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Master's Thesis:

Auditing Water Resources for Application to Water-Sensitive Urban Design - A Case Study in the Lima (Perú) Metropolitan Area

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Abstract

The Lima (Perú) Metropolitan Area faces numerous challenges to water and wastewater management which have become more urgent in recent years due to the effects of urban growth and climate change. These effects have also intensified the city's struggle to provide and maintain an amount of green space adequate for its population. Issues related to both water resources management and the provision of green space in Lima might be addressed through the application of water-sensitive urban design (WSUD) concepts which incorporate constructed wetlands for the treatment of wastewater and surface water for reuse in the irrigation urban green areas. A water audit can be implemented to rapidly yet effectively assess the quantity and quality of water resources available to a WSUD project in order to guide design proposals towards technically feasible solutions. In this study, a water audit was formulated for and carried out in the Lima neighborhood of Chuquitanta (San Martin de Porres) in support of a WSUD project being undertaken within the framework of the German BMBF "Future Megacities" project "Sustainable Water and Wastewater Management in Urban Growth Centres Coping with Climate Change — Concepts for Lima Metropolitana (Perú)" (LiWa). The audit was developed and undertaken in three phases, with regular feedback from and interaction with a concurrent three-phase preliminary design process aimed at the development of water-sensitive ecological infrastructure in the study area. A variety of tools including observation, estimation, and field and laboratory testing were implemented to determine values for a customized set of parameters related to water quantity, temperature, oxygen balance, salt content, acidity, nutrient content, microbiology and heavy metal content in several different local water sources. Parameter values were then compared to quality standards for surface- and wastewaters treated for reuse in irrigation. Finally, audit results were considered alongside results from the preliminary design process to suggest constructed wetland configurations which could be incorporated into WSUD prototypes for each of four different water sources in Chuquitanta. The recommendations made were not only technically feasible with regard to observed water qualities/quantities and water usage/treatment goals, but strived to stay true to the vision proposed in preliminary designs. Suggestions included a recycled vertical flow constructed wetland for treatment of domestic greywater, a surface flow constructed wetland for treatment of river water channeled into a system of irrigation canals, a system of constructed wetland "modules" built into a riverbank terrace for simultaneous greywater treatment and flood protection/dike reinforcement, and a subsurface flow constructed wetland as a stop-gap measure for secondary wastewater treatment. A simple, Excel-based wetland dimension estimation tool was also developed and implemented to generate estimations for the land area required by each of the recommended wetland configurations. With some adjustments to auditing methods and the timing of steps carried out during the auditing vs. design phases, the auditing methodology described in this study should be transferable to other infrastructure design projects.

Resumen

Actualmente el área metropolitana de Lima (Perú) enfrenta múltiples desafíos concernientes al manejo del recurso hídrico y al tratamiento de aguas residuales, factores que en los últimos años se han vuelto más críticos debido a los efectos del crecimiento de la población y del cambio climático. Dichos efectos también han repercutido en la problemática que tiene la ciudad para proveer y mantener una proporción adecuada de espacios verdes para su población. Aspectos relacionados tanto con el manejo de dichos recursos hídricos como con la provisión del espacio verde en Lima, podrían ser considerados a través de la aplicación del concepto del Diseño Urbano Hidro-sensible (DUHS), el cual incorpora la construcción de humedales para el tratamiento de aguas residuales y aguas superficiales para su reutilización en la irrigación de zonas verdes urbanas. Una auditoria en aguas puede implementarse rápidamente para evaluar efectivamente la cantidad y calidad de los recursos hídricos disponibles para un proyecto DUHS, a fin de orientar propuestas dirigidas a la obtención de soluciones técnicamente viables. En el presente estudio, una auditoria en aguas fue formulada y llevada a cabo en la localidad de Chuquitanta (San Martín de Porres) de la ciudad de Lima como soporte a un DUHS proyecto dentro del marco del proyecto alemán BMBF "Future Megacities" "Gestión sostenible del agua y las aguas residuales en centros urbanos en crecimiento afrontando el cambio climático — Conceptos para Lima Metropolitana (Perú)" (LiWa). La auditoria fue desarrollada y puesta en marcha en tres fases, y con información periódica de la interacción con un proceso de diseño preliminar concurrente de tres fases dirigido al desarrollo de la infraestructura ecológica hidro-sensible en el área de estudio. Un sinnúmero de herramientas que incluyen la observación, estimación y experimentación tanto en laboratorio como en campo, fueron implementadas para así determinar los valores de un conjunto de parámetros relacionados con la cantidad de agua, temperatura, balance de oxígeno, contenido de sales, acidez, contenido de nutrientes, microbiología y contenido de metales pesados en varias fuentes de recursos hídricos. Estos parámetros fueron a su vez comparados con los estándares de calidad vigentes que aplican a aguas superficiales y residuales tratadas con fines de irrigación. Finalmente, los resultados de dicha auditoria fueron evaluados junto con los resultados del proceso de diseño preliminar con el fin de sugerir configuraciones de humedales artificiales, los cuales pudieran ser incorporados a prototipos de DUHS para cada una de las cuatro diferentes fuentes de agua. Las recomendaciones formuladas probaron ser no solamente técnicamente viables en lo concerniente a las cantidades/calidad y a los objetivos uso/tratamiento observados, sino que se mantuvieron consistentes a la visión propuesta en diseños preliminares. Entre las propuestas se incluyó la construcción de un humedal de reciclado de flujo vertical para el tratamiento de aguas grises domesticas, un humedal de flujo superficial para el tratamiento de agua de río canalizada hacia un sistema de irrigación por canales, un sistema de módulos de humedales construidos hacia la terraza de una ribera con el fin de proveer tratamiento de aguas grises y reforzar el dique/protección contra inundaciones y un humedal de flujo subterráneo como

medida provisional para el tratamiento secundario de aguas residuales. Se desarrollo e implemento también una herramienta simple en Excel para el dimensionamiento de humedales con el fin de estimar la superficie de tierra requerida para cada una de las configuraciones de humedales recomendados. Con algunos ajustes a los métodos de evaluación y al cronometraje de los tiempos de los pasos seguidos durante la auditoria vs. las fases de diseño, la metodología de evaluación descrita en este estudio se debería poder transferir a otros proyectos de diseño de infraestructura.

Abstract

Die Stadtregion von Lima (Perú) sieht sich mit diversen Herausforderungen im Bereich Wasser- und Abfallmanagement konfrontiert. Diese Probleme werden mit zunehmenden Bevölkerungswachstum und durch den Einfluss des globalen Klimawandels immer dringlicher. Zusätzlich verstärken die genannten Faktoren den ohnehin schon hohen Bedarf an Grünflächen. Probleme im Zusammenhang sowohl mit der Bewirtschaftung von Wasserressourcen als auch mit der Bereitstellung von Grünflächen in urbanen Gebieten in Lima, könnten mit dem Einsatz von Pflanzenkläranlagen als wassersensible städtebauliche Maßnahme (water-sensitive urban design (WSUD)), entgegengewirkt werden. Mit dem Einsatz dieser Anlagen könnten etwa Ab- und Oberflächenwasser gereinigt und für die Bewässerung von städtischen Grünanlagen wiederverwendet werden. Um Kosten und Zeit zu minimieren, kann im Rahmen der Planungsphase eines WSUDs ein Wasseraudit zu einem technisch geeigneten und nachhaltigen Entwurf beitragen. Der Vorteil eines Audits bietet die Möglichkeit Wasserqualität und -quantität von verschiedenen Wasservorkommen bereits im Vorfeld der Planung abzuschätzen und diese daraufhin an die lokalen Gegebenheiten anzupassen. Der Inhalt dieser Master-Arbeit ist die Planung und Durchführung eines Wasseraudits für die Umgebung Chuquitanta (San Martín de Porres) in Lima. Sie wird im Zusammenhang des Forschungsprojektes "Future Megacities - Megastädte von morgen" "Nachhaltiges Management von Wasser und Abwasser in urbanen Wachstumszentren unter Bewältigung des Klimawandels - Konzepte für Lima Metropolitana - (LiWa), Perú" des deutschen Bundesministerium für Bildung und Forschung (BMBF) durchgeführt. Das Wasseraudit wurde in drei Phasen entwickelt und umgesetzt. Hierbei wurde ein besonderer Schwerpunkt auf die Einbindung des gleichzeitig und ebenfalls in drei Phasen ablaufenden Entwurfsprozesses der Entwicklung einer wassersensiblen ökologischen Infrastruktur im Untersuchungsgebiet gelegt. Im Zuge des Wasseraudits wurde eine Vielzahl von Beobachtungen, Feld- und Laborversuchen durchgeführt und mit Abschätzungen ergänzt, um die Wasserquantität und -qualität von mehreren Wasservorkommen in der Nähe von Chuquitanta zu bestimmen. Zu den untersuchten Parametern gehörten Fließgeschwindigkeit, Temperatur, Sauerstoffbilanz, Salz-, Säure- und Nährstoffgehalt, Mikrobiologie und Schwermetallkonzentrationen. Anschließend wurden die Ergebnisse mit Standards für Oberflächen- und Abwasser zum Zweck der Bewässerung verglichen. Die gesammelten Daten bildeten weiterhin die Grundlage für den parallel ablaufenden und vorläufigen Entwurfsprozess von Pflanzenkläranlagen, welche in jeweils eines der WSUD Entwürfe von vier Wasservorkommen in Chuquitanta eingebunden werden sollen. Die Empfehlungen basieren jedoch nicht nur auf der technischen Machbarkeit, welche die Wasserqualität und -quantität sowie die Ziele Wasseraufbereitung und -wiederverwertung berücksichtigt, sondern auch auf den ursprünglichen Entwürfen und den damit zusammenhängenden Ideen der Architekten. Die Vorschläge beinhalten eine vertikaldurchströmte Pflanzenkläranlage zur Behandlung von häuslichen Abwässern, ein System mit freier Wasseroberfläche zur Reinigung

von Flusswasser und eine unterirdisch durchströmte Pflanzenkläranlage als vorläufige Ersatz von einer konventionellen Kläranlage. Desweiteren wird eine Pflanzenkläranlage empfohlen, die aus einzelnen Modulen besteht, und am Flussufer installiert werden kann um gleichzeitig Grauwasser zu behandeln sowie den Hochwasserschutz zu verbessern. Abschließend wurde ein einfaches Excel-basierendes Dimensionierungstool entwickelt, um die benötigte Fläche der jeweiligen Pflanzenkläranlage zu bestimmen. Das in dieser Arbeit dargestellte Konzept eines Wasseraudits ist grundsätzlich auf ähnliche infrastrukturelle Projektentwürfe übertragbar, benötigt jedoch geringe Verbesserungen der Methode und der Synchronisation der Arbeitsschritte in Bezug auf die individuellen Entwurfsphasen.

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List of Symbols & Abbreviations

A	required wetland area
Al^{3+}	aluminum ion
ANA	Autoridad Nacional del Agua (English: National Water Authority)
AOX	adsorbable organohalogens
BMBF	Deutsche Bundesministerium für Bildung und Forschung (English: German Federal Ministry of Education and Research)
BOD	biochemical oxygen demand
C^*	background concentration of dimensioning parameter
C_i	inflow concentration of dimensioning parameter
C_o	target outflow concentration of dimensioning parameter
Ca	calcium
Ca^{2+}	calcium ion
Cd	cadmium
CIAC	Centro de Investigación de la Arquitectura y la Ciudad (English: Center for Research on Architecture and the City)
CITRAR-UNI	Centro de Investigación en Tratamiento de Aguas Residuales y Residuos Peligrosos - Universidad Nacional de Ingeniería (English: Universidad Nacional de Ingeniería's Center for Research on Wastewater Treatment and Hazardous Waste)
Cl^-	chloride ion
CO_3^{2-}	carbonate ion
COD	chemical oxygen demand

Cr	chromium
CSBR-3	three-chamber modified sequencing batch reactor
Cu	copper
DO	dissolved oxygen
EC	electric conductivity
eco	*Escherichia coli*
ecosan	ecological sanitation
ET	evapotranspiration
EUR	Euro
FAO	Food and Agriculture Organization of the United Nations
Fe	iron
Fe^{2+}	iron(II) ion
Fe^{3+}	iron(III) ion
fec	fecal coliforms
FWSW	free water surface constructed wetland
H^+	hydrogen ion
H_2SO_4	sulfuric acid
HCO_3^-	bicarbonate ion
HSSFW	horizontal subsurface flow constructed wetland
ILPÖ	Institut für Landschaftsplanung und Ökologie (English: Institute for Landscape Planning and Ecology)
K	potassium
k	modified first-order areal constant
LiWa	Sustainable Water and Wastewater Management in Urban Growth Centres Coping with Climate Change — Concepts for Lima Metropolitana
mbgl	meters below ground level

Mg	magnesium
Mg^{2+}	magnesium ion
Mn	manganese
MPN	most probable number
N	nitrogen
N_{org}	organic nitrogen
N_{tot}	total nitrogen
Na^{+}	sodium ion
NGO	non-governmental organization
NH_3	ammonia
NH_4^+	ammonium ion
NO_2^-	nitrite ion
NO_3^-	nitrate ion
N.V.	no value
OH^-	hydroxide ion
P	phosphorus
P	number of tanks-in-series
P_{tot}	total phosphorus
Pb	lead
PEN	Peruvian Nuevo Sol
PO_4^{3-}	(ortho)phosphate ion
PR	precipitation
PUCP	Pontificia Universidad Católica del Perú
pwe	parasitic worm (helminth) eggs/cysts
Q	flow rate
Q_i	inflow rate

S	sulfur
sal	*Salmonella*
SCH	Santa Cruz Hill Residential Area
SEDAPAL	Servicio de Agua Potable y Alcantarillado de Lima (English: Potable Water and Sewerage Service of Lima)
SMP	District of San Martin de Porres
SO_4^{2-}	sulfate ion
SUNASS	Superintendencia Nacional de Servicios de Saneamiento (English: National Superintendence of Sanitation Services)
SuSanA	Sustainable Sanitation Alliance
TKN	total Kjeldahl nitrogen
TOC	total organic carbon
toc	total coliforms
TSS	total suspended solids
ttc	thermotolerant coliforms
UDDT	urine diverting dry toilet
UNI	Universidad Nacional de Ingeniería
VFW	vertical flow constructed wetland
WHO	World Health Organization
WP9	LiWa Work Package 9: Integrated Urban Planning Strategies and Planning Tools
WSUD	water-sensitive urban design
WWTP	wastewater treatment plant
Zn	zinc

1 Introduction

1.1 Lima's challenges to the management of water resources and the provision of green space

Lima, the capital of Perú, is a metropolis of 9 million people located on the west coast of South America in one of the driest deserts in the world. The aridity of coastal Perú results from a combination of climatological and geographical factors. The Pacific Ocean's cold Humboldt Current flows northward along the western coast of South America from Chile to northern Perú, cooling ocean air and reducing its capacity to carry moisture which would fall as precipitation in coastal areas. Additionally, the Andes Mountain range, which has an average height of 4,000 m and extends along the entirety of the western coast of South America from Argentina in the south to Venezuela in the north, is as an effective barrier to precipitation and moisture-laden air moving towards coastal Perú from the Amazon basin in the east (Figure 1.1). [109] These influences combine to minimize precipitation in Lima; on average the city and surrounding area receive less than 8 mm of rain per year (Table 1.1). [43]

The metropolitan area made up by the provinces of Lima and Callao is considered the world's second-largest desert city, after Cairo, Egypt. [2] However, there is a major difference between hydrological conditions in Lima Metropolitana and Cairo, a city of 15 million people which receives an average of 25 mm of precipitation annually: Cairo is situated along the Nile River, which has an average flow rate of 2,830 m^3/s. [33] [118] In contrast, the average flow rates of Lima's three rivers, the Rímac, the Chillón, and the Lurín, are 31.5 m^3/s, 8.8 m^3/s, and 4.1 m^3/s, respectively. (Figure 1.2). [25] The lack of surface water in Lima is indicative of a more general imbalance between the distribution of water resources and population in Perú. While most of the country's surface water is contained east of the Continental Divide in the Atlantic

Table 1.1: Total Annual Precipitation in the Lima Department [mm] [43]

2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
8.0	7.6	10.3	4.5	3.0	3.4	2.9	7.7	9.4	15.3	6.9

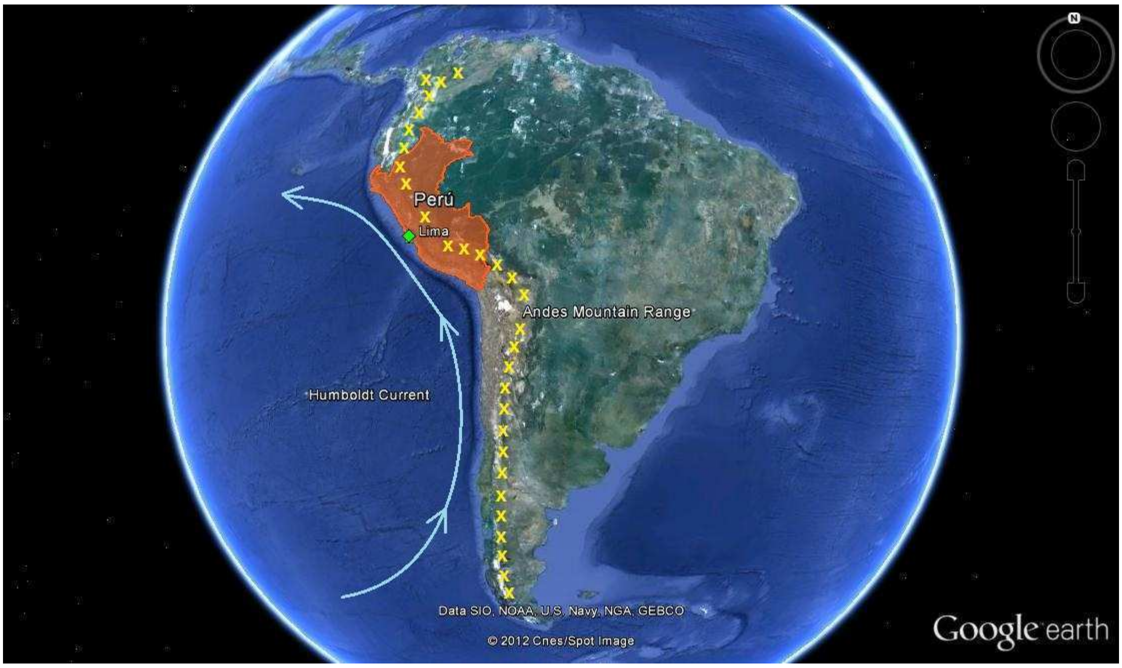


Figure 1.1: Lima, Perú is located on the west coast of South America; coastal Perú's arid climate is influenced by both the Humboldt Current and the Andes Mountain Range.

