both of these diseases are caused by viruses

Bull World Health Organ 2014;92:283–289 | doi: http://dx.doi.org/10.2471/BLT.13.119594

Fig. 2. **Intermittency in piped water supplies in six countries**



Note: The data are presented as "box-and-whisker" plots. The bottom and top of each box indicate the 25th and 75th percentiles, with the height of the box therefore indicating the interquartile range. The line dissecting the box is the median value. The "whiskers" indicate the range of values.
The data presented are for the latest year reported by each supplier to the International Benchmarking Network for Water and Sanitation Utilities and come from that Network's web site.[27] These data were provided by 65 suppliers in Albania, 43 in Bangladesh, 32 in India, 62 in Kenya, 43 in Nigeria and 48 in Peru – for a year between 2006 and 2011, a year between 2010 and 2012, a year between 2005 and 2009, 2010, a year between 2004 and 2011, and a year between 2007 and 2008, respectively.

that are spread by *Aedes aegypti* and this species of mosquito often oviposits in uncovered domestic containers used to store water.

Unsafe piped water

A piped-to-plot water supply was available to an estimated 54% of the world's population in 2010.[2] The proposed post-2015 metrics include criteria for reliability and quality for a good reason: many existing piped water supplies do not consistently supply microbiologically safe water. Although piped water at the point of delivery can only be as safe as the water entering the system, this fact is not considered in current indicators of access to safe water. Some water suppliers, such as the small private suppliers common across Cambodia, simply pipe untreated or minimally treated water from high-risk sources.[25,26] According to current definitions, the water leaving these suppliers' pipes can still be considered as coming from an "improved" source. More common, however, than the lack of adequate centralized treatment, are water supplies that are intermittent or marked by a range of other challenges related to operation and maintenance, with implications for health.

Although country-level data on the intermittency of water services are limited, estimates from utility surveys indicate that such intermittency is widespread across many countries (Fig. 2).[28,29] Some supplies, like those that we studied in Cambodia, operate not only intermittently but also seasonally. So many households switch to rainwater during the rainy season that piped delivery becomes unprofitable for the water suppliers. Other systems may be intermittent because of the need for frequent repair and maintenance.[30] There may also be pump failures and electrical outages or there may be intentional rationing when capacity is insufficient for a continuous supply. Systems that operate intermittently are unlikely to deliver safe water to users consistently. As leaks in buried water pipes are unavoidable, even with active programmes of maintenance and repair, the safety of a piped water supply relies heavily on maintaining positive pressure within the pipes to prevent the infiltration of environmental waters. When supply is intermittent, positive pressure cannot be maintained and water from outside the pipes – which is often highly contaminated, especially where sanitary improvements are lacking – may then contaminate the piped supply and cause health risks. In addition, consumers who have only intermittent access to piped water have to rely on household-level storage to meet their demand for water whenever the supply is interrupted.

Numerous studies have linked outbreaks of cholera and other waterborne diseases to interruptions in water supplies.[31,32] The microbial risks associated with intermittent water supplies have also received some attention[28,33–35] but there seem to have been no prospective studies in which the health outcomes of populations with access to intermittent supplies have been compared with those of populations with continuous supplies. Such studies would enable a better evaluation and identification of the risks associated with piped water systems that do not function well. As so many water-safety issues are linked with infrastructure function,[36,37] safety and sustainability cannot be meaningfully considered as separate issues.