Figure 1.2: Lima Metropolitana is the metropolitan area made up by the urban provinces of Lima and Callao; the major surface water resources in the area are the Rímac, Chillón, and Lurín Rivers.

catchment, or on Perú's southern border with Bolivia in Lake Titicaca, 65% of the country's almost 30 million inhabitants live west of the Continental Divide in the dry Pacific catchment which contains only 1.8% of the country's surface water resources. [8], [111]

The Rímac and Chillón Rivers are Lima's major sources of drinking water. During the rainy season in the Andes from December to April, roughly 18 m^3/s is diverted from the Rímac River to the La Atarjea water production plant operated by the Servicio de Agua Potable y Alcantarillado de Lima (English: Potable Water and Sewerage Service of Lima) (SEDAPAL), the state authority-turned-private enterprise which is responsible for providing water and sanitation services in Lima. The amount of flow diverted from the Rímac for potable water production during the dry season in the Andes from May to November goes down to about 16.5 m^3/s. [7], [23] The Chillón water production plant, operated for SEDAPAL by the Consorcio Agua Azul S.A., diverts roughly 2 m^3/s of the Chillón River's flow for water production between December and April; between May and November when the flow of the Chillón can slow to a trickle, the Consorcio Agua Azul extracts up to 1 m^3/s for water production from a system of groundwater wells located in the Chillón watershed. [13] In addition to the wells operated for SEDAPAL by Agua Azul, SEDAPAL owns and operates a network of 471 groundwater wells which are used to supplement surface waters utilized for potable water production. On average, 2.5 m^3/s is extracted from this network between December and April while 3 m^3/s is extracted between May and November. [23] SEDAPAL's piped water supply network services about 80% of Lima's population, most living in central neighborhoods, through connections inside or just outside the home (Figure 1.3). [42] Peripheral neighborhoods are serviced by water delivery trucks, less than half of which are operated by SEDAPAL [25]; the balance are privately owned and operated. [109]

In recent years, the consequences of rapid, generally undirected population growth have put strain on local water resources and their distribution in Lima Metropolitana. The metropolitan area's growth since the first half of the 20th century has been fast: its population increased about 14 times between 1940 and 2010. [126] Large peripheral areas stretching into the hills north, south and east of central Lima were informally settled via rural-urban migration at the beginning of this period (Figure 1.4). Unable to provide housing alternatives, authorities first tolerated and then gave their support to the improvement and extension of these peri-urban neighborhoods, setting a precedent for low-density growth and establishing a general philosophy towards urban settlement of "first build, then legalize and integrate". The political strife and economical insecurities which Perú faced in the 1980s and early 1990s led to an increase in the influx of immigrants to Lima [80]; the already long-standing housing shortage forced their settlement in undeveloped areas further and further from the historical urban center. [25] Lima's most recent metropolitan development plan was

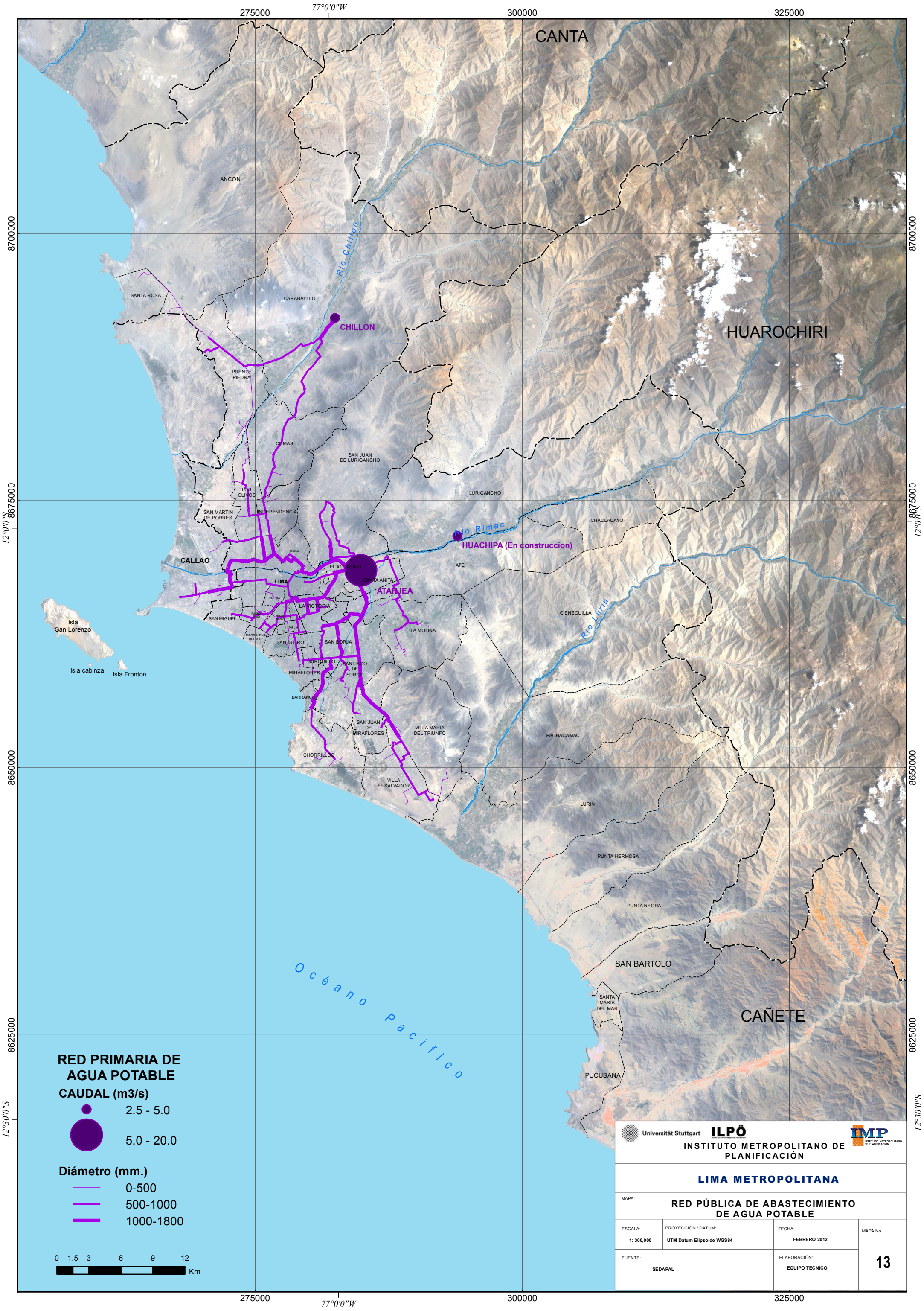


Figure 1.3: Lima's piped potable water distribution network serves roughly 80% of the population with connections inside or outside the home [109]; shown here are Lima's two water production facilities (and a third which is under construction) with their average discharge rates, as well as the extent of the distribution network with corresponding pipe diameters.

Figure 1.4: Informal settlement stretching into the hills south of downtown Lima in the District of Villa María del Triunfo.

developed for the period from 1990-2010, and though it has been temporarily renewed each year since then, the city has no current legal instrument to discourage low-density growth. [12], [126] As of 2010, Lima Metropolitana had the same population density as Stuttgart (roughly 3,000 inh/km^2), but almost 15 times the number of inhabitants (living in an area 15 times as large). [101], [109]

Understandably, water delivery infrastructure in the metropolitan area has not been able to keep up with rapid, low-density population growth and currently serves only 80% of inhabitants, despite almost continuous efforts by SEDAPAL since 1980 to provide complete coverage. [25], [109] Further, years of under-financing and poor management of public utilities have resulted in a distribution network which exhibits losses estimated at 35-40% [98], half of which can be attributed to illegal connections. [20] With network losses, average daily per capita water usage in Lima is estimated at 250 L. [19], [109] The roughly 20% of Lima Metropolitana's inhabitants which are not connected to the piped distribution network and therefore depend on potable water delivered by truck are often the poorest residents living in the most peripheral and hard-to-reach areas (Figure 1.5). The majority of water deliveries made by truck are handled by private companies; deliveries are often infrequent and no mechanism exists for controlling the source or quality of delivered water or the proper maintenance of truck water tanks. Further, potable water delivered by truck can cost up to 9 times more than water delivered via the city's piped distribution network. [109] The

(a) Water delivery truck in Chuquitanta

(b) Filling water cisterns in Lima [photo: Independencia]

Figure 1.5: In peripheral and hard-to-reach neighborhoods in Lima, (a) water is delivered by truck and (b) stored in metal or plastic cisterns.

deficiencies in Lima's municipal water supply service and the high cost of water in peripheral communities have led to a profusion of illegal groundwater wells; 1,733 unlicensed wells were counted in 2009. Though SEDAPAL ensures that it does not over-exploit its own well network by maintaining extraction rates which are under the maximum allowable and allowing wells time to recover (and even goes so far as to claim that groundwater tables are rising), without more investigation no one can be sure of the consequences that unregulated illegal groundwater wells will have on the long-term sustainability of Lima's subsurface water resources. [23]

Climate change is also negatively impacting Lima's water resources. The metropolitan area's three rivers are fed by glacial meltwater which is stored and managed in a network of upstream reservoirs. Global warming has caused the mass of all Andean glaciers to shrink by 20% since 1970 and is also responsible for reduced precipitation in Perú's mountainous regions. Both of these factors have contributed to a reduction in upstream reservoir volumes which has led not only to concerns about downstream water availability, but also to conflict with electricity providers who utilize upstream waters for hydropower production. 80% of Perú's electricity is currently generated using hydropower, and as populations in Lima and other urban centers continue to increase while mountain reservoir volumes decrease, arguments about whether to optimize water resources management for hydropower production or for drinking and irrigation water provision will surely intensify. [109] It is also worth mentioning that the strong link between the availability of water resources in Perú and the country's capacity for energy production would effectively rule out a seawater desalination plant for the production of potable water in Lima because of the high energy consumption and operational costs associated with this type of facility.

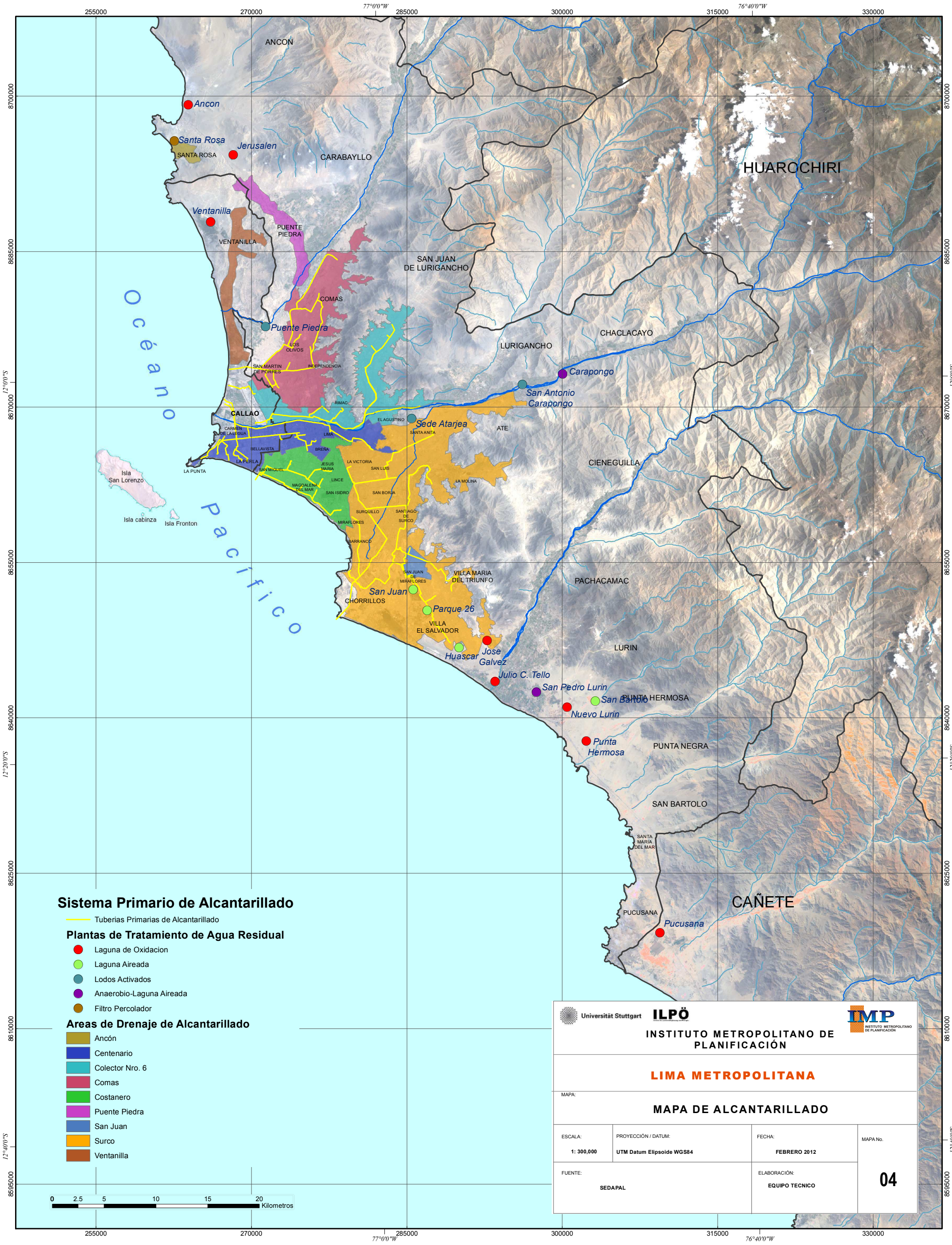


Figure 1.6: Lima's piped sewage infrastructure serves roughly 85% of the population [42]; shown here are the extent of the sewerage pipe network, the locations of 18 of Lima's 41 sewage treatment facilities and their types, and the different drainage basins for which the city provides sewerage service.

Table 1.2: Wastewater Treatment Technologies used in Lima [75]

Treatment Technology	Number of Facilities	Percentage of Total Collected Wastewater Treated
Facultative Lagoons	10	4.6
Aerated Lagoons	5	2.2
Aerated Lagoons w/Sedimentation & Polishing	3	44.2
Anaerobic Lagoons w/Aeration & Polishing	3	29.1
Anaerobic Reactors & Facultative Lagoons	2	2.5
Activated Sludge	14	16.9
Trickling Filters	2	0.3
Constructed Wetlands	2	0.1

Wastewater management presents another challenge in Lima. As with its piped water distribution network, SEDAPAL has had difficulty expanding its sewerage network rapidly enough to accommodate urban growth and only roughly 85% of the metropolitan area's households are connected to the sewage collection network (Figure 1.6). [42] Wastewater treatment facilities in Lima Metropolitana have also not kept pace; currently only 16-17% of the 18,850 L/s of wastewater collected by SEDAPAL receives any form of treatment at all, while the balance is discharged untreated into the Pacific Ocean. [75], [114] However, the metropolitan area is taking steps towards some form of treatment for 100% of its wastewater. The first of these is Taboada, a large central wastewater treatment plant (WWTP) under construction in Lima which will begin operation in August to process an additional 57% of the city's wastewater. Noteworthy however is that because more advanced treatment of such a large quantity of collected wastewater has been deemed too costly, the new plant will provide only primary wastewater treatment (removal of sand, oil and grease) before discharging collected waters to the sea. [61], [75]

Lima Metropolitana currently has 41 facilities for treatment of the 16-17% of domestic wastewater collected by SEDAPAL: 19 are operated by SEDAPAL, 14 by various municipal governments, 5 by private enterprises, 2 by the Ministry of Defense and 1 by a public university. Almost 83% of the wastewater currently collected for treatment is treated using facultative, aerobic, or anaerobic lagoons with or without complimentary treatment steps; for example, 44% is handled at 3 facilities which utilize aerated lagoons with sedimentation and polishing steps while an additional 29% is treated at 3 facilities which use anaerobic lagoons with aeration and polishing steps (Table 1.2). The most primitive treatment technology utilized in Lima is the facultative lagoon, employed by 10 facilities handling just under 5% of collected wastewater which is to undergo treatment. This technology was the first implemented in Lima for wastewater treatment and is therefore frequently encountered, though many of the facilities which originally utilized facultative lagoons have been upgraded to anaerobic or aerated systems. 2.2% of collected wastewater is treated in aerated lagoons, and 2.5% in anaerobic reactors & facultative lagoons. Just under 17% of the wastewater collected by SEDAPAL for treatment is handled in 14 facilities which utilize activated sludge technology, and less than 0.5% is treated in 4 facilities employing trickling filters or constructed wetlands. [75] Lima's wastewater treatment plants generally produce low-quality effluents because many do not function as designed or are under-designed for influent pollutant loads and types [114]; further, none of Lima's plants are designed to remove nutrients or chemical contaminants from wastewater. [75] The majority of treatment plants in Lima receive influents in quantities or with biochemical oxygen demands (BOD) or organic loads higher than those which they were designed to handle. Influents often contain industrial or mining pollutants which facilities are not equipped to remove. Though 27 of Lima's plants were designed to include a disinfection step at the end of the treatment process, in the majority of cases this step is not in operation. For these reasons, although all of Lima Metropolitana's treatment facilities (with the exception of the 2 plants which employ trickling filters) provide some form of secondary treatment, achieved treatment efficiencies are frequently inadequate for the safe discharge of effluent into surface waters or for its use in irrigation. [75]

Another difficulty faced by Lima Metropolitana is the provision of an amount of urban green space sufficient for its population. The World Health Organization (WHO) recommends that cities maintain an average of 9 m^2 of green space per person; for a population of 9 million, meeting this recommendation would require 8,100 hectares of green space. However, it is estimated that Lima Metropolitana has just over 2,000 hectares of green space and on average only about 2.4 m^2 of green space per capita. [75] Un-built spaces in Lima are in peril. Especially in the absence of a valid and current urban plan, there is pressure on authorities to allocate undeveloped and agricultural areas for residential and industrial development. These zoning types are considered more urgently needed and economically fruitful than recreational space, which is typically not assigned much financial or other value. [16], [58] In areas which are already used as recreational space or for which parks are planned, green space development is generally seen as needing to be just that — green — and expensive, limited potable water supplies are widely used for the irrigation of grass and other water-needy park plantings (Figure 1.7). [84], [89] In order to discourage the use of potable water for irrigation, in 2010 the Peruvian government passed minsterial resolution 176-2010-VIVIENDA: "Aprueban Lineamientos de Política para la promoción del tratamiento para el reuso de las aguas residuales domésticas y municipales en el riego de areas verdes urbanas y periurbanas" (English: "Approval of policy guidelines for the promotion of treatment of domestic and municipal wastewater for reuse in the irrigation of urban and peri-urban

Figure 1.7: Expensive and limited potable water supplies are often used to irrigate green spaces in arid Lima, like this public area in the District of Punta Hermosa.

green areas") which effectively legalized the use of treated wastewater for irrigation. [45] Though they do not specify the extent to which wastewater should be treated for reuse in irrigation, the guidelines propose the development of quality standards for domestic and municipal wastewater reused in irrigation and the updating of legislation related to the various treatment technologies which might be implemented for this purpose. [68] In 2011, Perú's Superintendencia Nacional de Servicios de Saneamiento (English: National Superintendence of Sanitation Services) (SUNASS) proposed that municipalities begin to pay market rates for potable water used in green space irrigation instead of government-subsidized tariffs, and encouraged Peruvian mayors to seek financing for the construction of treatment facilities for municipal wastewater which could be reused in irrigation. [50] Despite this encouragement, the construction and proper maintenance of decentralized treatment plants for irrigation of urban green spaces remains financially cumbersome for municipalities, and irrigation of these areas with potable water continues. [18]

1.2 Water-sensitive urban design

Lima's challenges to potable water supply and distribution, wastewater collection and treatment, and the provision and maintenance of green space have been brought on by a variety of natural (ex., arid climate; poor surface water distribution) and man-made (ex., fast, informal, low-density population growth; climate change) stressors. The development of lasting and effective solutions to the complex problems which Lima faces requires a change in the fundamental way water is managed within the urban environment, with a renewed focus on sustainability and integration. One tool which can be implemented to support a new approach to urban water management is water-sensitive urban design (WSUD). WSUD is a departure from the traditional design paradigm which tends to uphold negative perceptions of urban water as a vector for disease, a means for transporting waste, or a source of inconvenience or annoyance. While the conventional "out of sight, out of mind" approach hides urban water and the infrastructure that carries or constrains it until water comes out of a tap, or gets flushed down a toilet, or is channeled into a gutter, WSUD rather supports the idea that urban water infrastructure can be more to a city than just a means for controlling flooding, or bringing clean water in and taking excess or dirty water out. Engineers Australia defines WSUD as follows: "Water sensitive [means] sustainable solutions for managing water resources [and] protecting aquatic ecosystems...[while] urban design [means] integrating total urban water cycle management into the urban design and built form, enhancing the landscape/recreation/habitat, [and] creating an 'urban ecology' " [24] Water infrastructure can and should be seen and experienced by city inhabitants via its integration into the urban landscape, opening up its potential to serve an additional purpose by supporting natural aquatic and riparian/lacustrine habitats or as an urban recreational space. Further, WSUD supports a renewed approach to urban water management which considers the total water cycle and incorporates a view towards long-term sustainability.