Access not a guarantee of consistent use

Regrettably, the availability of and access to low-risk water sources do not guarantee the consistent use of such sources over sustained periods. There is substantial heterogeneity and complexity in water-related behaviours among users of the variable and multiple sources that are the norm in many locations. For example, in Kandal province in Cambodia – where water is plentiful and access to "improved" water sources is common – we observed tremendous complexity in household water management.[19] There were multiple water sources in use at any given time and the sources in use varied according to the season and whether the water was needed for drinking, cooking, hygiene or laundry.[19] Some households that had a piped water supply or access to a nearby well preferred to use stored rainwater for drinking. When their piped supplies were interrupted during the dry season, some households purchased untreated river water from tanker trucks. Such sourcing decisions are driven by convenience, perceptions of safety, aesthetic concerns – such as taste and smell – and a host of other factors. They may also lead to mixing of water from different sources. In our study of 914 Cambodian households, three quarters of the containers that held piped water also contained water from other sources; at least 20% of the containers of each of the main types that we considered contained water from at least two sources; and many containers held water from both "improved" and "unimproved" sources.[19] Each of the sources and types of storage container that we investigated carried its own risk factors for microbial contamination. Households' perceptions of the relative safety of a source were also found to be uncorrelated with the level of microbial contamination of water from that source.[7] Similar use and mixing of water from multiple sources appear to be common in many other areas.[38,39] Hence, the creation of the infrastructure needed to deliver safe water does not always result in safe drinking water for consumers at the point of consumption. The use of multiple sources of water also complicates efforts to quantify the proportion of households with access to safe water.

A better understanding of the complex behavioural factors surrounding the ways in which water is sourced and handled at the household level, as well as a better understanding of hygiene- and sanitation-related behaviours at the same level, could help inform future interventions to promote optimal water use.[40,41] It remains possible that interventions to promote increased access to safe water may lead to compensating behaviours, such as reduced in-house water treatment or a degradation in general hygiene, that diminish the effectiveness of the interventions. The phenomenon of "prevalence elasticity" – in which the beneficiaries of health interventions reduce their investment in self-protection – has been widely discussed among health economists but scarcely considered by the water sector.[42]

Discussion

The discussion over the JMP's current definitions of "improved" and "unimproved" water sources and the process of revising those definitions for use in post-2015 assessments have been useful in highlighting several important unknowns. Among the most important of these is the question of whether people obtain meaningful reductions in their health risks when they gain access to so-called "improved" sources, such as stored rainwater, protected wells and springs, public standpipe or on-plot piped water supplies. On-plot piped supplies theoretically remove the need for both water collection and in-house water storage and may allow consumption of increased volumes of water and improvements in hygiene and provide other health and non-health benefits. It has been generally assumed that water delivered to a household through a pipe will be of higher microbiological quality than water from other sources and that piped supplies will be reliable enough to remove the need for the domestic storage of water. For many households with piped water supplies, these assumptions have proved to be incorrect. The larger question for the public health community seems to be "how good does a water source have to be to interrupt endemic transmission of the pathogens that cause diarrhoeal disease and to prevent major outbreaks of such disease?" Although the end goal remains a piped water supply that is uninterrupted and safe for every household, millions of households are unlikely to obtain such a supply for several decades.[43]

The authors of *The Lancet*'s Global Burden of Disease series[44] recently conducted an updated review of experimental and quasi-experimental epidemiological studies in which the effect of water- or sanitation-related interventions on the risk of diarrhoeal disease were investigated. The authors found that, compared with the risk associated with other "improved" sources of water, disease risk was not significantly reduced by access to an on-plot piped supply of water or by any interventions to improve water quality. In a subsequent analysis, the disease burden attributable to inadequacies in water supply and sanitation was assumed to apply only to those without access to an "improved" source – as defined by the JMP – and no attempt was made to quantify the effects of personal hygiene. The analysis appeared to reveal that the water- and sanitation-attributable burden had fallen to 0.9% of the global burden of disease in 2010, which was less than the corresponding values recorded in 1990 (6.8%) and 2000 (3.7%).[45] Leaving aside several other issues that have been raised in response to this analysis,[46] the analysts assumed that there are no positive health benefits of a safe, on-plot water supply over and above those associated with other "improved" sources. This assumption highlights the poor quality of the epidemiological evidence base for water, sanitation and hygiene, which is a problem that Lim et al. emphasized in qualifying their analysis.[44] It also raises the question of whether all "improved" water supplies are microbiologically safe. Even a superficial look at the state of the world's water delivery infrastructure would indicate that such a conclusion is invalid. Even piped-to-plot drinking water may originate from an unsafe or untreated source, may be supplied only intermittently and therefore be susceptible to contamination, and may be stored unsafely once collected.

Unfortunately, there is a dearth of epidemiological evidence on the benefits associated with safer water in low-income settings,[47] where routes of exposure are rarely through drinking water only, current indicators of microbial quality are imprecise measures of risk, most commonly used measures of health outcomes are subjective and experimental and blinded studies are difficult to implement. Although there is a growing body of evidence on the health and non-health advantages offered by on-plot access to consistently treated water,[9,48,49] the sustainable scaling up of access remains a major challenge. The results of recent studies indicate that the consistency of access to water of high quality may be central to delivering health benefits,[50] since such benefits can be compromised by just a few days of consuming higher-risk water or even by modest reductions in adherence to interventions that have been designed to improve water quality.[34,51] Improved epidemiological and risk assessment studies that account for the complex, dynamic, human and environmental factors that influence microbial water quality would provide further insight into the importance of drinking-water safety to public health in "real-world" – and especially low-income – settings. ■

Competing interests: None declared.

ملخص

لماذا لا تعتبر مصادر المياه "المحسنة" مأمونة دائماً

يتمثل الغرض من القياسات القائمة والمقترحة لخدمات مياه الشرب المنزلية في قياس توفر مصادر المياه ومأمونيتها وإمكانية الوصول إليها. ومع ذلك، من الممكن أن تكون السمات شديدة التغاير بمرور الوقت واختلاف المكان، ويعقد هذا التغاير من مهمة إنشاء وتنفيذ قياسات بسيطة وقابلة للتطوير. و نسلط الضوء في هذا البحث على تلك العوامل – خاصة تلك المتعلقة بما يطلق عليه مصادر المياه المحسنة – التي تسهم في قابلية التغير في مأمونية المياه ولكن قد لا يتم الاعتراف بأهميتها بشكل عام من قبل غير الخبراء. وقد تسهم المشكلات المتعلقة بتوفير المياه بكميات كافية وبجودة كافية – وهي مشكلات مترابطة وغالباً ما تتأثر بالسلوك البشري – في ازدياد مخاطر تردي الوضع الصحي. وقد يتم حجب هذه المخاطر بقياسات المياه العالمية التي توضح أننا في طريقنا لتلبية احتياجات مياه الشرب العالمية. وبالنظر إلى تعقد الموضوع والفجوات المعرفية الحالية، يجب توخي الحذر الشديد عند تفسير القياسات الدولية حول إمكانية الوصول إلى مياه الشرب. ونحن نحتاج إلى مزيد من الأبحاث المستهدفة بشأن التأثيرات الصحية المرتبطة بالتحسينات في إمدادات مياه الشرب.

摘要

为什么“经过改善”的水源并不总是安全的

现有和拟议的家庭饮用水供水指标旨在衡量水源是否够用、是否安全以及是否容易获取。然而，这些属性可能随着时间的推移以及空间的改变发生很大变化，这种变化让建立和实施简单并且可伸缩度量标准的任务更加复杂。在本文中，我们强调那些导致用水安全变数但其重要性却通常被非专业人员忽略的因素，特别是那些涉及所谓水源改善的因素。保质保量供水方面存在的问题（经常受到人类行为影响的相关问题）可能造成不良健康状况的风险更高。单从全球用水指标上看我们正按部就班满足世界饮用水需求，这样就可能掩盖了这种风险。鉴于这个主题的复杂性和目前的知识差距，在饮用水的获取方面，对其国际指标的解读应慎之又慎。在与改善饮用水供应相关联的健康影响的研究方面，我们需要进行更进一步有针对性的研究。

Résumé

Pourquoi les sources d'eau «améliorées» ne sont pas toujours sûres

Les indicateurs existants et proposés pour la distribution de l'eau potable des ménages visent à mesurer la disponibilité, la salubrité et l'accessibilité des sources d'eau. Cependant, ces caractéristiques peuvent être très variables dans le temps et l'espace, et ces variations compliquent la tâche de création et de mise en œuvre d'indicateurs simples et extensibles. Dans le présent article, nous mettons l'accent sur ces facteurs – en particulier, sur ceux qui concernent les sources d'eau soi-disant améliorées – qui contribuent à la variabilité de la salubrité de l'eau, mais qui peuvent ne pas être perçus généralement comme importants par les non-spécialistes. Les problèmes d'approvisionnement en eau, en quantité suffisante et en qualité satisfaisante – ces problèmes interdépendants sont souvent influencés par le comportement des hommes – peuvent contribuer à un risque accru d'être en mauvaise santé. Ce risque peut être masqué par les indicateurs globaux de l'eau qui indiquent que nous sommes en bonne voie de répondre aux besoins en eau potable de la planète. Compte tenu de la complexité du sujet et des lacunes des connaissances actuelles, les indicateurs internationaux pour l'accès à l'eau portable doivent être interprétés avec une grande prudence. Nous avons besoin de recherches ciblées et plus approfondies sur les effets sanitaires des améliorations dans le domaine de l'approvisionnement en eau potable.