It has been argued that the mismanagement of water, and not a lack of water resources, is the real culprit behind water scarcity problems in the Lima Metropolitan Area. Peru's desert coast is said to have more water than the entire country of Israel [109], and evidence suggests that Lima does have enough water to meet all of its needs — city water resources just need better stewardship. [22] The potential for more effectively and efficiently managing water resources in Lima by applying the principles of WSUD is high, and would not only alleviate issues related to water supply and distribution (i.e., water scarcity), but could also address some of the challenges related to wastewater management and the provision and maintenance of green space in the city. For example, under a different management scheme it would be possible to use the city's wastewater to irrigate an amount of green space in Lima Metropolitana large enough to exceed the per capita green space recommendation given by the WHO. One scenario even suggests that if the amount of the city's wastewater undergoing secondary treatment were increased from current levels of 16-17% to 37%, 9,600 hectares of green space and an additional 4,000 hectares of agricultural land currently irrigated with river water could be irrigated with treated wastewater at a flow rate of 6,800 L/s. [75], [76] While it would not solve the problem of high network losses or address issues related to water distribution outside the piped network in Lima, the use of recycled wastewater for irrigation would indirectly help

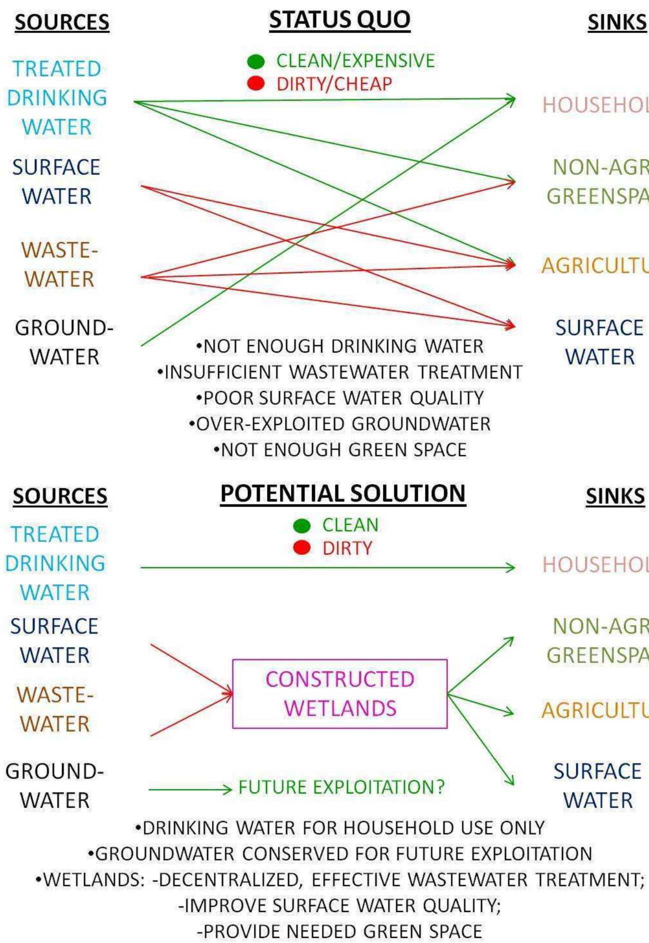


Figure 1.8: Schematic illustrating the status quo for water resources management in Lima Metropolitana and constructed wetlands as a potential treatment option for waste- and surface waters.

water supply issues by freeing up limited potable water resources for exclusive use in households and as drinking water. In turn, this could lessen or alleviate the pressure on groundwater resources currently tapped for potable water production, reserving them for future exploitation, and avoid the need for additional, expensive potable water supply projects (i.e., a second trans-Andean tunnel, a desalination plant for Lima, etc.) [93] Based on recent legislation, authorities recognize the benefits of using treated wastewater for irrigation and have begun to encourage local governments to install appropriate wastewater treatment facilities of any type. However, additional motivation for municipalities and an even truer application of the principles of WSUD in Lima might be possible through the specific promotion of constructed wetlands as the recommended means of treating wastewater for irrigation purposes.

Though of course not the only treatment choice for wastewater intended for reuse in irrigation [106], constructed wetlands are a proven method for the effective treatment of polluted waters and have been championed for their potential for application in developing countries. [49], [79] Their wide-scale implementation in Lima would support improved wastewater management and green space provision/maintenance in the metropolitan area towards the overall goal of increased sustainability and integration in water resources management (Figure 1.8). Constructed wetlands are essentially green areas which work to clean the water which keeps them green, thus serving a dual purpose as wastewater treatment infrastructure and green space. In many cases, constructed wetlands can be even further integrated into the built environment as urban recreational space or as city habitats for hydrophilic flora and fauna. [24] Treated wetland effluent can also be used in the irrigation of additional green spaces. [21] While championing the incorporation of constructed wetlands into Lima's urban infrastructure would not address the fundamental question of whether urban green spaces need actually be green, constructed wetlands as the status quo for wastewater treatment for irrigation would enable an increase in the amount of "traditional" green space in the metropolitan area in two ways: firstly as a mechanism for producing treated wastewater which might be reused in the irrigation of green areas, and secondly as green spaces themselves. It seems that up to this point, concerns about high capital and land costs associated with the installation of constructed wetlands as well as proper wetland operation and maintenance (for example, those related to Lima's Oasis de Villa artificial wetland as expressed by Julio César Moscoso Cavallini in his 2011 report) have been the primary barrier to the wider-scale implementation of constructed wetlands in Lima. [75] All wastewater treatment systems require proper operation and maintenance in order to be effective. Constructed wetlands are no exception, and this would be a pre-requisite for their success in Lima. However, despite their relatively high installation costs, operation and maintenance costs are far lower for constructed wetlands than in a conventional treatment plant, and there is also potential for recuperating some investment costs via the harvesting of wetland plants for use as fuel and for other purposes. [79] Municipalities might be further incentivized to allocate space for the construction of wetlands despite high land costs because of their potential to provide multiple urban services (ex., a constructed wetland could function as a secondary wastewater treatment step AND as a recreational area, etc.) Spreading awareness of constructed wetlands as multi-purpose urban infrastructure elements might not only increase the perceived value of green areas in the city in and of themselves, but also promote the idea that setting aside urban land for use as (multi-purpose) green space is not a waste of potential residential or commercial space but on the contrary, actually adds value to adjacent real estate. [88] Finally, de-centrally treating wastewater in constructed wetlands would help improve wastewater management in Lima on a larger scale by increasing the amount of wastewater treated in the metropolitan area while avoiding costs associated with the construction of new central treatment plants or the extension of the pre-existing sewerage network.

1.3 What is a water audit?

A water audit is a water accounting procedure aimed at an assessment of the quantity and/or quality of water resources available in an area or to a project. The purpose and scale of water audits vary; for example, a public utility provider could implement an audit to assess how much water is being lost in its distribution network [121], a family could audit how much water they use for various household purposes in a given day, etc. A water audit supports the preliminary stages of WSUD by providing information about specific water quality and quantity parameters which can be used to constrain and guide early design development, leading to savings in money and time at future stages of the project. When considered alongside project goals for water usage or treatment, "boundary conditions" based on information about water flow rates or contaminant levels collected via an early-stage audit can help ensure that initial design prototypes function as envisioned, and serve as a starting point for the selection of specific water treatment or other technologies to complement the proposed designs. Further, information collected during an audit can help steer project resources away from ideas which simply won't work, before much time or money is wasted on investigating them more thoroughly. A well-thought out audit might be particularly helpful in rapid planning because it streamlines the collection of a customized set of technical data which could contribute to more informed decision-making, providing reliable information about the project in early planning phases and reducing the overall time needed for project development.

1.4 Research framework, thesis goals and link to LiWa project

The LiWa project, officially named "Sustainable Water and Wastewater Management in Urban Growth Centres Coping with Climate Change — Concepts for Lima Metropolitana," is a five-year scheme being funded by the Deutsche Bundesministerium für Bildung und Forschung (English: German Federal Ministry of Education and Research) (BMBF) which is part of the "Future Megacities" Programme, an initiative which seeks to address three universal challenges faced by the world's megacities: climate change, urban growth management, and the promotion of sustainability. [15] LiWa aims at the development and application of tools for participatory decision-making related to the sustainable planning and management of water and sanitation in Lima Metropolitana, especially in consideration of future effects of climate change and urban growth. [104], [105] Work Package 9 of the LiWa project, "Integrated Urban Planning Strategies and Planning Tools" (WP9) is being led by the Institut für Landschaftsplanung und Ökologie at Universität Stuttgart (English: Institute for Landscape Planning and Ecology) (ILPÖ) and is centered on the establishment of an overall strategy for natural space and green structures in

Figure 1.9: Prototypes for water-sensitive ecological infrastructure were developed for a neighborhood in San Martín de Porres, a district located within the Province of Lima but bordering the Province of Callao to the west.

Lima. [103] The intention is that work package results support a shift in urban water management from existing ad hoc tactics towards a more coherent and integrated approach, and that they contribute to an updated urban plan being developed for the metropolitan area.

One specific goal of WP9 is the creation of planning tools which can be used to identify potential strategies for the development of a water-sensitive system of ecological infrastructure in Lima that considers the multi-functional potential of green spaces in relation to their present and future water demands. [116] A related goal is the development of prototypes for water-sensitive ecological infrastructure at pilot sites in Chuquitanta, a neighborhood located within Lima's District of San Martin de Porres (Figure 1.9). In support of the latter, a group of architecture students from Universität Stuttgart traveled to Lima to participate in the "Lima: Beyond the Park" Summer School sponsored by ILPÖ in collaboration with the Centro de Investigación de la Arquitectura y la Ciudad (English: Center for Research on Architecture and the City) (CIAC) of the Pontificia Universidad Católica del Perú (PUCP) in February/March of 2012. [89] The workshop partnered the students from Germany with a group of Peruvian architecture and engineering students to generate new concepts for the development of public spaces which utilize a water-sensitive approach and integrate the total water cycle, as well as strategies for ecological parks based on performance design and not just aesthetics. [115] Student work in Lima was focused on several different water sources in and near Chuquitanta and was complemented by pre- and post-Summer School design work they carried out within a larger framework for the development of preliminary WSUD concepts for the sites. The framework can be considered in three phases, each of which incorporates design work carried out by the students, as well as a technical component (Figure 1.10):

- Organizational Phase I — Initital Impressions: Design work in this phase focused on preparatory work for the Summer School, specifically overall strategic planning for the different types of waters found in and near Chuquitanta and the exploration of WSUD concepts in ecological parks which might be appropriate for Lima within the larger urban context. Technical work involved initial observations made at the site, research into water-related challenges in Chuquitanta and in Lima in general, and first steps in developing a water auditing strategy for Chuquitanta.

- Organizational Phase II — "Lima: Beyond the Park" Summer School: Design work in this phase focused on the development of concepts for water-sensitive ecological infrastructure at four sites in or near Chuquitanta as elaborated above. Technical work involved final steps in developing a water auditing strategy for Chuquitanta, as well as conducting interviews, collecting other existing data, and carrying out preliminary field testing as part of conducting the audit.

- Organizational Phase III — Anteproyecto: Design work in this phase focused on the development of more detailed WSUD concepts for various sites in Chuquitanta based on the Summer School results and experience. Technical work involved field sampling and testing as part of conducting the audit as well as the compilation of final audit results.

The first objective of this thesis was to plan and undertake a water audit in Chuquitanta by carrying out the technical work described above for each of the three organizational phases. A second goal was to encourage interaction between the technical and design work carried out during preliminary WSUD project phases in order to generate sounder, more robust design prototypes in early project stages. One of the steps towards this goal was the presentation of data and other technical information in a manner appropriate for comprehension by a more general audience. Additionally, during Phases II and III, technical information and design ideas were shared and used to inform work carried out in subsequent project phases. The third thesis objective was to generate a set of final deliverables based on final audit results AND the more refined design concepts generated at the end of Phase III, supplemented by additional research on constructed wetland technologies and the implementation of a simple tool developed to estimate required wetland areas. These deliverables, namely final recommendations for constructed wetland configurations which might be successfully implemented in WSUD prototypes for Chuquitanta and estimations

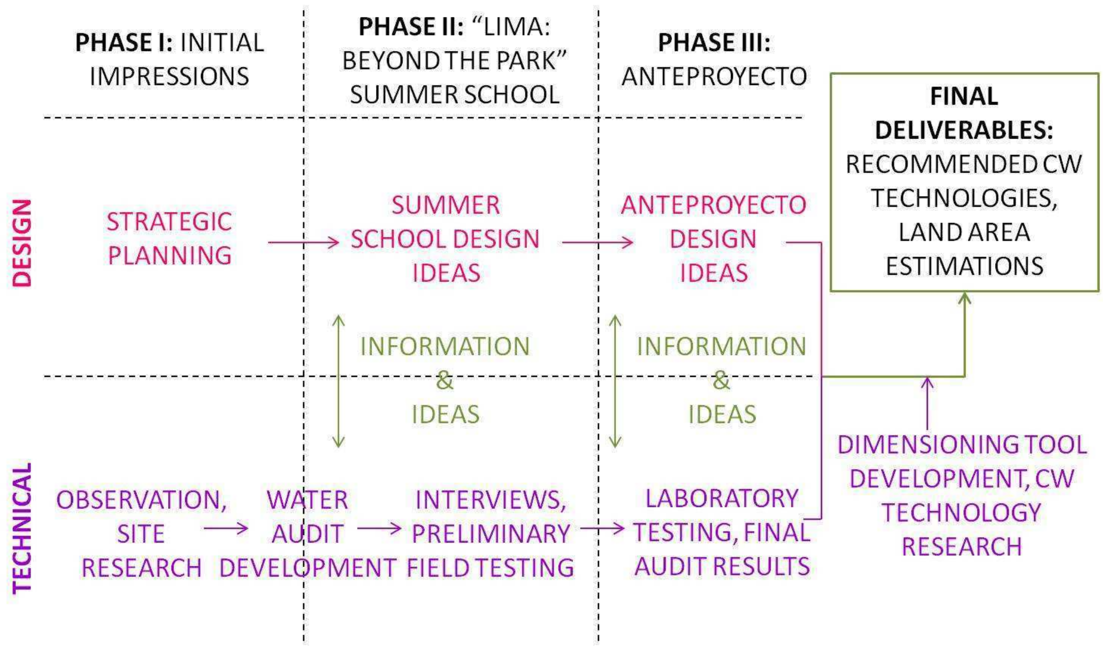


Figure 1.10: Schematic illustrating work flow throughout preliminary phases of Chuquitanta WSUD project, with points of interaction between design and technical work and final deliverables.

of the land area these configurations would require, would not only fulfill technical requirements for water treatment or utilization within the study area, but also be specifically catered to the vision embodied in the proposed designs.

In summary, the three major goals of the work presented in this thesis were as follows:

1. To develop and conduct a water audit in order to rapidly produce a set of data which adequately characterizes the quantity and quality of water sources in Chuquitanta for the purpose of their application in WSUD concepts which incorporate constructed wetlands for the treatment of wastewater and/or polluted surface water for reuse in the irrigation of urban agriculture and green areas.

2. To support WP9 by utilizing final audit results to:

   (a) guide and refine student design work throughout the preliminary phases of the WSUD project, and

   (b) generate suggestions for technically feasible and design-appropriate constructed wetland configurations which could be incorporated into WSUD prototypes developed for various water sources in Chuquitanta, with an estimation of the land area they require. Fulfillment of this objective involved the development of an Excel-based tool for wetland area estimation.

3. To challenge the traditional parallelism of the preliminary design and technical phases of an infrastructure development project by encouraging interaction and communication between design and technical work and promoting the sharing of information and ideas towards the goal of generating more robust design prototypes at early project stages.

2 Developing a Water Audit

2.1 Organizational Phase I: Initial Impressions

Technical and design work carried out during Phase I of the preliminary development of WSUD concepts for Chuquitanta was aimed at becoming familiar with the project area and its water resources and developing initial ideas about how local water resources might be managed in a more sustainable and integrated way.

2.1.1 Phase I Technical Work

The technical part of Phase I was primarily devoted to gaining a basic understanding of the project sites in and near northeastern Chuquitanta, especially with regard to available water resources and their management. While some quantitative information was gathered in this phase, the focus was not on the collection of numerical data, but rather on gaining a sense of the state of affairs in the study area. Chuquitanta is located in the northwestern part of San Martín de Porres (SMP), a district in northern Lima which borders the Province of Callao to the west (District of Callao) and northwest (District of Ventanilla), and the following districts in the Province of Lima: the District of Puente Piedra to the northeast, the Districts of Los Olivos, Independencia and Rímac to the east, and the District of Lima to the south. The Rímac River forms SMP's southern border while the Chillón River forms its northern border (Figure 2.1). The neighborhood bordering Chuquitanta to the east, also within SMP, is San Diego. Land in Chuquitanta is primarily used for residential or agricultural purposes, with some commercial activity. Most of the residential development is informal and illegal, though more than half of inhabitants have lived in the area for more than 15 years. Roughly 14% of inhabitants are children under age 12 while 16% are children between the ages of 13 and 18; average household income is estimated at 1525 PEN (roughly 475 EUR). [87] Most land in Chuquitanta is devoted to agriculture; products grown in the area include lettuce, onions, cabbage and corn, and field parcel sizes range from 0.25 to 4 hectares. [57] Commercial activity includes small general stores and eateries, as well as (illegal) livestock farming.