Резюме

Почему «улучшенные» водные источники не всегда безопасны

Существующие и предлагаемые контрольные показатели работы коммунальных служб снабжения питьевой водой предназначены для оценки наличия, безопасности и доступности водных источников. Однако критерии оценки могут сильно меняться с течением времени и в разных местах, и эти изменения усложняют задачу выработки и внедрения простых и масштабируемых контрольных показателей. Данная работа ставит целью выделение этих факторов – особенно таких, которые касаются так называемых «улучшенных» водных источников и создают разброс в оценке безопасности воды, но которые не все неспециалисты рассматривают в качестве важных. Снабжение водой надлежащего качества и в достаточном количестве – это взаимосвязанные проблемы, которые часто обусловлены поведением людей и могут отрицательно влиять на состояние их здоровья. Такой риск может не выявляться с помощью глобальных контрольных показателей воды, указывающих лишь на то, что мы идем по пути к удовлетворению мировых потребностей в питьевой воде. Учитывая сложность темы и существующие пробелы в знаниях, международные контрольные показатели доступа к питьевой воде следует интерпретировать с большой осторожностью. Необходимы дальнейшие целенаправленные исследования, связывающие улучшение снабжения питьевой водой и состояние здоровья населения.

Resumen

Por qué las fuentes de agua «mejoradas» no siempre son seguras

Las mediciones existentes y propuestas para los servicios de agua potable de los hogares pretenden considerar la disponibilidad, seguridad y accesibilidad de las fuentes de agua. No obstante, estas características pueden variar mucho a lo largo del tiempo y del espacio, lo que complica la tarea de crear y poner en práctica mediciones sencillas y ampliables. En este documento destacamos los factores, en particular los relacionados con las llamadas fuentes de agua mejoradas, que contribuyen a la variabilidad de la seguridad del agua pero que, por lo general, los legos no identifican como importantes. Los problemas en el suministro de agua en cantidad y calidad suficientes, problemas interrelacionados en los que el comportamiento humano influye a menudo, pueden contribuir a un mayor riesgo de problemas sanitarios. Ese riesgo puede quedar oculto por mediciones de agua globales que indican que vamos camino de satisfacer las necesidades de agua potable en el mundo. Dada la complejidad del tema y las lagunas de conocimiento actuales, las mediciones internacionales sobre el acceso al agua potable deberían interpretarse con mucha cautela. Necesitamos más investigaciones específicas sobre el impacto sanitario asociado a las mejoras de los suministros de agua potable.

References

1. Resolution 64/292. The human right to water and sanitation. In: *Sixty-fourth Session of the United Nations General Assembly, New York, 28 July 2010*. Agenda Item 48 (A/RES/64/292). New York: United Nations; 2010. Available from: http://www.un.org/waterforlifedecade/human_right_to_water.shtml [accessed 24 May 2013].
2. *Progress on drinking-water and sanitation: 2012 update*. Geneva: World Health Organization; 2012.
3. Clasen TF. Millennium Development Goals water target claim exaggerates achievement. *Trop Med Int Health* 2012;17:1178–80.
4. Onda K, LoBuglio J, Bartram J. Global access to safe water: accounting for water quality and the resulting impact on MDG progress. *Int J Environ Res Public Health* 2012;9:880–94. doi: http://dx.doi.org/10.3390/ijerph9030880 PMID:22690170
5. Post 2015 Water Monitoring Working Group [Internet]. Geneva: World Health Organization; 2013. Available from: http://watermonitoring2015.org/ [accessed 26 May 2013].
6. Post-2015 WASH targets and indicators [Internet]. New York: United Nation Children's Fund; 2013. Available from: http://www.unicef.org/wash/files/4_WSSCC_JMP_Fact_Sheets_4_UK_LoRes.pdf [accessed 16 November 2013].
7. Orgill J, Shaheed A, Brown JM, Jeuland MA. Water quality and willingness to pay for clean water in peri-urban Cambodia. *J Water Health* 2013;11:489–506. doi: http://dx.doi.org/10.2166/wh.2013.212 PMID:23981877
8. Brown JM, Proum S, Sobsey MD. Escherichia coli in household drinking water and diarrheal disease risk: evidence from Cambodia. *Water Sci Technol* 2008;58:757–63. doi: http://dx.doi.org/10.2166/wst.2008.439 PMID:18776609
9. Brown JM, Hien VT, McMahan L, Jenkins MW, Thie L, Liang K et al. Relative benefits of on-plot water supply over other 'improved' sources in rural Vietnam. *Trop Med Int Health* 2013;18:65–74. doi: http://dx.doi.org/10.1111/tmi.12010 PMID:23107456
10. Özdemir S, Elliott M, Brown JM, Nam OK, Hien VT, Sobsey MD. Rainwater harvesting practices and attitudes in the Mekong delta of Vietnam. *J Water San Hyg Dev* 2011;1:171–7. doi: http://dx.doi.org/10.2166/washdev.2011.024
11. Bain R, Wright J, Yang H, Pedley S, Gundry S, Bartram J. *Improved but not necessarily safe: water access and the Millennium Development Goals* [GWF Discussion Paper 1225]. Canberra: Global Water Forum; 2012. Available from: http://www.globalwaterforum.org/wp-content/uploads/2012/07/Improved-but-not-necessarily-safe_Water-access-and-the-Millennium-Development-Goals_GWF1225.pdf [accessed 24 July 2013].
12. Godfrey S, Labhasetwar P, Wate S, Pimpalkar S. How safe are the global water coverage figures? Case study from Madhya Pradesh, India. *Environ Monit Assess* 2011;176:561–74. doi: http://dx.doi.org/10.1007/s10661-010-1604-3 PMID:20635198
13. *Guidelines for drinking-water quality*. 4th ed. Geneva: World Health Organization; 2011.
14. Pickering AJ, Davis J. Freshwater availability and water fetching distance affect child health in sub-Saharan Africa. *Environ Sci Technol* 2012;46:2391–7. doi: http://dx.doi.org/10.1021/es203177v PMID:22242546
15. Geere JA, Hunter PR, Jagals P. Domestic water carrying and its implications for health: a review and mixed methods pilot study in Limpopo province, South Africa. *Environ Health* 2010;9:52. doi: http://dx.doi.org/10.1186/1476-069X-9-52 PMID:20796292