There are six major water sources in or near the northeastern part of Chuquitanta

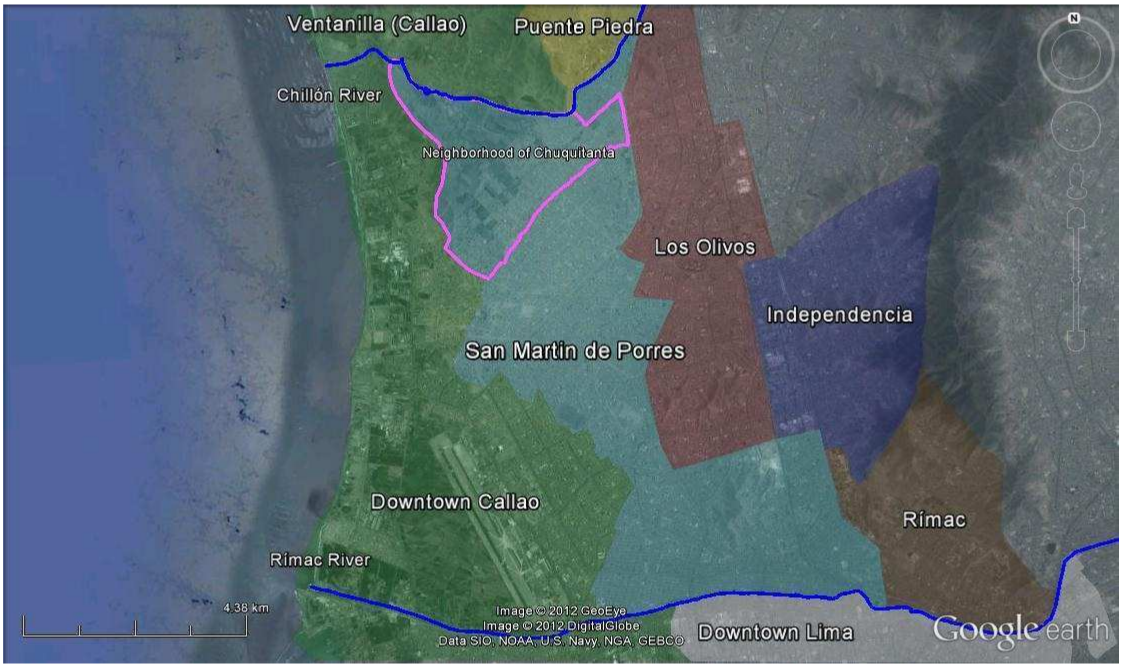


Figure 2.1: The neighborhood of Chuquitanta is located in the northwestern corner of the District of San Martín de Porres, shown here with bordering districts and two of Lima's three rivers to the north and south.

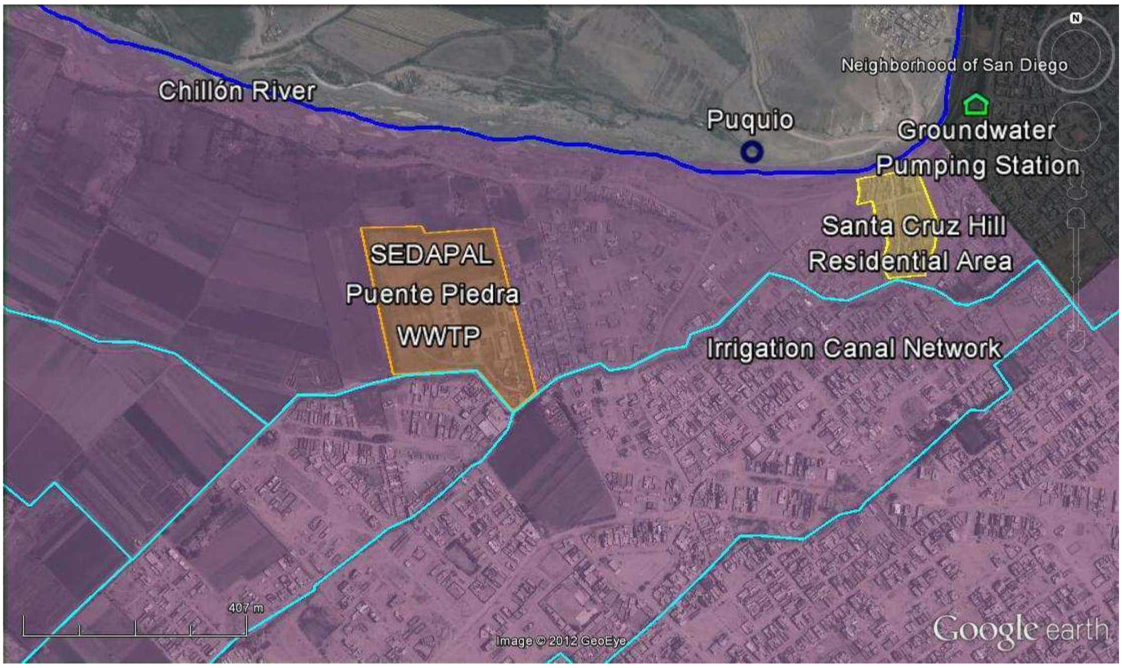


Figure 2.2: Six major water water sources in or near northeastern Chuquitanta were considered in this study. The area shaded in pink is within Chuquitanta; that shaded in dark grey is within the adjacent neighborhood of San Diego (also in SMP).

(a) Chillón River in February 2012 [photo: Emma Hillard]

(b) Chillón River in November 2011

Figure 2.3: The flow of the Chillón River varies greatly throughout the year; (a) during the period of high flow between Dec. and Apr. flow rates have risen to 28,000 L/s during flooding events [3] while (b) during the period of low flow from May to Nov. flow can cease entirely.

which were explored in the context of this study: the Chillón River, effluent from the SEDAPAL Puente Piedra WWTP, groundwater from a local pumping station, a spring or "puquio" forming a small groundwater pond, domestic wastewater from the Santa Cruz Hill residential area, and a network of irrigation canals channeling redirected river water through the neighborhood (Figure 2.2). For various reasons related to project development, not all of these sources were explored in Phase II or evaluated in the final audit during Phase III, but considered together they do give a complete picture of local water availability, usage and management and were therefore all explored in this phase of the study.

For much of the year, the **Chillón River** is a major water element in the study area, though there are annual periods when it runs dry (Figure 2.3). River flow rates experienced at the project site are artificial; they are manipulated first in the management of a system of Andean reservoirs far upstream which contains the source waters of the Chillón, and again further downstream (though still upstream of Chuquitanta) as water is diverted from the river for the production of drinking water or for agricultural irrigation. Despite these human interventions, Chillón River flow volumes increase dramatically as the result of upstream rain events. For example, the flow rate of the Chillón River in Lima increased 128% to 24.3 m^3/s as a result of upstream rainfall in February 2012; though the river flow rate did not reach the historical maximum of 28 m^3/s at this time, it was a cause for concern. [3] Local flooding often occurs when the volume of the Chillón River increases, and results can be severe; an Inca bridge which used to span the river in northeastern Chuquitanta was washed away by flooding which occurred several years ago [80], and river flooding in 2001 affected 500 homes in SMP. [91] Since that time, the municipal government of SMP has erected some flood retention walls (gabions) along the Chillón directly upstream of the study area in the neighborhood of San Diego, which because of its low elevation and high water table is particularly prone to flooding, but as of 2010 SMP did not have the finances necessary to extend this infrastructure to Chuquitanta. [26] Though a dike separates riverside settlements from the Chillón in the study area, river banks are not reinforced here, and annual preventative flood protection measures such as sediment removal from the river channel are not always carried out due to the limited availability of required machinery. [108] The threat of local flooding events in the area has increased as more and more solid waste has been illegally dumped into the river or dry riverbed, further impeding the river's natural course and forcing water into riverside settlements. [91] The residential flooding problem is not helped in that, especially in areas along the Lower Chillón both up- and downstream of the project site, people have settled not only in the floodplain, but in the river channel itself; it seems not uncommon for solid waste to be dumped in the riverbed during periods of low flow, leveled out, and then rapidly built up with informal residential structures, all in a matter of days. [6] With regard to water quality, general consensus amongst the locals is that Chillón River water is too dirty to drink or use for household purposes. This is a reasonable assumption considering the diversity of legal and illegal activities conducted in the Upper and Middle Chillón catchments, or upstream of the project site in the Lower Chillón catchment, which could impact river water quality in the project area. These include agriculture and animal husbandry, industrial activities, mining, the channeling of domestic wastewater into the river and the dumping and/or burning of solid waste. The illegal dumping of industrial and especially mining waste in the river is acknowledged as a particularly significant problem, but effective emissions monitoring and mining facility inspections by government authorities have been hampered by a lack of available resources and low accountability. [85] It is also worth noting that just downstream of the study area, within Chuquitanta as well as across the river in the District of Ventanilla, significant tracts of riverside land are devoted to illegal pig farming. Pigs are fed with unsorted solid waste, and the river likely receives most of the by-products from this activity. River water quality downstream of the study area is also affected by solid waste which is illegally dumped into the river or burned in the riverbed, agricultural runoff, and the dumping of domestic wastewater. [36], [80]

The **Puente Piedra WWTP** was built in 2002 on 6 hectares of land in Chuquitanta for the treatment of domestic wastewater from 150,000 inhabitants of Puente Piedra, Chaclacayo, Ate Vitarte, Santa Anita and other districts in northern Lima (NOT including SMP. Despite the wastewater treatment plant in their backyard, residents of Chuquitanta remain without connection to the public sewerage system, in part because the legality of their claims to the land they live on is questioned.) At a

Figure 2.4: Outflow from the SEDAPAL Puente Piedra WWTP is used to irrigate local agriculture. [photo: ILPÖ]

cost of 9.5 million USD (roughly 75% provided by the World Bank and 25% by SEDAPAL), the WWTP was equipped with the most advanced wastewater treatment technology employed in Lima at the time, and was lauded as a means for reducing pollution of the Chillón River and Pacific Ocean as well as health risks related to the irrigation of vegetables with untreated wastewater. [59] The plant was designed to process 422 L/s (36,460 m^3/day) of wastewater for reuse in irrigation of agricultural areas and other green spaces in the Chillón River Valley. As designed, biological treatment is via activated sludge and aeration/sedimentation steps carried out in a three-chamber modified sequencing batch reactor (CSBR-3); the first two chambers alternate between sedimentation and aeration processes, while the third is used for aeration only. Mechanical pre-treatment with an automatic screening chamber and removal of sand and fats/oil along with final disinfection using chlorine round out the treatment process; sludge is treated by thickening, dewatering and drying in a centrifuge in preparation for landfilling. When operated as designed, the plant reduces organic load, partially removes nitrogen, and lowers thermotolerant coliform counts to levels suitable for reuse of the effluent in irrigation. [95] However, influent volumes and organic loads higher than those which the plant was designed to handle have caused major operational problems, and the effluent released into open channels in Chuquitanta is generally malodorous and of visibly poor quality (Figure 2.4). Despite this, it is still used for irrigation of agriculture in the surrounding area, though not in full capacity since the treatment plant outflow is located at an

(a) Extraction well with tubing

(b) Groundwater pump in San Diego

Figure 2.5: San Diego's pumping station was erected to prevent flooding in areas where the groundwater table is high and to provide water for irrigation of green spaces throughout SMP.

elevation below that of most surrounding agriculture. [75] SEDAPAL plans to upgrade and/or expand this facility in the future, though detailed plans for this are unavailable.

Between 2008 and 2010, the municipal government of SMP erected a **groundwater pumping station** just outside Chuquitanta in the neighborhood of San Diego. The long-term goal was to extract groundwater from parts of San Diego where the water table is naturally high (in some places shallower than 4 mbgl) in order to reduce their susceptibility to flooding [125], and then to route the extracted water into a system of subterranean reservoirs for subsequent use in the irrigation of green spaces throughout SMP. Two extraction wells (Figure 2.5a) and two 50 hp electric pumps (Figure 2.5b) were installed to withdraw 80-100 L/s of groundwater collected in a 3 m-deep drainage piping matrix. 10 km of the pipe network necessary for transfer of the extracted groundwater to sub-surface holding tanks were also laid, but because holding tanks have not yet been constructed, extracted groundwater is currently transported by truck for use in irrigation of green areas throughout the municipality. [78] In the future, the municipality would like to transport effluent from the Puente Piedra WWTP for use in irrigation throughout SMP via the same pipe network currently under construction for the transport of groundwater, alternating between the two flow streams rather than mixing them.

The groundwater pumping station in San Diego is not in operation all day or every day; further, often more groundwater flows through the subterranean drainage matrix than the pumping station is equipped to extract. Non-extracted groundwater flows by gravity through the subsurface matrix to a ground outlet located on the opposite side of the Chillón River in the District of Ventanilla (Province of Callao) to form a

Figure 2.6: The puquio in Ventanilla (Callao) is a small pond which is fed by a matrix of drainage pipes that carry groundwater from an area near the pumping station in San Diego.

small pond which locals call the "**puquio**", a Quechua word meaning "spring" (Figure 2.6). Ownership of and jurisdiction over the puquio is in question and the controversy is mired in rumors and misinformation. SMP believes that since it is fed by water from their district, the puquio belongs to them, while Ventanilla argues that since it is located on their land, they own and control the puquio. A large "private property" sign and rumors that the puquio actually belongs to the same individual who owns adjacent agricultural land complicates matters; so do claims from representatives of SMP that the drainage matrix outlet was originally in the Chillón riverbed, but that during a dry period the government of Callao used heavy machinery to alter the river channel such that the puquio outlet was subsequently situated on the bank on their side of the river. Regardless of who owns it, the puquio is used by everyone, including residents of Chuquitanta and San Diego (who reach Ventanilla via a pedestrian bridge over the Chillón located just upstream of the groundwater pumping station in San Diego) as well as people from Ventanilla, Puente Piedra, and more distant districts. It also seems to be used for a variety of purposes including swimming and recreation, bathing, clothes washing, mototaxi washing, and irrigation. [17] The puquio water is clear and cool, and supports a population of small fish.

The **residential area on Santa Cruz Hill (SCH)** is one of several in Chuquitanta with no connection to the public water supply or sewerage networks (Figure 2.7). As

Figure 2.7: The residential community on Santa Cruz Hill is one of several settlements in Chuquitanta without connection to Lima's piped water supply or sewerage networks. [photo: ILPÖ]

one of the oldest established residential areas in Chuquitanta, SCH is particularly well-organized with respect to political activism and community involvement, and residents have achieved much as a result of their collective efforts. Community members have formed themselves into committees which organize and carry out common services such as the collection of trash and recyclables and the fair distribution of government food assistance to families with children, etc. They also successfully lobbied for connection to the municipal electricity network several years ago. SCH has now turned its focus to bringing piped water supply and sewerage connections to the community, and hopes to achieve this in the next few years. For now, potable water is delivered by truck and stored in plastic or metal cisterns outside homes. Domestic greywater is generally discarded in the street, often as a means for controlling dust; no formal latrine or other hygienic facilities are available and it is assumed that blackwater generally finds its way into the river. [17] An interview with community representatives yielded the following demographic and water consumption-related information for SCH: there are about 59 households in SCH, and the average household size is 5 people. Each household has 3-4 cisterns for storing potable water; a cistern has an average volume of 200 L. In general, one household requires about 1 cistern of potable water per day for domestic needs. Water delivery trucks visit Chuquitanta about 3 times per week, but sometimes run out of water at the base of the hill, leaving households at the top without enough. Residents pay about 2 PEN (roughly 0.62 EUR) per cis-

Figure 2.8: The network of canals which passes through Chuquitanta carries water diverted from the Chillón River for use in flood irrigation of local agriculture; the opening and closing of sluice gates along the network controls the inundation of field parcels. [57] [photo: ILPÖ]

tern of potable water, which equates to on average 10 PEN (roughly 3.10 EUR) per m^3.

The final water source in or near Chuquitanta considered within the context of this study is the **network of irrigation canals** which snakes through the neighborhood. The network of open channels is fed by water diverted from the Chillón River at a point upstream of the study area in Los Olivos and is used for irrigation of roughly 23 hectares of agriculture in Chuquitanta and 24 hectares further downstream in the neighborhood of Oquendo (Callao). Local irrigation infrastructure was built in the 1960s and utilizes basic technology: irrigation is by flooding controlled at each field parcel via the opening or closing of a sluice gate (Figure 2.8). The canal network serving Chuquitanta and Oquendo is one of 17 serving the Lower Chillón River Valley. [92] The total monthly volume of river water diverted into each of these irrigation canal networks is determined by Peru's Autoridad Nacional del Agua (ANA) (English: National Water Authority) according to seasonal river flow rates, the volume of river water reserved for potable water production, and estimated water demand of the crops irrigated using the canal systems. In turn, water usage within each canal network is managed by a local irrigation board made up of farmers; decisions regarding the canal network in Chuquitanta are made by two boards: that of Chuquitanta and that of Oquendo. Members of the irrigation board meet weekly to create an irrigation schedule for the field parcels serviced by their canal network based on the type of crop being grown and the area planted, seasonal weather conditions, and the amount of water which has been allocated to their canal network that month. In general however, it can be assumed that each field parcel is irrigated at least once a week. The amount of water diverted into the network of canals passing through Chuquitanta varies throughout the year; during the upstream rainy season between December and April, flow rates are typically between 800 and 1000 L/s, while between May and November they decrease to between 40 and 50 L/s, but do not fall to 0. Flow rates also vary throughout the day and with location along the network depending on which fields are being irrigated at what time. Regardless of what crops are grown and how much water they require, farmers pay 250 PEN (roughly 78 EUR)/hectare/year for their irrigation water, a portion of which goes towards reimbursement of local irrigation board members. [57] The demand for housing in Lima Metropolitana has generally made it more profitable to sell land for residential development than to farm it, and because agricultural land is not protected by zoning laws, it is disappearing from the city. Much former agricultural land in Chuquitanta is now built up, and sections of the irrigation network which serviced these areas have consequently been closed off. Other parts of the network now pass through residential developments on their way to the fields. Domestic grey- and blackwater are often dumped into these sections of the network, along with so much solid waste that irrigation board members meet monthly to clear the canals of trash in order to ensure that water reaches the fields beyond. Residents have also called for the covering of open channels in settled areas for health and safety reasons.

2.1.2 Phase I Design Work

In the design part of Phase I, carried out in Stuttgart during Winter Semester 2011/12, German architecture students focused on the exploration of WSUD concepts for an ecological park which might be appropriate for implementation with the different water types present in Chuquitanta or elsewhere in Lima. Their main ideas at the end of this phase are briefly summarized as follows:

- *Green Lifeblood Irrigation Park* for Chuquitanta's irrigation canals: It is inevitable that agricultural areas in Chuquitanta will be replaced by residential settlements, and that the people living in these settlements will need water. The system of irrigation canals is an established network connecting local green spaces, and especially because water flows through them year round, rather than covering it over, the connective function of this network could be exploited in a future recreational space to bring people together around water.

- *The Colourful Grey* for Chuquitanta's irrigation canals: Rural and urban spaces meet in Chuquitanta and are connected via its network of irrigation canals. In anticipation of future urban expansion along these waterways, wastewater and solid waste streams could be optimized to reduce local pollution via the introduction of constructed wetlands for the treatment and reuse of canal water and the development of systems for the collection, sorting and recycling of solid waste which is currently discarded in the canals.

– *Re-Cycles Park* for the Chillón River in Chuquitanta: Much as the pig farms of Ventanilla have succeeded through the unconventional practice of recycling solid waste by using it as livestock feed, the key to a truly sustainable riverside park in Chuquitanta might lie in incorporating the recycling and reuse of water and materials wherever possible towards the improvement of water and soil quality and the provision of flood protection. Implemented recycling systems could be specialized for local conditions and serve as an example of integrated waste management to all of Lima.

– *Phase Change* for the Chillón River in Chuquitanta: By integrating the functions of the local irrigation canals and the WWTP with new surface and sub-surface flow constructed wetlands, river water quality could be improved and maintained while river volumes are effectively managed in all flow phases, i.e., in seasonal low- and high-water periods, as well as during extreme El Niño-influenced events.