16. Jensen PK, Ensink JHJ, Jayasinghe G, van der Hoek W, Cairncross S, Dalsgaard A. Domestic transmission routes of pathogens: the problem of in-house contamination of drinking water during storage in developing countries. *Trop Med Int Health* 2002;7:604–9. doi: http://dx.doi.org/10.1046/j.1365-3156.2002.00901.x PMID:12100444
17. Levy K, Nelson KL, Hubbard A, Eisenberg JNS. Following the water: a controlled study of drinking water storage in northern coastal Ecuador. *Environ Health Perspect* 2008;116:1533–40. doi: http://dx.doi.org/10.1289/ehp.11296 PMID:19057707
18. Wright J, Gundry S, Conroy R. Household drinking water in developing countries: a systematic review of microbiological contamination between source and point-of-use. *Trop Med Int Health* 2004;9:106–17. doi: http://dx.doi.org/10.1046/j.1365-3156.2003.01160.x PMID:14728614
19. Shaheed A, Orgill J, Ratana C, Montgomery MA, Jeuland MA, Brown JM. Water quality risks of 'improved' water sources: evidence from Cambodia. *Trop Med Int Health* Epub 2013 Nov 20. PMID:24252094
20. Reller ME, Mendoza CE, Lopez MB, Alvarez M, Hoekstra RM, Olson CA et al. A randomized controlled trial of household-based flocculant-disinfectant drinking water treatment for diarrhea prevention in rural Guatemala. *Am J Trop Med Hyg* 2003;69:411–9. PMID:14640502
21. Quick RE, Venczel LV, Mintz ED, Soleto L, Aparicio J, Gironaz M et al. Diarrhoea prevention in Bolivia through point-of-use water treatment and safe storage: a promising new strategy. *Epidemiol Infect* 1999;122:83–90. doi: http://dx.doi.org/10.1017/S0950268898001782 PMID:10098789
22. Günther I, Schipper Y. Pumps, germs and storage: the impact of improved water containers on water quality and health. *Health Econ* 2013;22:757–74. doi: http://dx.doi.org/10.1002/hec.2852 PMID:22700378
23. Roberts L, Chartier Y, Chartier O, Malenga G, Toole M, Rodka H. Keeping clean water clean in a Malawi refugee camp: a randomized intervention trial. *Bull World Health Organ* 2001;79:280–7. PMID:11357205
24. Dada N, Vannavong N, Seidu R, Lenhart A, Stenström TA, Chareonviriyaphap T et al. Relationship between Aedes aegypti production and occurrence of Escherichia coli in domestic water storage containers in rural and sub-urban villages in Thailand and Laos. *Acta Trop* 2013;126:177–85. doi: http://dx.doi.org/10.1016/j.actatropica.2013.02.023 PMID:23499713
25. *Improving local service delivery for the MDGs in Asia: water and sanitation sector in Cambodia*. New York: United Nations Children's Fund; 2009.
26. Country paper: Cambodia. Proceedings of the: *Asian Water Development Outlook 2007*. Manila: Asian Development Bank; 2007.
27. The International Benchmarking Network for Water and Sanitation Utilities (IBNET) [Internet]. Washington: World Bank; 2013. Available from: http://www.ib-net.org/ [accessed 26 May 2013].
28. Kumpel E, Nelson KL. Comparing microbial water quality in an intermittent and continuous piped water supply. *Water Res* 2013;47:5176–88. doi: http://dx.doi.org/10.1016/j.watres.2013.05.058 PMID:23866140
29. van den Berg C, Danilenko A. *The IBNET Water Supply and Sanitation Performance Blue Book: the International Benchmarking Network for Water and Sanitation Utilities Databook*. Washington: The World Bank; 2011.
30. Musemwa M. From "Sunshine City" to a landscape of disaster: the politics of water, sanitation and disease in Harare, Zimbabwe, 1980–2009. *J Dev Soc* 2010;26:165–206. http://dx.doi.org/10.1177/0169796X1002600202