– *The Valley of Gardens* for the neighborhood of Chuquitanta and beyond: To foster a cohesive yet diverse garden community which is ecologically aware and engaged, different types of green space could be employed for a diversity of purposes in and near Chuquitanta: backyard gardens and green corridors to green the densely settled area to the south, farms providing learning and economic opportunities in the neighborhood's agricultural areas, recreational green space along the Chillón River, and a naturally dry wilderness in the hills of Ventanilla.

– *The Rising One - Let it Grow!* for the neighborhood of Chuquitanta and beyond: A park could grow step-by-step starting with treatment and reuse of domestic wastewater in a vegetable garden at a local school, expanding to treatment and reuse of WWTP effluent for more extensive irrigation and groundwater recharge, then incorporating steps for river renaturation to protect against local flooding and to support natural wildlife habitats, and finally to support a network of urban agriculture criss-crossing the city.

– *Lurín(e)Scape* for the Lower Lurín River Watershed: In the face of increasing pressure from residential and industrial development, an integrated development strategy for the Lower Lurín Valley which incorporates traditional technologies for water management, constructed wetlands, agricultural terracing, and recreational and educational infrastructure will help preserve the area as Lima's agricultural center and rural escape.

2.2 Selection of audit parameters and auditing methods

From the end of Phase I through the beginning of Phase II, a strategy was developed for undertaking a water audit in Chuquitanta. In particular, the set of parameters to be evaluated in the audit was established, along with the method which would be used to determine the value of each parameter for each source.

Several considerations were made in order to decide which set of parameters would give the best overview of the quantities and qualities of the six water sources described in Section 2.1.1. It was decided early on that information on the quantity of water contained in or flowing through each source should be collected, with consideration of how that amount might vary with time (ex., over the course of a day, throughout the year, etc.) With regard to quality parameters, constraints related to money, time and logistics made it clear that the same set of water quality parameters would be evaluated at each source, ex., it would not be the case that levels of heavy metals would be measured at the river and canal, but not in domestic wastewater, or that AOX would be measured at the WWTP, but not for any of the other sources, etc. But which set of quality parameters would provide an adequate overview of such a diverse set of water sources? Thought was first given to which parameters are generally considered in assessments of surface waters and wastewaters. In order to facilitate this decision-making process, quality parameters were grouped into several broad categories; shown in **bold** are those water quality parameters which can be directly measured:

– *Temperature*: **Temperature** affects the rates of biological and chemical processes in water and affects the health of aquatic organisms. The typical temperature range experienced in a water body largely dictates which species of fish will be found there, and also has a direct relationship to levels of dissolved oxygen (DO) (as temperature increases, DO decreases) and the rate of photosynthesis in aquatic plants. Temperature is measured in degrees Celsius or Fahrenheit. [113]

– *Oxygen Balance*: The amount of oxygen in a water body is often measured in its dissolved form as **dissolved oxygen (DO)**. In water bodies, DO is gained from the atmosphere and through photosynthesis by aquatic plants and consumed via the respiration of aquatic animals, the decomposition of organic matter, and in various other chemical reactions. Because of its churning, running water dissolves more oxygen from the atmosphere than still water, and DO levels are therefore typically higher in rivers and streams than in lakes or ponds. As mentioned, temperature also influences DO levels, as does altitude (as altitude increases, DO decreases). DO is measured in mg/L or % saturation. **Biochemical oxygen demand (BOD)** is a measure of the amount of oxygen consumed by microorganisms as they decompose organic matter in water, and as such is an indirect indicator of the amount of organic matter present. Organic materials in the form of leaves and woody debris, dead animals and plants, and animal manure are often present in waterbodies and contribute to a balanced ecosystem. However, in waters which receive large additional volumes of organic material in the form of untreated sewage waste or stormwater runoff from urban streets or agricultural areas, high rates of organic matter decomposition (i.e., high BOD levels) may cause DO levels to drop to the extent that the water body can no longer support aquatic plant or animal life. Tests for measuring BOD consider the amount of oxygen consumed by organisms over a specific period of time and at a certain temperature, usually 5 days at 20°C via the BOD_5 test. The rate of oxygen consumption by microorganisms during decomposition is affected by temperature, pH, the type and number of microorganisms present, and the types of organic and inorganic materials in the water. The greater the BOD, the more rapidly oxygen is consumed by microorganisms and the less DO is available to support other aquatic plant and animal life. [11], [113]

Though BOD_5 is the most established and widely used indicator for the amount of organic matter in water, levels of organic matter can also be measured via a faster indirect test for chemical oxygen demand (COD) or directly as total organic carbon (TOC). **Chemical oxygen demand (COD)** is a measure not only of the amount of oxygen consumed by microorganisms as they decompose *organic* matter in water, but also the amount of oxygen extracted from water during chemical reactions involving *inorganic* matter in water (i.e., chemical oxidation). COD tests are generally much faster than the BOD_5 test (some only take 2-3 hours) and yield results which are higher than or in some cases equal to (but never lower than) those for BOD_5. That being said, there is no fixed ratio between BOD_5 and COD or between BOD and COD, though it is possible to develop non-generalizable correlations between the two parameters for a specific pollutant in a specific waterbody. **Total organic carbon (TOC)** is a direct measure of the amount of organic matter in water which was specifically developed as a technique for measuring the quality of drinking water. BOD, COD and TOC are all measured in mg/L. [11], [113]

– *Salt Content*: Salts are ionic compounds, many of which dissolve in water to negatively-charged anions such as **chloride** ($\mathbf{Cl^-}$), **nitrate** ($\mathbf{NO_3^-}$), **sulfate** ($\mathbf{SO_4^{2-}}$), **phosphate** ($\mathbf{PO_4^{3-}}$), **bicarbonate** ($\mathbf{HCO_3^-}$), and **carbonate** ($\mathbf{CO_3^{2-}}$) and positively-charged cations such as **sodium** ($\mathbf{Na^+}$), **magnesium** ($\mathbf{Mg^{2+}}$), **calcium** ($\mathbf{Ca^{2+}}$), **iron** ($\mathbf{Fe^{2+}}$ **and** $\mathbf{Fe^{3+}}$), and **aluminum** ($\mathbf{Al^{3+}}$), among others. Base levels of salts in surface waters are largely influenced by the presence or absence of ionizable materials in the geology of the area through which surface waters or contributing groundwaters flow. Positive and negative deviations from natural levels can indicate the influence of pollutant streams; for example, sewage discharge would raise levels of Cl^-, NO_3^- and PO_4^{3-}. High salt levels in freshwater bodies or in water used for irrigation can negatively affect native plant and animal life and contribute to soil and groundwater salinization. Levels of individual salts in water can be measured (in mg/L) using tests for concentration, while overall salt content can be measured via electric conductivity (EC). **Electric conductivity (EC)** is measure of the ability of a medium to pass electrical current. The presence of anions and cations facilitate the passing of electrical current through water and generally the higher the EC, the higher the salt content in the water. Because temperature also has an affect on EC (as temperature increases, EC increases), EC readings are typically reported as conductivity at 25°C. EC is measured in microsiemens per centimeter (μs/cm). [11], [113]

– *Acidity/Alkalinity*: The acidity or alkalinity of water can be determined on a scale of 1.0 (acidic) to 14.0 (basic/alkaline) as **pH**. As described by the United States Environmental Protection Agency, "The pH scale measures the logarithmic concentration of hydrogen (H^+) and hydroxide (OH^-) ions which make up water...When both types of ions are in equal concentration, the pH is 7.0 or neutral. Below 7.0, the water is acidic (there are more hydrogen ions than hydroxide ions). When the pH is above 7.0, the water is alkaline, or basic (there are more hydroxide ions than hydrogen ions). Since the scale is logarithmic, a drop in the pH by 1.0 unit is equivalent to a 10-fold increase in acidity." pH levels affect many biological and chemical processes which occur in water; levels between 6.5 and 8.0 are conducive to the largest variety of aquatic life. [11], [113]

  pH levels in water bodies can increase or decrease due to the influence of domestic and industrial wastewaters and the occurrence of acid rain. **Total alkalinity** is an indicator of a water body's ability to neutralize acidic pollution from sources such as these. Alkaline compounds such as HCO_3^-, CO_3^{2-} and OH^- which are present in the water are able to combine with H^+ introduced by acidic influences to make new (neutral pH) compounds, keeping the acidity of the water low and acting as a buffer against decreasing pH. The higher the number of alkaline compounds in the body of water, i.e., the higher the total alkalinity, the less sensitive the body of water is to extreme changes in pH caused by acidic inputs. Total alkalinity is measured by measuring the amount of acid needed to raise the pH of a water sample to 4.2 (i.e., the pH at which all of the alkaline compounds in the sample will have been incorporated into new compounds and where the alkaline buffering capacity will thus be exhausted). Total alkalinity is measured in mg/L of calcium carbonate ($CaCO_3$). [11], [113]

– *Nutrient Content*: Nutrients are essential substances that an organism needs to live and grow. The most important nutrients for plants which are not derived from water are nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), sulfur (S) and calcium (Ca). Nitrogen and phosphorus compounds can have very negative effects on surface water bodies when present in certain forms or large amounts, and monitoring levels of these parameters is important to the proper assessment of water quality. Nitrogen in the environment is converted between its various chemical forms according to what is known as the nitrogen cycle. Nitrogen can enter water bodies in several forms, including as organic nitrogen (N_{org}) from urea in domestic wastewater discharge. The cycle begins with the partial conversion of organic nitrogen by bacteria to nitrogen which exists in the form of ammonium (i.e., **ammonium-nitrogen (NH_4-N)**). This in turn is oxidized by oxygen-consuming microorganisms to **nitrate-nitrogen (NO_3-N)** in a process known as nitrification. NO_3^- can also enter water bodies directly via agricultural runoff which contains excess nitrogen-based fertilizers, or via industrial discharge. Depending on pH and temperature in the water body, excess NH_4^+ may also be converted to **ammonia (NH_3)**, which is very toxic to fish. Also, incomplete oxidation of NH_4-N during nitrification can lead to the formation of **nitrite (NO_2^-)**, which is also toxic to fish and when ingested causes cancer in humans. As an important nutrient for algae, elevated amounts of NO_3^- in water bodies can rapidly lead to eutrophic conditions in which low dissolved oxygen levels threaten aquatic plant and animal life. Ingestion of NO_3^--rich water also causes methemoglobinemia, or "blue baby syndrome," a condition which affects the oxygen-carrying capacity of the blood in newborn babies and can lead to death. In the next step of the nitrogen cycle, under conditions of low dissolved oxygen, NO_3-N is converted by heterotrophic microorganisms to gaseous, elementary nitrogen (N_2) which enters the atmosphere. Plants then fixate atmospheric nitrogen to meet their nutritional needs; they are in turn consumed by animals and humans, and the cycle begins again. **Total Kjeldahl nitrogen (TKN)** is the sum of organic nitrogen, NH_3-N, and NH_4-N, and is a helpful parameter to measure when trying to determine N_{org}, a parameter which is not directly measurable. **Total nitrogen (N_{tot})** is the sum of TKN, NO_3-N and NO_2-N. In general, NO_3-N is the best nutrient indicator for wastewater pollution in dry climates because NO_3^- dissolves readily in water, facilitating its rapid detection in water bodies. Other nutrients like PO_4-P, which has a greater tendency to adsorb to soil particles than to dissolve in water, could be present in the environment long before they are detected in surface water (in some cases, detection is only possible after a rain event causes the erosion of soil into water bodies). [11], [102], [113]

Phosphorus is another important nutrient which warrants monitoring in water bodies. Even at only moderately elevated levels, phosphorus can cause significant eutrophication in water bodies because it naturally occurs in only very low amounts. Elemental phosphorus (P) is rare in nature, and instead usually occurs as phosphate (PO_4-P) in either an inorganic (ex., orthophosphate, polyphosphate) or organic form. PO_4-P in water bodies can come from domestic wastewater (via raw sewage and from detergents in greywater), agricultural runoff (containing excess phosphorus-based fertilizers), industrial wastewater, or from natural sources such as dead animals, animal waste and geology. Phosphorus levels in water bodies can be measured in unfiltered samples as **orthophosphate (PO_4-P)**, in filtered samples as **dissolved phosphorus**, and in unfiltered, digested samples as **total phosphorus (P_{tot})**, which includes inorganic and organic phosphorus in both dissolved and particulate states. Concentration of all nutrients and nutrient forms in water samples is measured in mg/L. [11], [102], [113]

– *Microbiology*: Levels of bacteria commonly found in the feces of humans and animals are often tested in waters as an indicator of sewage pollution. These bacteria are generally not harmful themselves, but their detection indicates the possible presence of pathogenic bacteria, viruses, and protozoans that also live in human and animal digestive systems but are much more time-consuming and expensive to test for directly. The most commonly tested fecal bacteria indicators are **total coliforms**, **fecal coliforms**, ***Escherichia coli***, **fecal streptococci**, and **enterococci**. All coliforms can occur in human feces, but some can also be present in animal manure, soil, and submerged wood and in other places outside the human body. For this reason, fecal coliforms and also **thermotolerant coliforms** (distinguished from total coliforms in that they tolerate elevated incubation temperatures during culturing) have been preferred over total coliforms as more fecal-specific indicators, though they too can be found in other places. *Escherichia coli* is a fecal bacteria specific to fecal material from humans and other warm-blooded animals; until recently it was difficult to measure but advances have made testing more straightforward and it is now the preferred fecal bacteria indicator in water quality testing. Enterococci, a subset of fecal streptococci, is frequently used as an indicator for human fecal material in salt water. ***Salmonella*** is a pathogenic bacteria (i.e., not an indicator) which can cause gastrointestinal problems in humans and which is often transmitted in raw or uncooked food or via water polluted by animal feces. Bacteria levels are measured in units of "most probable number" (MPN) per volume, i.e., the statistically likely number of bacteria in the sample based on the number of bacteria counted in a dilution. If ingested, **parasitic worm (helminth) eggs and cysts** can spawn parasites which live in the human digestive tract and act to disrupt nutrient absorption, leading to disease. In addition to polluted water, infected food, mosquitoes, and infected soil can act as a vector for helminths. Levels of parasitic worm eggs and cysts are given in count per volume. [37], [113]

– *Other*: Additional parameters which may be helpful in the characterization of water qualities include **taste**, **odor** and **color**; **total solids**, **total suspended**

solids (TSS) and **turbidity**; **fats & oils**; **total hardness** and **carbonate hardness**; heavy metals and metalloids such as **cadmium (Cd)**, **copper (Cu)**, **chromium (Cr)**, **iron (Fe)**, **manganese (Mn)**, **lead (Pb)**, and **zinc (Zn)**; **adsorbable organohalogens (AOX)**, harmful by-products which result from the application of common disinfectants such as chlorine to wastewater or other waters containing elevated levels of organic matter; organic and inorganic chemicals and other pollutants from industry and mining; pesticides, herbicides and other pollutants from agriculture; radioactive pollutants; and pharmaceutical and hormonal pollutants. Much of the organic content in water is contained in suspended and settleable solids, and high levels of these parameters can indicate pollution. Further, toxic substances including excess pesticides in agricultural runoff cling to suspended solids in water that passes through irrigation canals, causing problems for the water bodies into which the canal systems discharge. High TSS levels can also cause operational problems in irrigation systems and WWTPs, and along with high turbidity levels, slow photosynthesis, increase water temperatures and lower levels of DO in surface water bodies. Elevated levels of fats & oils or of total or carbonate hardness can cause clogging problems in irrigation systems and WWTPs and are thus important to monitor, while high heavy metals levels can be toxic to human and animal life and should also be controlled. [53], [113]

The first consideration made in deciding which set of quality parameters would give the best overview of water sources in Chuquitanta was: *which of the water quality parameters described above are typically considered in the assessment of surface waters and wastewaters in Germany and in Perú?* The two countries differ greatly in terms of the number and type of parameters normally measured. Germany typically monitors a very wide variety of parameters in surface waters and wastewaters discharged into surface water bodies which covers all of the categories listed above and includes many parameters which are not described here. The monitoring of microbiological parameters is not of extreme importance in Germany as levels don't tend to be high enough to pose a threat to surface water qualities or human health, and the focus in wastewater treatment and water quality monitoring is moving towards the development of specialized or optimized treatment technologies, ex., for the reduction of pharmaceutical pollutants in WWTP effluent and surface water bodies, for innovative and more efficient methods for recovering nutrients from wastewater, etc. On the other hand, the three most important parameters for assessing wastewater and surface water qualities in Perú are BOD_5, total coliforms, and parasitic worm (helminth) eggs/cysts. Threats to human health from bacteria and other water-borne pathogens are very real in Perú: few have forgotten the cholera epidemics of the 1990s which were fueled by poor sanitary conditions and low drinking water qualities and which killed thousands and infected millions of people. [97] As such, levels of microbiological parameters are generally monitored in surface- and wastewaters. At treatment plants, parameters which affect operations such as temperature and TSS may also be measured, and in the case of pollution issues which have recently received a lot of public attention, ex., the contamination of Lima's rivers by industrial and mining waste, additional relevant parameters (ex., levels of heavy metals in the Chillón River and other rivers in Lima and Perú) may be monitored as well. Nutrient content seems to be only very rarely measured in water bodies and effluent streams, if ever.

The next consideration made was: *which parameter levels in the water sources in Chuquitanta might be affected by "upstream" activities or by day-to-day uses?* Domestic wastewater tends to have a fairly predictable composition which does not change appreciably without significant changes in lifestyle or domestic behavior. Similarly, the quality of the WWTP effluent would likely change only with worsening or improving operating conditions at the plant, and then only with regard to an established set of parameters over a predictable range. If WWTP effluent is chlorinated before it is released from the plant, AOX levels could be a significant problem. Groundwater quality, especially in and near Chuquitanta where the water table is relatively high, is strongly affected by land use. Nutrients from agriculture, salts from agriculture and domestic sewage, and other pollutants from industry or urban settlement could all find their way into the groundwater in Chuquitanta, and consequently into puquio water as well. As the puquio is also used for washing clothes, vehicles, etc., its water also likely contains elevated levels of phosphates, fats & oils, etc. The variety of upstream activities which might affect levels of downstream parameters in the Chillón River and the water in Chuquitanta's irrigation canal system is enormous: mining and industrial activities could affect levels of heavy metals and water temperatures; agricultural runoff could affect levels of chemicals from pesticides and fertilizers as well as nutrient content; the dumping of solid waste and domestic wastewater could affect oxygen balance, acidity, levels of microbiological parameters; erosion and flooding could affect TSS levels; etc...though these were important relationships to think about, approaching the problem in this manner was overwhelming.

An additional consideration made which provided some useful constraints was: *which parameter levels are important to the intended or "downstream" uses of the water sources in Chuquitanta?* The goal was to use constructed wetlands to treat water from the various sources in Chuquitanta for use in irrigation. Constructed wetlands are dimensioned using, among other data, the flow rate and level of BOD_5 in the incoming water. Information about these parameters would be necessary for the determination of estimated wetland sizes. Further, especially because wetlands have been shown effective in reducing levels of nutrients and microbiological parameters, having information about these parameters would help in the determination of projected wetland efficiencies. With regard to the subsequent use of wetland effluent in irrigation, it would be helpful to have information about pH, salt content, heavy metal content, and excess pesticides to ensure that wetland effluent would be suitable

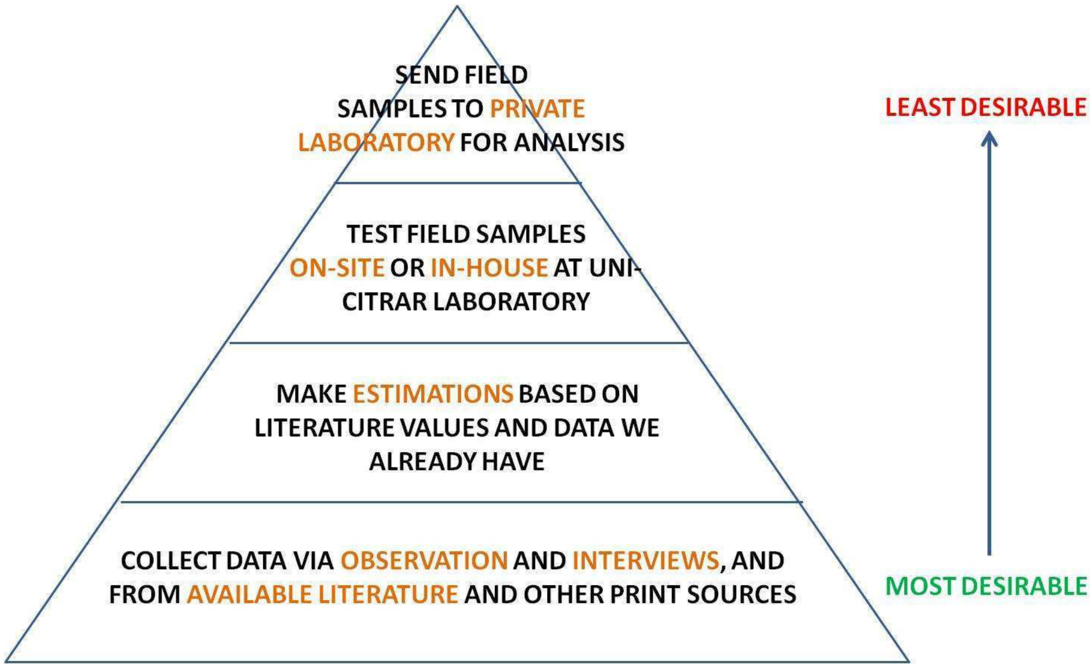


Figure 2.9: Methods used to collect audit information about the water sources in Chuquitanta were prioritized to save money and time and with thought to logistics.

for irrigation and that the proper configurations and plant types were chosen to maximize wetland treatment capabilities. [14]

The final consideration made was: *which parameters are easiest and cheapest to obtain information about?* This consideration is directly related to the choice of methods available for collecting information about water qualities in Chuquitanta, namely: collecting data directly via observation, interviews, available literature and other print sources (i.e., "Data We Have"); making estimations based on information collected via observation, interviews, and print sources (i.e., "Data We Can Estimate"); carrying out field testing or collecting samples in the field for testing "in-house" at the laboratories of the Centro de Investigación en Tratamiento de Aguas Residuales y Residuos Peligrosos at the Universidad Nacional de Ingeniería (English: Center for Research on Wastewater Treatment and Hazardous Waste) (CITRAR-UNI); and collecting samples to send to a private laboratory for testing, in this case EnviroLab Perú S.A.C. (i.e., "Data We Will Measure"). Chuquitanta is a challenging place to conduct a water audit, and in addition to constraints of money and time there were several incentives to keeping parameter testing simple and to a minimum. For one, Chuquitanta is far away from everything, including sizeable stores, computer facilities, laboratory facilities, and even a refrigerator for storing water samples. Everything needed for field sampling or testing had to be carried in and out. The neighborhood is also not particularly safe, and every time the project sites were visited it was with a security escort (generously provided by the municipality of SMP) which had to be taken away from its everyday duties to accompany the testing team. Roads are unpaved, which usually meant a bumpy ride to each source in a pick-up truck full of people and supplies, and dust, sun and heat were especially intense in the summer months when the audit was carried out. Apart from challenges presented at the site, in general equipment and materials needed for water quality testing in Lima are expensive and hard to come by, if they are available at all (see Section 5.1). For all of these reasons, and to save time and money on unnecessary testing, methods for obtaining information about water quality parameters in Chuquitanta were prioritized according to Figure 2.9.

From this point, audit development focused on potential WSUD projects involving the Chillón River, the irrigation canals, domestic wastewater from SCH, and effluent from the Puente Piedra WWTP. The pumping station was not considered in audit development because SMP had already allocated this water for the irrigation of green areas in other parts of the district, while the puquio was left out due to political issues which might impede any development of the source. After determining the parameters for which print information was available or which could be determined via interviews, observation, or estimation for those four sources, decisions were made about additional parameters to measure by testing, largely based on the considerations described above. While domestic wastewater was included in the water audit, it was not considered in the choice of which additional parameters to measure by testing because of health risks involved in handling untreated blackwater and the potential to make good estimates of grey- and blackwater quality based on literature values.

A summary of the parameters which the audit considered for each source, along with the method which was used to collect each piece of information, is shown in Tables 2.1, 2.2, 2.3, and 2.4. Testing equipment which was selected for use in the collection of audit testing results in the field and in-house at CITRAR-UNI included a set of field probes and meters, an Aquamerck® Compact Laboratory for Water Testing, and Merck Spectroquant® Cell Tests (discussed in more detail in future sections). In essence, almost all parameters which could be directly determined for each source via observation, interviews, print sources or reasonably determined via estimation were included in the audit. With regard to the choice of parameters which were selected for determination by testing, DO, temperature, EC and pH were all chosen because of the relative ease with which they can be measured in the field using probes and meters. Because of their importance to constructed wetland dimensioning and efficiency determinations for all sources, the decision was made to measure several nutrient parameters at the in-house laboratory, along with COD, which in comparison to BOD_5 is the much easier indicator of organic content to measure accurately in the laboratory. Cl^- was also selected for measurement as a representative indicator of salt content (along with EC). Finally, the decision was made to send samples to the private laboratory for eval-

Table 2.1: Summary of Source Data for Quality and Quantity Parameters: **SCH Domestic Wastewater**

	Data We Have	**Data We Can Estimate (Method)**	**Data We Will Measure (Method)**
Water Quantity	**avg. household size, avg. cistern size, avg. household water consumption** 2012 [82]; **number of households** 2012 [82], [GIS Data]	**daily per capita wastewater production** (based on number of households, avg. household size, avg. cistern size, avg. household water consumption)	—
Temperature	—	—	—
Oxygen Balance	—	$\mathbf{BOD_5}$ (based on data in Norma OS.090 Sec. 4.3.6)	—
Salt Content	—	—	—
Acidity	—	—	—
Nutrient Content	—	$\mathbf{NO_3}$**-N, TKN,** $\mathbf{P_{tot}}$ (based on data in Norma OS.090 Sec. 4.3.6)	—
Microbiology	—	**fecal coliforms, *Salmonella*, parasitic worm (helminth) eggs/cysts** (based on data in Norma OS.090 Sec. 4.3.6)	—
Other	—	**TSS** (based on data in Norma OS.090 Sec. 4.3.6)	—

Table 2.2: Summary of Source Data for Quality and Quantity Parameters: **Puente Piedra WWTP Effluent**

	Data We Have	**Data We Can Estimate (Method)**	**Data We Will Measure (Method)**
Water Quantity	**actual flow rate** 2003-2010 [43]; **design flow rate** [43], [75]	—	—
Temperature	2002-2010 [43]	—	(hand-held conductivity meter and cell or hand-held oxygen meter and cell)
Oxygen Balance	**actual $\mathbf{BOD_5}$** 2002-2008 [43], [75]; **design $\mathbf{BOD_5}$** [60]; **DO** 2002-2007 [43]	—	**DO** (WTW hand-held oxygen meter Oxi 325 & oxygen sensor CellOx 325), **COD** (Merck Spectroquant® Cell Test 1.14895.0001), **$\mathbf{BOD_5}$** (EnviroLab Perú using EPA 405.1)
Salt Content	—	—	**EC** (WTW hand-held conductivity meter LF 340/SET & standard conductivity cell TetraCon 325), **$\mathbf{Cl^-}$** (Merck Spectroquant® Cell Test 1.14730.0001)
Acidity	**pH** 2002-2010 [43]	—	**pH** (WTW hand-held multimeter pH 91 & probe)
Nutrient Content	—	—	**$\mathbf{NO_3}$-N** (Merck Spectroquant® Cell Test 1.14764.0001, **$\mathbf{NH_4}$-N** (Merck Spectroquant® Cell Test 1.14558.0001), **$\mathbf{PO_4}$-P** & **$\mathbf{P_{tot}}$** (Merck Spectroquant® Cell Test 1.14543.0001)
Microbiology	**total coliforms** 2003-2007 [43]; **actual thermotolerant coliforms** 2003-2008 [43], [75]; **design thermotolerant coliforms** [60]; **parasitic worm (helminth) eggs/cysts** 2008 [75]	—	**total coliforms** (EnviroLab Perú using SM 9221-B), **parasitic worm (helminth) eggs/cysts** (EnviroLab Perú by observation)
Other	**TSS** 2002-2008 [43], [75]	—	—

Table 2.3: Summary of Source Data for Quality and Quantity Parameters: **Chillón River**

	Data We Have	Data We Can Estimate (Method)	Data We Will Measure (Method)
Water Quantity	**flow rate**, Pte. Magdalena (Yangas) May 10, 2007 [96]; **avg. monthly flow rate**, Obrajillo (Canta) Sep 2007 - Aug 2008 [90]; **historical max., min., avg. flow rates**, Pte. Magdalena (Yangas) 1920 - 1998 [1], [40], [77]; **monthly flow rates & volumes diverted for potable water production** [13], [7]; **monthly volumes diverted for irrigation** [7]	**avg. monthly flow rate**, Chuquitanta (based on average monthly flow rates observed at Pte. Magdalena, river flow diverted for potable water production, river flow between Pte. Magdalena and Chuquitanta diverted for irrigation, estimates of river water lost via infiltration and evapotranspiration)	—
Temperature	Border of San Diego 2010 [65]	—	(hand-held conductivity meter and cell or hand-held oxygen meter and cell)
Oxygen Balance	**BOD_5, DO**, Puente Chillón 2003 [44]	—	**DO** (WTW hand-held oxygen meter Oxi 325 & oxygen sensor CellOx 325), **COD** (Merck Spectroquant® Cell Test 1.14895.0001), **BOD_5** (EnviroLab Perú using EPA 405.1)
Salt Content	**EC, Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, Cl^{-}, CO_3^{2-}, HCO_3^{-}, SO_4^{2-}, NO_3^{-}**, Puente Chillón 2003 [44]	—	**EC** (WTW hand-held conductivity meter LF 340/SET & standard conductivity cell TetraCon 325), **Cl^{-}** (Merck Spectroquant® Cell Test 1.14730.0001)
Acidity	**pH, total alkalinity**, Puente Chillón 2003 [44]	—	**pH** (WTW hand-held multimeter pH 91 & probe)
Nutrient Content	**PO_4-P, NH_4-N**, Puente Chillón 2003 [44]	—	**NO_3-N** (Merck Spectroquant® Cell Test 1.14764.0001, **NH_4-N** (Merck Spectroquant® Cell Test 1.14558.0001), **PO_4-P** & **P_{tot}** (Merck Spectroquant® Cell Test 1.14543.0001)
Microbiology	**total coliforms** Border of San Diego 2010, Feb 2011 [65], [66]); **thermotolerant coliforms** Border of San Diego 2010, Feb. 2011 [65], [66]); ***Escherichia coli*** Border of San Diego 2010, Feb. 2011 [65], [66]); **fecal coliforms** Puente Chillón, 2003 [44]	—	**total coliforms** (EnviroLab Perú using SM 9221-B), **parasitic worm (helminth) eggs/cysts** (EnviroLab Perú by observation)
Other	**Cd, Cu, Cr, Fe, Mn, Pb, Zn**, Border of San Diego 2010, Feb. 2011 [65], [66]); **fats & oils**, Border of San Diego 2010 [65]; **turbidity, cyanides, carbonate hardness, total hardness, As, Hg, Ni, B, Ras proteins**, Puente Chillón 2003 [44]	—	—

Table 2.4: Summary of Source Data for Quality and Quantity Parameters: **Chuquitanta Irrigation Canals**

	Data We Have	**Data We Can Estimate (Method)**	**Data We Will Measure (Method)**
Water Quantity	**avg. monthly flow rate** [57]	—	—
Temperature	—	—	(hand-held conductivity meter and cell or hand-held oxygen meter and cell)
Oxygen Balance	—	—	**DO** (WTW hand-held oxygen meter Oxi 325 & oxygen sensor CellOx 325), **COD** (Merck Spectroquant® Cell Test 1.14895.0001), $\mathbf{BOD_5}$ (EnviroLab Perú using EPA 405.1)
Salt Content	—	—	**EC** (WTW hand-held conductivity meter LF 340/SET & standard conductivity cell TetraCon 325), $\mathbf{Cl^-}$ (Merck Spectroquant® Cell Test 1.14730.0001)
Acidity	—	—	**pH** (WTW hand-held multimeter pH 91 & probe)
Nutrient Content	—	—	$\mathbf{NO_3\text{-}N}$ (Merck Spectroquant® Cell Test 1.14764.0001, $\mathbf{NH_4\text{-}N}$ (Merck Spectroquant® Cell Test 1.14558.0001), $\mathbf{PO_4\text{-}P}$ & $\mathbf{P_{tot}}$ (Merck Spectroquant® Cell Test 1.14543.0001)
Microbiology	—	—	**total coliforms** (EnviroLab Perú using SM 9221-B), **parasitic worm (helminth) eggs/cysts** (EnviroLab Perú by observation)
Other	—	—	—

uation of BOD_5, total coliforms and parasitic worm (helminth) eggs/cysts since these parameters are key indicators of water quality in Perú. Naturally, several compromises were made in these decisions; ex., it would have been very interesting to test for heavy metals, but since there are so many different metals and because recent information is available about heavy metal content in the Chillón River (the source most likely to exhibit high levels of heavy metals), they were not measured. TSS was also reluctantly left off the list of parameters examined because of concerns regarding access to an oven for drying samples and preparing the necessary filters. In general it should be noted that, especially where final audit results are derived from testing, there are changing conditions throughout the year and results will provide only a snapshot in time.

2.3 Organizational Phase II: "Lima: Beyond the Park" Summer School

Technical and design work carried out during Phase II of the preliminary development of WSUD concepts for Chuquitanta was conducted as part of the "Lima: Beyond the Park" Summer School (see Appendix A) and focused primarily on four of the six water sources described in Section 2.1.1: the Chillón River, the puquio, domestic wastewater from SCH and the system of irrigation canals (Figure 2.10). As mentioned, the pumping station was not considered in this phase or in audit development because SMP had already allocated this water for the irrigation of green areas in other parts of the district. Also, ideas were not developed for the effluent from the Puente Piedra WWTP in this phase due to objections voiced by SEDAPAL; even though the development of WSUD ideas for the puquio had already been ruled out, it was considered in this phase in place of the WWTP effluent.

2.3.1 Phase II Technical Work

Technical work in Phase II began with finalization of the auditing methodology for Chuquitanta as described in Section 2.2. Also, as part of the audit some interviews were carried out and additional print information was assembled to complete the collection of pre-existing data. Finally, a round of preliminary field testing was carried out for two purposes. The first was as a preparatory step to "formal" field sampling and testing conducted in Phase III. Results from preliminary testing provided rough estimates of the outcomes which could be expected from Phase III testing and thus ensured that the Merck Cell Tests ordered for use in Phase III would measure parameter values over the appropriate ranges. The second purpose was to support design work in this phase by giving the students some quantitative information about the quality of the waters they were working with during the Summer School.

Phase II testing was done using a set of portable probes and meters as well as

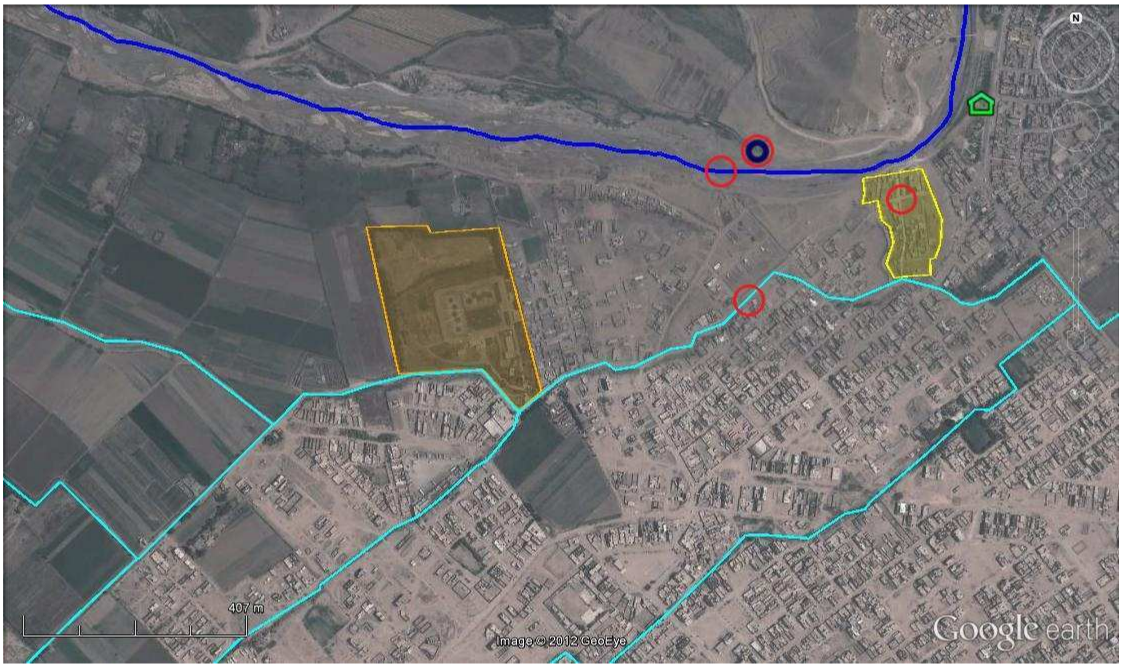
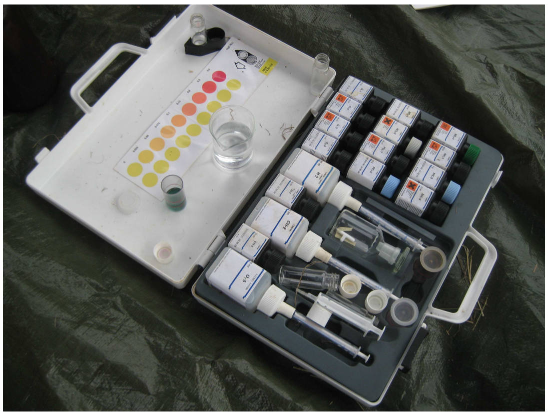


Figure 2.10: Work carried out during the "Lima: Beyond the Park" Summer School focused on four water sources in or near Chuquitanta: the Chillón River, the puquio, domestic wastewater from SCH and the system of irrigation canals. Shown here with red markers are the locations of design installations/for preliminary field testing.