31. Swain SK, Baral P, Hutin YJ, Rao TV, Murhekar M, Gupte MD. A hepatitis E outbreak caused by a temporary interruption in a municipal water treatment system, Baripada, Orissa, India, 2004. *Trans R Soc Trop Med Hyg* 2010;104:66–9. doi: http://dx.doi.org/10.1016/j.trstmh.2009.07.020 PMID:19716576
32. Shah HD, Shah VP, Desai AN. An epidemic outbreak of Vibrio cholerae El Tor 01 serotype ogawa biotype in a Lalpur town, Jamnagar, India. *J Postgrad Med* 2012;58:14–8. doi: http://dx.doi.org/10.4103/0022-3859.93247 PMID:22387643
33. Hunter PR, Zmirou-Navier D, Hartemann P. Estimating the impact on health of poor reliability of drinking water interventions in developing countries. *Sci Total Environ* 2009;407:2621–4. doi: http://dx.doi.org/10.1016/j.scitotenv.2009.01.018 PMID:19193396
34. Majuru B, Jagals P, Hunter PR. Assessing rural small community water supply in Limpopo, South Africa: water service benchmarks and reliability. *Sci Total Environ* 2012;435-436:479–86. doi: http://dx.doi.org/10.1016/j.scitotenv.2012.07.024 PMID:22885354
35. Smeets P. *Stochastic modelling of drinking water treatment in quantitative microbial risk assessment*. London: IWA Publishing; 2010.
36. Jalan J, Ravallion M. Does piped water reduce diarrhea for children in rural India? *J Econom* 2003;112:153–73. doi: http://dx.doi.org/10.1016/S0304-4076(02)00158-6
37. Lee EJ, Schwab KJ. Deficiencies in drinking water distribution systems in developing countries. *J Water Health* 2005;3:109–27. PMID:16075938
38. Bustamante R, Butterworth J, Callejo ID, Duran A, Herbas D, Hillion B et al. *Multiple sources for multiple uses: household case studies of water use around Cochabamba, Bolivia*. Pasadena: California Institute of Technology; 2004. Available from: www.its.caltech.edu/~e105/readings/cases/water_uses.pdf [accessed 26 May 2013].
39. Guardiola J, Gonzalez-Gomez F, Grajales AL. Is access to water as good as the data claim? Case study of Yucatán *Int J Water Resour Dev* 2010;26:219–33. doi: http://dx.doi.org/10.1080/07900621003655692
40. Parker Fiebelkorn A, Person B, Quick RE, Vindigni SM, Jhung M, Bowen A et al. Systematic review of behavior change research on point-of-use water treatment interventions in countries categorized as low- to medium-development on the human development index. *Soc Sci Med* 2012;75:622–33. doi: http://dx.doi.org/10.1016/j.socscimed.2012.02.011 PMID:22497845
41. Mosler H-J. A systematic approach to behavior change interventions for the water and sanitation sector in developing countries: a conceptual model, a review, and a guideline. *Int J Environ Health Res* 2012;22:431–49. doi: http://dx.doi.org/10.1080/09603123.2011.650156 PMID:22292899
42. Philipson T. Economic epidemiology and infectious diseases. In: Culyer AJ, Newhouse JP, editors. *Handbook of health economics*. Volume 1B. Amsterdam: Elsevier; 2000. pp. 1761–1799.
43. Jeuland MA, Fuente DE, Ozdemir S, Allaire MC, Whittington D. The long-term dynamics of mortality benefits from improved water and sanitation in less developed countries. *PLoS One* 2013;8:e74804. doi: http://dx.doi.org/10.1371/journal.pone.0074804 PMID:24116011
44. Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H et al. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet* 2012;380:2224–60. doi: http://dx.doi.org/10.1016/S0140-6736(12)61766-8 PMID:23245609
45. Engell RE, Lim SS. Does clean water matter? An updated meta-analysis of water supply and sanitation interventions and diarrhoeal diseases. *Lancet* 2013;381:S44. doi: http://dx.doi.org/10.1016/S0140-6736(13)61298-2
46. Watts C, Cairncross S. Should the GBD risk factor rankings be used to guide policy? *Lancet* 2012;380:2060–1. doi: http://dx.doi.org/10.1016/S0140-6736(12)62121-7 PMID:23245600
47. Levy K, Nelson KL, Hubbard A, Eisenberg JNS. Rethinking indicators of microbial drinking water quality for health studies in tropical developing countries: case study in northern coastal Ecuador. *Am J Trop Med Hyg* 2012;86:499–507. doi: http://dx.doi.org/10.4269/ajtmh.2012.11-0263 PMID:22403326
48. Bartram J, Cairncross S. Hygiene, sanitation, and water: forgotten foundations of health. *PLoS Med* 2010;7:e1000367. PMID:21085694
49. Sorenson SB, Morssink C, Campos PA. Safe access to safe water in low income countries: water fetching in current times. *Soc Sci Med* 2011;72:1522–6. doi: http://dx.doi.org/10.1016/j.socscimed.2011.03.010 PMID:21481508
50. Enger KS, Nelson KL, Rose JB, Eisenberg JNS. The joint effects of efficacy and compliance: a study of household water treatment effectiveness against childhood diarrhea. *Water Res* 2013;47:1181–90. doi: http://dx.doi.org/10.1016/j.watres.2012.11.034 PMID:23290123
51. Brown JM, Clasen T. High adherence is necessary to realize health gains from water quality interventions. *PLoS One* 2012;7:e36735. doi: http://dx.doi.org/10.1371/journal.pone.0036735 PMID:22586491