(a) pH probe calibration in Chuquitanta [photo: ILPÖ]



(b) Aquamerck® Compact Laboratory for Water Testing

Figure 2.11: Preliminary testing in Phase II was carried out using (a) a set of portable probes and meters and (b) a Compact Laboratory.

a portable water quality testing kit (Figure 2.11). Temperature and DO were measured with an Oxi 325 oximeter microprocessor using a CellOx 325 oxygen sensor, while pH was measured with a pH 91 probe and multimeter, all from WTW GmbH. According to its instruction manual, the CellOx 325 was calibrated in the OxiCal®

beaker and then inserted into the water being tested [124]; DO measurements were then read off the oximeter's display. The oximeter's "AutoRead" function was enabled to limit drift in DO readings. Temperature readings were also taken using the CellOx 325; these were subsequently used for manual temperature compensation in the pH readings. The pH 91 probe was calibrated using a two-point calibration with buffer solutions of pH 7 and 10 and the temperature reading made with the CellOx 325. [122] It was then inserted into the water being tested and the pH measurement read off of the meter display screen. Portable probes and meters are generally ideal for field testing because they are durable, easy to use and when used properly give accurate readings.

A clean plastic bottle was then used to collect a sample from each source; in some cases (i.e., for the puquio and the SCH cisterns), a combined sample was taken. An Aquamerck® Compact Laboratory for Water Testing was used to measure levels of NO_2^-, NO_3^-, NH_4^+ and PO_4^{3-} in the collected samples. The tests contained in the kit use colorimetry (a technique used to determine the concentration of colored compounds in solution) or titration (a technique used to determine the concentration of a known compound, in this case utilizing a colored indicator) to allow the rapid visual assessment of parameter concentrations. The kit contains chemical reactants which are added to a water sample in an amount and order specified for the parameter which is being measured. The additives cause a reaction which produces colored compounds that give the water sample a certain tint. The more of the parameter being measured which is present in the water sample, the greater the extent with which the additives will react with it and the more intense the resulting tint of the water sample will be. The colored water sample is then compared to a color card provided for each parameter; the value of the parameter being measured corresponds to the color on the card which is closest to the color of the water. Detailed procedures for each of the parameters measured in Phase II can be found in Appendix B. The kit can also be used to measure carbonate hardness, total hardness, pH, oxygen and oxygen consumption, temperature, and other parameters related to salt content, acidity/alkalinity, nutrient content and heavy metal content, but it cannot be used to measure any microbiological parameters. [62] Some tests need to be done immediately after water samples are taken because the parameters they measure (ex., NO_2^-, NH_4^+) have the tendency to react with other components in the water and their concentrations may change quickly. Others measure parameters which are more stable (ex., NO_3^-, PO_4^{3-}) and can be carried out up to several hours after samples are taken. Advantages to using the Compact Laboratory in this application included its simplicity and portability; its clear instructions and straightforward procedures make it appropriate for use by individuals without any specific training, and Phase II testing was logistically much easier to carry out than testing completed during Phase III. However, the kit's ease of use comes at the price of its sophistication. Results are ballpark values only, and because their determination depends in the end on a subjective color comparison, reliability is not guaranteed.

More detailed sampling information as well as results from preliminary testing are shown in Table 2.5. As mentioned, in the case of SCH, neither blackwater nor greywater were tested because of the possibility to make fairly accurate estimations about the quality of domestic wastewater based on information available in the literature (see Section 3.2) and because of the dangers associated with handling untreated blackwater. Instead, at the group's request the quality of the drinking water in the SCH cisterns was tested. Also, in addition to information about the four water sources in Chuquitanta examined during design work in this phase, results are also shown for two points along the Chillón River outside Chuquitanta which were sampled during a Summer School excursion to the part of the Lower Chillón River Watershed located in Canta Province (just upstream of the Lima and Callao Provinces): one at the border of the Lima and Canta provinces, and one further upstream within the limits of Canta City. These samples were taken in order to be able to compare river water qualities at different distances from Lima Metropolitana, but unfortunately they were unplanned and neither the colorimetry kit nor the set of probes were brought along on the excursion. For this reason, only a very limited number of tests could be run on these two samples as shown in the table. Additionally, it should be mentioned that the pH levels of these samples were determined using the Compact Laboratory, not the pH probe and meter. Testing results were compared to Peruvian environmental quality standards for water which is used in the irrigation of short-stemmed plants ("Estándares Nacionales de Calidad Ambiental para Agua, Categoría 3: Parámetros para Riego de Vegetales de Tallo Bajo" [English: "Approved National Standards for Water Quality, Category 3: Parameters for Irrigation of Short-stemmed Plants"], see Tables 3.2 and 3.3 for standard values) and shared with the students as described in more detail in Section 2.3.3; however, in order to avoid redundancy with the discussion of testing results from Phase III, preliminary testing results will not be discussed in detail here.

2.3.2 Phase II Design Work

In the design part of Phase II, students worked in mixed Peruvian-German/architecture-engineering student groups to develop designs for water-sensitive urban infrastructure at the four sites in Chuquitanta explored during this phase. Towards the end of the process, they built installations at the project sites to showcase their ideas. Schematics illustrating student ideas along with a brief description are shown in Figures 2.12, 2.13, 2.14, and 2.15.

2.3.3 Phase II Sharing Information & Ideas

Work produced in the technical and design parts of the project came together for the first time during Phase II. Whenever possible, encouragement and rough guidance was

Table 2.5: Results of Preliminary Water Quality Testing Carried Out During “Lima: Beyond the Park” Summer School

	Sample 1: Canta City	**Sample 2: Lima-Canta Border**	**Group 1: Puquio**	**Group 2: Chillón River**	**Group 3: Irrigation Canals**	**Group 4: SCH Cisterns**
Date	2/20/2012	2/20/2012	2/29/2012	2/29/2012	2/29/2012	2/29/2012
Sampling Start Time	4:55 PM	6:40 PM	11:00 AM	3:00 PM	4:10 PM	5:15 PM
Description of Sampling Location	At riverbank off “Road 18”, 10 minutes south of Canta City	At riverbank, just upstream of Puente Trapiche	Combined sample taken in the middle of the lagoon near spring outlet, and near the shore	From river shoreline adjacent to group work site	Just upstream of group work site	Combined sample taken from metal storage tank and plastic storage tank; water in both tanks meant for human consumption
Parameters Measured using Meter & Probes						
pH	7.5	7.75	7.1	8.1	8	7.3
Temperature (°C)	—	—	25.9	29.3	28.6	33.3
Dissolved Oxygen (DO) (mg/L)	—	—	4.6	7.3	8.9	9.0
Parameters Measured using Colorimetric Kit						
Nitrite (NO_2^-) (mg/L)	—	—	0.025	0.15	0.2	0
Nitrate (NO_3^-) (mg/L)	10	17	25	25	25	10
Ammonium (NH_4^+) (mg/L)	—	—	0	0	0	0
Orthophosphate (PO_4^{3-}) (mg/L)	0	10	0.5	0.25	0.25	0

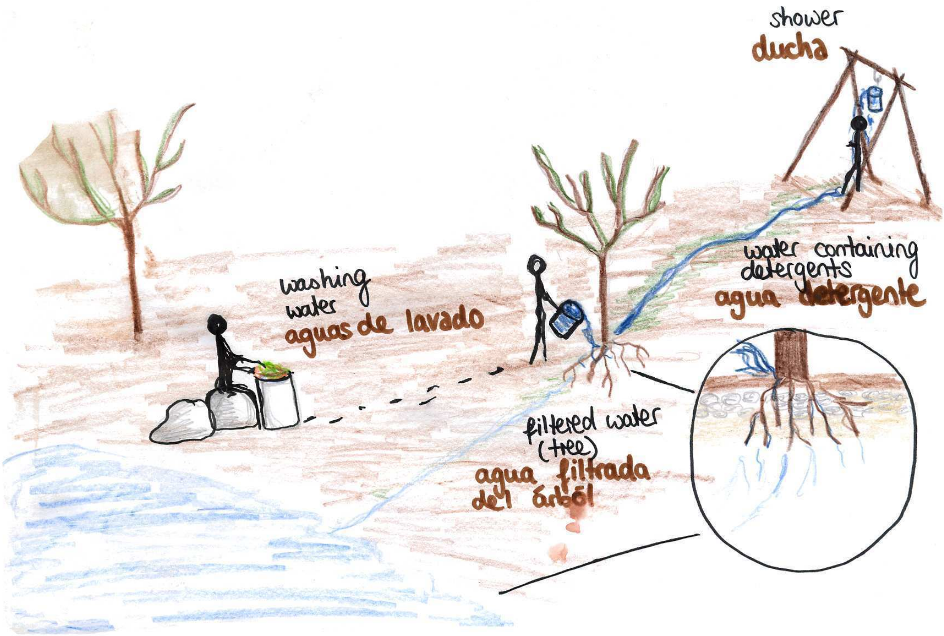


Figure 2.12: **Group 1 Puquio** developed a basic shower next to the puquio and using puquio water; greywater from the shower and from clothes-washing on the shore of the puquio would be channeled towards a green area for direct irrigation of trees. [graphic: ILPÖ]

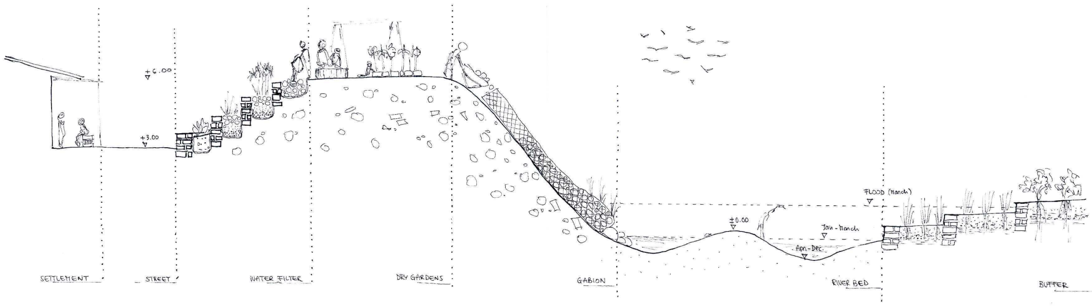


Figure 2.13: **Group 2 Chillón River** created a linear connection between the settlement behind the dike and the river itself by incorporating a terraced wetland for greywater treatment on the settlement-side of the dike, a dry park on top of the dike, and enhanced flood protection on the river-side of the dike using gabions. [graphic: ILPÖ]

offered regarding different technical components included in the designs (i.e., yes, exposure to sunlight has been shown to reduce bacteria levels in water so routing it into clear plastic bottles for disinfection by the sun would probably work; no, cylindrical gabions might not be effective as bank reinforcement, but maybe shaping them conically would provide some stability; etc.) and by the end of the phase most groups had sought out this "technical support" in some form. Though the student groups did

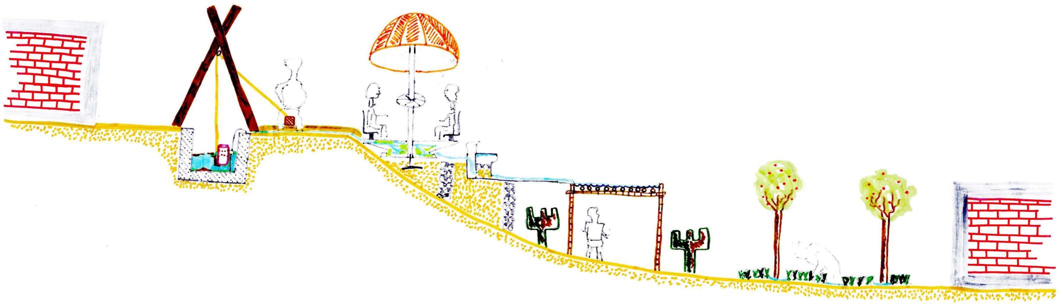


Figure 2.14: **Group 3 Irrigation Canals** incorporated recreational space for children (i.e., a playground) into a system for canal water purification constructed largely out of recycled and “found” materials. [graphic: ILPÖ]

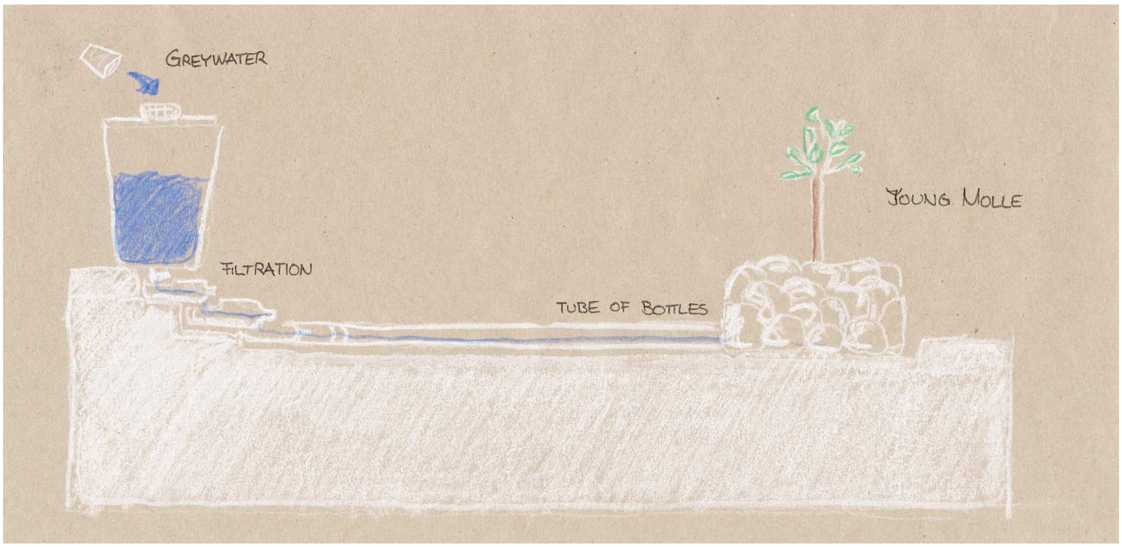


Figure 2.15: **Group 4 SCH Domestic Wastewater** opted to collect greywater at each house and to use gravity and an in-line filtration system to clean the water while moving it towards a green area for direct irrigation of trees. [graphic: ILPÖ]

not have much specific information about the qualities of the different source waters until towards the end of the phase, the general assumption seemed to be that source waters were dirty, and most groups tried to incorporate some mechanism for water purification into their designs. Particularly interesting and thought-provoking were ideas which might be considered unconventional from a technical standpoint, such as the terraced wetlands for greywater treatment on the side of the dike at the Chillón River. Once some quantitative information on water quality was available and shared with the students, it became apparent that a blunt presentation of the facts was generally unhelpful to them (ex., Me: “Results show that nitrate levels in the river water are high.” Architecture student: “What’s nitrate?” Me: “It’s a nutrient that plants need to grow. But when levels of nitrate are too high in water, they can cause negative effects for humans, like blue baby syndrome." Architecture student: "Blue baby syndrome?! What's that?" Me: "I don't really know. But it's bad. Anyway, nitrate levels in the river are high." Architecture student: "Oh.") For a final exhibition of Summer School results, preliminary results were presented visually, using colors (ex., green if the parameter was under the standard of comparison, red if it was over) to at least make relative parameter levels easier to see, even if the full meaning behind the results could not be adequately communicated. The students adapted their own method for displaying preliminary testing results in the final Summer School Booklet, utilizing a legend, symbols and different typefaces to indicate relative parameter levels. [17]

3 Conducting a Water Audit

This chapter is devoted to a description of the technical part of Phase III: Anteproyecto. A description of results from the design part of Phase III will be given as part of the discussion of the application of water audit results in Sections 4.3, 4.4, 4.6 and 4.5. As mentioned, because of concerns voiced by SEDAPAL, effluent from the Puente Piedra WWTP was not considered in Phase II; however, because it does constitute a major water source in the area providing both opportunities and challenges to the community of Chuquitanta, in the end the WWTP effluent was considered in Phase III and therefore in the water audit.

3.1 Collecting information from observation, interviews, and print sources

Various methods and different sources, including observation, interviews and questionnaires; laws and legal norms; reports and presentations by government ministries, private enterprises, non-governmental organizations (NGO), and international organizations; statistics made publicly available by governments; published scientific research; and newspaper articles were considered in the collection of "pre-existing" information relative to the audit. Information collection started rather informally during Phase I, and as it became clear which types of water quantity and quality information the audit would consider, continued into Phase II with more direction. In general, the most information from these types of sources was available for the Chillón River, where some water quality testing and river flow rate measurements had been carried out, and for the Puente Piedra WWTP, where limited monitoring data had been released to the public by SEDAPAL. A summary of the types of data collected and the sources from which they came can be found in Tables 2.1, 2.2, 2.3, and 2.4.

3.2 Estimation methods

Simple estimation methods were used in conjunction with pre-existing data to estimate the per capita daily domestic wastewater (combined blackwater and greywater) production in SCH along with the quality of this wastewater, as well as the average monthly flow rate of the Chillón River in Chuquitanta.

3.2.1 Quantity & Quality: SCH Domestic Wastewater

Domestic wastewater production volumes can be assumed roughly equal to water consumption volumes. Using data about water consumption habits in SCH given in Section 2.1.1, the average amount of wastewater produced in SCH every day was estimated as

$$\left(\frac{1 \text{ tank}}{\text{family/day}}\right)\left(\frac{200 \text{ L}}{\text{tank}}\right)(59 \text{ families}) = \frac{11,800 \text{ L water}}{\text{day}}.$$

Assuming a child under age 12 produces 1/3 as much wastewater as an adult and a child between the ages of 13 and 18 produces 2/3 as much wastewater as an adult [48], daily average per capita wastewater production in SCH was estimated using

$$\left(\frac{5 \text{ people}}{\text{family}}\right)(59 \text{ families})(0.14)\left(\frac{1}{3}x\right) + \left(\frac{5 \text{ people}}{\text{family}}\right)(59 \text{ families})(0.16)\left(\frac{2}{3}x\right) + \left(\frac{5 \text{ people}}{\text{family}}\right)(59 \text{ families})(0.70)(x) = \frac{11,800 \text{ L water}}{\text{day}}$$

$$\text{as} \qquad x = \frac{47 \text{ L water}}{\text{capita/day}}.$$

Concentrations of certain parameters in SCH domestic wastewater, namely BOD_5, NO_3-N, TKN, P_{tot}, fecal coliforms, *Salmonella*, parasitic worm (helminth) eggs/cysts and TSS, were estimated using the daily average per capita volume of wastewater production in SCH as calculated above along with information on daily per capita pollutant masses given in Peruvian legal norm OS.090: "Plantas de Tratamiento de Aguas Residuales" (English: "Wastewater Treatment Plants"). [69] For example, using the OS.090 value of 50 g BOD_5/capita/day, BOD_5 concentration was estimated as

$$\left(\frac{50 \text{ g BOD}_5}{\text{capita/day}}\right)\left(\frac{\text{capita/day}}{47 \text{ L water}}\right)\left(\frac{1000 \text{ mg}}{\text{g}}\right) = \frac{1100 \text{ mg BOD}_5}{\text{L}}.$$

Values for the other SCH domestic wastewater parameters were calculated similarly and can be found in Tables 3.2, 3.3, and 3.4.

3.2.2 Quantity: Chillón River

Rough estimations of the flow rates of the Chillón River in Chuquitanta during the upstream rainy period (Dec. - Apr.) and the upstream dry period (May - Nov.) can be made based on monthly average river flow rates recorded between 2007 and 2008 in Obrajillo (100 km upstream of Chuquitanta, in the Canta Province near Canta City) [90], data from ANA on the amount of water diverted from the Chillón River for use in irrigation or for drinking water production in the Lima Province each month from 2008 to 2009 [7], estimations of monthly average precipitation rates based on monthly precipitation volumes in Lima Province in 2009 [43], and an estimation of the rate of evapotranspiration from the river between Obrajillo and Chuquitanta. Inflow to the river outside of precipitation is assumed negligible. Where Q is flow rate, ET is evapotranspiration and PR is precipitation, in general

$$Q_{Chuquitanta} = Q_{Obrajillo} - Q_{irrigation/drinking\ water} + PR - ET.$$

Assuming an average monthly evapotranspiration in central coastal Pacific Perú of 70.13 mm [81], the average evaporation rate over a 100-km stretch of the Chillón River with an average width of 20 m was estimated as

$$ET = (70.13 \text{ mm }) \left(\frac{1 \text{ m}}{1000 \text{ mm}}\right) \left(\frac{100 \text{ km length}}{1}\right) \left(\frac{1000 \text{ m}}{1 \text{ km}}\right) *$$
$$(20 \text{ m width}) \left(\frac{1 \text{ month}}{30 \text{ d} * 24 \text{ h} * 3600 \text{ s}}\right) = \frac{0.05 \text{ m}^3}{\text{s}}.$$

Monthly average precipitation rates were estimated similarly using the area of the Lima Province. Determining $\mathrm{Q_{Chuquitanta}}$ for each month using the equation above and averaging results over the corresponding period led to estimated flow rates for the Chillón River in Chuquitanta of 6250 L/s from Dec. through Apr. and 2400 L/s from May through Nov. These estimations are likely high, and could be made more precise if they were able to include data about river water losses due to infiltration and seepage as well as the amount of water diverted from the Chillón River for irrigation in the Canta Province between Obrajillo and the border with the Lima Province.

3.3 Field measurements

Audit data which was not collected using either of the two methods above was determined via field sampling and laboratory testing. As mentioned, the groundwater pumping station is not considered in Phase III because SMP plans to use this water in expanded irrigation network to irrigate green spaces throughout the district. However, the decision was nonetheless made to carry out audit testing only (i.e., no collection of

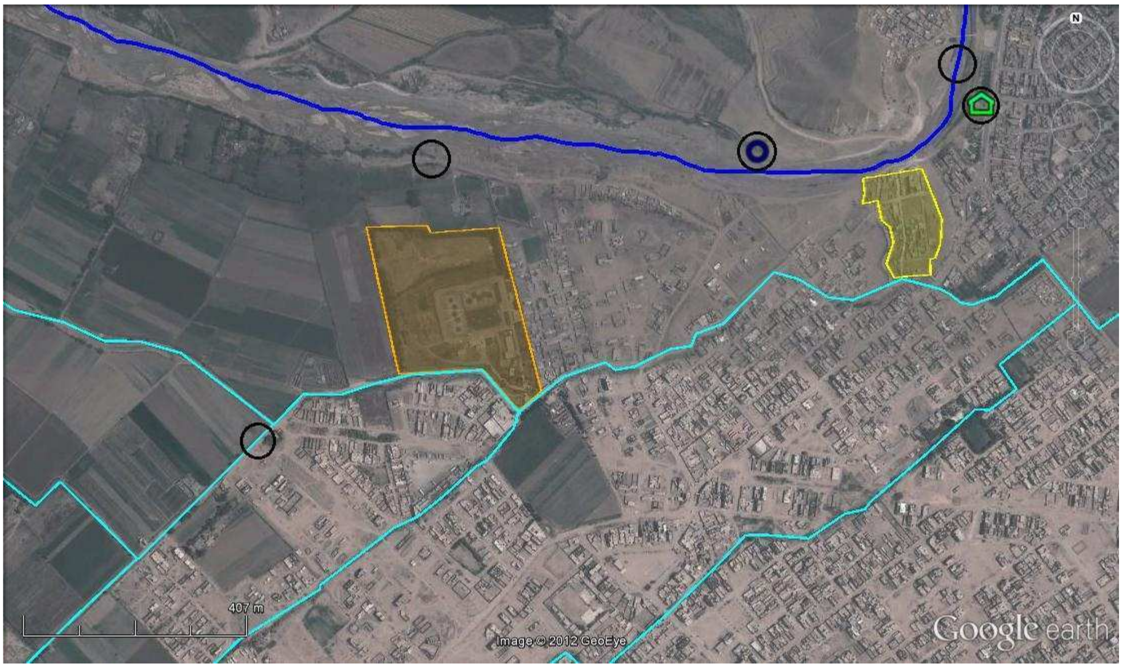


Figure 3.1: Phase III testing focused on five water sources in or near Chuquitanta: the Chillón River, the puquio, the system of irrigation canals, the groundwater pumping station, and effluent from the Puente Piedra WWTP. Shown here with black markers are the locations where samples were taken and field testing was carried out.

literature or estimated values) for this source to provide some quantitative information about it to the district. Further, though the puquio was not considered as a potential area for WSUD initiatives or in the audit, ideas for this source were developed by a student group in Phase II and Phase II preliminary testing was also carried out here. Because of this, it was decided to carry out Phase III testing here as well in order to round out the Summer School investigation.

Field sampling and testing was carried out over two days at the five water sources in or near Chuquitanta shown in Figure 3.1. In two cases where the sources had already been evaluated during the round of preliminary testing carried out in Phase II, the sampling/field testing location was changed: a point slightly upstream of the Phase II testing point but with much easier access from the bank was chosen along the Chillón River, while the system of irrigation canals was measured further downstream, at the limit of Chuquitanta's residential area, in order to be able to observe the full effect of domestic settlement on the canal water quality. Groundwater was measured at an open outlet located inside the pumping station, the puquio was measured at the western edge of the waterbody, and the Puente Piedra WWTP effluent was measured at the mouth of the outlet canal, which is located in a public area in Chuquitanta just north of the WWTP by the river. The limited availability of testing materials did not allow the sampling and testing of each source on both days; because it had

(a) Collecting samples in Chuquitanta

(b) Carrying out Merck Spectroquant® Cell Tests [photo: CITRAR-UNI]

Figure 3.2: The technical part of Phase III involved field testing using a set of probes and meters and the collection of samples for (a) testing in a private laboratory as well as (b) in-house testing at CITRAR-UNI.

already been decided that the groundwater pumping station and the puquio would not be included in the final audit, these sources were sampled and tested only on the first day in the field.

At each source on each day it was visited, three steps were taken: a set of portable probes and meters was used to measure temperature, pH, DO, and EC; a sample was taken for in-house testing at CITRAR-UNI for COD, NO_3-N, NH_4-N, PO_4-P, P_{tot} and Cl^- using Merck Spectroquant® Cell Tests; and another sample was taken for delivery to a private laboratory for analysis of BOD_5, total coliforms, and parasitic worm (helminth) eggs/cysts. The set of meters and probes used is the same as that described Section 2.3.1, with the addition of a WTW LF 340/SET meter and standard cell TetraCon 325 for the measurement of electric conductivity. The electric conductivity probe and meter were operated using temperature compensation for natural waters at 25°C and automatic range selection, and as with the other meters and probes, measurements were taken by inserting the probe into the water being tested and reading results off the meter display screen. [123] Unfortunately, on the first day of testing with the conductivity meter, automatic range selection was not enabled; readings taken on this day were therefore highly variable and thus discarded. On the second day of testing, after taking measurements using the meters and probes, a roughly 1 L-sample was collected at each source using materials provided by the private laboratory (i.e., bottles, cooler) and at the end of the day the samples were delivered to the laboratory for analysis (Figure 3.2a). On both days of testing, roughly 1 L-samples were also taken at each source for subsequent analysis using Merck Spectroquant® Cell Tests (Figure 3.2b); these were collected in clean plastic bottles,

(a) Merck Spectroquant® Cell Test testing cell

(b) Merck SQ 118 Photometer loaded with a testing cell

Figure 3.3: During in-house Phase III testing carried out at CITRAR-UNI, (a) water samples were added to special testing cells before (b) analysis with a photometer. [photos: CITRAR-UNI]

stored in a cooler, and brought to CITRAR-UNI at the end of each day for storage in a refrigerator. There, 2 mL of sulfuric acid (H_2SO_4) was added to each sample to preserve it for later analysis. This was necessary due to a roughly one-week delay between sample collection and receipt of the materials necessary for sample analysis.

In-house laboratory testing was carried out using a set of Merck Spectroquant® Cell Tests along with a Merck SQ 118 Photometer and a Merck Spectroquant® TR 320 Thermoreactor. The principle behind the Cell Tests is the same as that behind the tests included in the Compact Laboratory used during Phase II: reactants are added to a water sample in an amount and order specified for the parameter which is being measured. These additives cause a reaction which produces colored compounds that give the water sample a certain tint; the intensity of the tint can then be related to the amount of the parameter which the sample contains. However, the system for carrying out and evaluating Cell Tests is more refined than the Compact Laboratory system. For each test, a specified amount of the water sample is added to a 16-mm diameter test tube, or "cell", which is made from glass that has special optical properties which allow it to be used in photometric analyses (Figure 3.3a). The cell is pre-dosed with the first chemical which is required in the colored compound-generating reaction; additional reactants are then added to the cell in an amount and order specified for the parameter which is being measured. The glass cell is then loaded into a photometer, which directs a beam of light at the cell. Depending on the colored tint of the sample, some amount of the light directed at it will be absorbed. The light which passes through the sample is converted into an electrical current and then into a concentration by a microprocessor; the concentration is then output on the photometer display screen (Figure 3.3b). [63]

Additional preparatory steps were taken before photometric analysis, sometimes depending on the parameter being measured and the quality of the samples. In order to preserve the samples, H_2SO_4 had been added to each sample to lower its pH below 2. Because the NH_4^+ cell test requires a pH above 4, the pH of all samples was raised before commencing with sample preparation and analysis. The thermoreactor was used in preparation for the P_{tot} analysis to heat the cells to 120°C for 30 minutes in order to allow digestion (i.e., boiling with acids and oxidation agents) for conversion of all inorganic and organic forms of P to PO_4-P. It was also used before the COD analysis to heat the cells to 148°C for 120 minutes. Because turbidity can interfere with the accuracy of photometric analysis, all samples were also filtered using syringe filters before they were analyzed (for the PO_4-P and COD tests, this was done after digestion/heating with the thermoreactor). In the case of the WWTP effluent, because levels of PO_4-P and P_{tot} were higher than the detection limit for the Cell Tests, these samples were diluted by 10% using distilled water before analysis. For each test, samples were tested against blanks containing distilled water and the reagents used in the test. Detailed procedures for each of the parameters measured in Phase III can be found in Appendix C.

Field testing results are shown in Table 3.1. In comparing these to the Phase II testing results and to one another, some interesting observations can be made. For the three sources measured in both Phases II and III (the puquio, the Chillón River, and the irrigation canals), NO_3-N levels were lower in Phase III than anticipated, though this could be due to the very rough precision with which the Compact Laboratory allows levels of this parameter to be measured. As expected, water from the puquio and from the groundwater pumping station exhibited similar qualities, except with regard to levels of and NO_3-N and PO_4-P which were *lower* in the puquio: this could imply that some mechanism is working to reduce levels of these parameters in groundwater as it moves through the subsurface. Higher PO_4-P and P_{tot} levels in the irrigation canals as compared to the Chillón River indicate that the residential areas in Chuquitanta are contributing to canal pollution. Finally, WWTP effluent qualities confirm that plant operation needs to be improved.

3.4 Audit results & comparison to water quality standards

Audit results have been compiled in three parts shown in Tables 3.2, 3.3, and 3.4. The method used to collect each result has been indicated via typeface: **boldface** indicates values directly determined by observation, interviews or from information

Table 3.1: Results of Water Quality Testing Carried Out as Part of Chuquitanta Water Audit

	Sample 1: BOM	**Sample 2: PUQ**	**Sample 3: RIO 1**	**Sample 4: RIO 2**	**Sample 5: IRR 1**	**Sample 6: IRR 2**	**Sample 7: WW 1**	**Sample 8: WW 2**
Date	4/4/2012	4/4/2012	4/3/2012	4/4/2012	4/3/2012	4/4/2012	4/3/2012	4/4/2012
Sampling Start Time	10:20 AM	10:50 AM	AM	11:10 AM	AM	1:10 PM	AM	1:40 PM
Description of Sampling Location	**Groundwater pumping station**	**Puquio**	**Chillón River** just downstream of the bridge between Chuquitanta and Ventanilla, Callao		Secondary **irrigation canal** off Josefina canal		**SEDAPAL Puente Piedra WWTP effluent** at mouth of outlet canal	
Parameters Measured using Meter & Probes								
pH	7.39	7.48	—	8.40	7.96	8.22	7.32	7.28
Temperature (°C)	23.4	24.0	25.6	22.8	23.6	24.3	26.6	27.2
Dissolved Oxygen (DO) (mg/L)	3.02	3.27	8.02	8.46	7.86	7.40	8.17	1.38
Electric Conductivity (EC) (μs/cm)	606	603	—	440	—	439	—	1820
Parameters Measured using Merck Cell Tests								
Chemical Oxygen Demand (COD) (mg/L)	< 15	< 15	28	52	104	17	1652	454
Nitrate (NO_3-N) (mg/L)	19	9	12	19	13	9	7	4
Ammonium (NH_4-N) (mg/L)	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	28.1	29.4
Orthophosphate (PO_4-P) (mg/L)	< 0.05	< 0.05	< 0.05	0.17	0.89	0.56	4.72	7.00
Total Phosphorus (P_{tot}) (mg/L)	1.5	0.3	0.4	1.5	2.4	8.0	28.0	14.0
Chloride (Cl^-) (mg/L)	45	33	16	18	16	14	200	270
Parameters Analyzed by Private Lab								
Biochemical Oxygen Demand (BOD_5) (mg/L)	ND	ND	—	7	—	5	—	135
Total Coliforms (MPN/100 mL)	540	7,900	—	79,000	—	490,000	—	46,000,000
Parasitic Worm (Helminth) Eggs/Cysts (count/1000 mL)	< 1	< 1	—	< 1	—	< 1	—	30

Table 3.2: Chuquitanta Audit Results & Comparison to Standards **Part I: Quantity, Temperature, Oxygen Balance, Salt Content, Acidity**

Parameter	**SCH Domestic Wastewater**	**Puente Piedra WWTP Effluent**	**Chillón River**	**Chuquitanta Irrigation Canals**	**Standard for Comparison**
Water Quantity	*47 L/person/day*	**498 L/s (as of 2010)** [43]	*6250 L/s (Dec. - Apr.); 2400 L/s (May - Nov.)*	**900 L/s (Dec. - Apr.); 45 L/s (May - Nov.) (as of 2012)** [57]	—
Temperature (°C)	—	26.9	24.4	24.0	< 35[a]
Oxygen Balance					
Biochemical Oxygen Demand (BOD_5) (mg/L)	*1100*	135	7	5	15[b]
Chemical Oxygen Demand (COD) (mg/L)	—	1053	40	61	40[b]
Dissolved Oxygen (DO) (mg/L)	—	4.78	8.24	7.63	≥ 4[b]
Salt Content					
Electric Conductivity (EC) (μs/cm)	—	1820	440	439	2000[b]
Chloride (Cl^-) (mg/L)	—	235	17	15	100[b]
Acidity					
pH	—	7.3	8.4	8.1	6.5 – 8.5[b]

[a] As per Peruvian decree 003-2010-MINAM: "Aprueba Límites Máximos Permisibles para los efluentes de Plantas de Tratamiento de Aguas Residuales Domésticas o Municipales" (English: "Approved Maximum Allowable Limits for Effluent of Domestic or Municipal Wastewater Treatment Plants")

[b] As per Peruvian decree 002-2008-MINAM: "Aprueban los Estánderes Nacionales de Calidad Ambiental para Agua, Categoría 3: Parámetros para Riego de Vegetales de Tallo Bajo" (English: "Approved National Standards for Water Quality, Category 3: Parameters for Irrigation of Short-stemmed Plants")

Table 3.3: Chuquitanta Audit Results & Comparison to Standards **Part II: Nutrient Content & Microbiology**

Parameter	**SCH Domestic Wastewater**	**Puente Piedra WWTP Effluent**	**Chillón River**	**Chuquitanta Irrigation Canals**	**Standard for Comparison**
Nutrient Content					
Nitrate (NO_3-N) (mg/L)	*170*	6	16	11	10[b]
Ammonium (NH_4-N) (mg/L)	—	28.8	< 0.2	< 0.2	80[c]
Total Kjeldahl Nitrogen (TKN) (mg/L)	*260*	—	—	—	—
Orthophosphate (PO_4-P)	—	5.86	0.11	0.73	1[b]
Total Phosphorus (P_{tot}) (mg/L)	*65*	21	1.0	5.2	7[c]
Microbiology					
Fecal Coliforms (MPN/100 mL)	*440,000,000*				20[d]
Thermotolerant Coliforms (MPN/100 mL)	—	**51,000 (as of 2008)** [75]	**340,000 (max. monthly 2010)** [65]	—	1000[b]
Total Coliforms (MPN/100 mL)	—	46,000,000	79,000	490,000	5000[b]
Escherichia coli (MPN/100 mL)	—	—	**130,000 (max. monthly 2010)** [65]	—	100[b]
Salmonella (MPN/1000 mL)	*2,200,000*	—	—	—	0[b]
Parasitic Worm (Helminth) Eggs/Cysts (MPN/1000 mL)	*8,700*	30	< 1	< 1	< 1[b]

[c] Maximum allowable level for treated wastewater used in irrigation as established by the Standards Institution of Israel

[d] Maximum allowable level for unrestricted use of treated wastewater in agricultural irrigation as established by the Standards Institution of Israel

Table 3.4: Chuquitanta Audit Results & Comparison to Standards **Part III: Other Parameters**

Parameter	SCH Domestic Wastewater	Puente Piedra WWTP Effluent	Chillón River	Chuquitanta Irrigation Canals	Standard for Comparison
Other					
Cadmium (Cd) (mg/L)	—	—	**0.021 (max. monthly 2010)** [65]	—	0.005[b]
Chromium (Cr) (mg/L)	—	—	**0.028 (max. monthly 2010)** [65]	—	0.1[b]
Copper (Cu) (mg/L)	—	—	**0.226 (max. monthly 2010)** [65]	—	0.2[b]
Iron (Fe) (mg/L)	—	—	**12.46 (max. monthly 2010)** [65]	—	1[b]
Manganese (Mn) (mg/L)	—	—	**1.99 (max. monthly 2010)** [65]	—	0.2[b]
Lead (Pb) (mg/L)	—	—	**0.222 (max. monthly 2010)** [65]	—	0.05[b]
Zinc (Zn) (mg/L)	—	—	**0.518 (max. monthly 2010)** [65]	—	2[b]
Fats & Oils (mg/L)	—	—	**19.0 (max. monthly 2010)** [65]	—	1[b]
Total Suspended Solids (TSS) (mg/L)	*2000*	**11 (as of 2008)** [75]	—	—	150[a]

in a print source, *italics* indicate values determined by estimation, while regular typeface indicates values determined via sampling and testing carried out during Phase III. Average values are shown where sources were sampled and tested on two consecutive days. The rightmost column in each table shows the standard value used for comparison of each audit result; the corresponding footnote indicates the source of the standard.

Many sets of quality standards exist for treated wastewater reused in the irrigation of both agricultural areas and non-agricultural green space; there are even more for treated wastewater in general. Specific quality standards have not yet been established in Perú for wastewater reused in irrigation. However, the country has set general national water quality standards for waters used for different purposes (ex., drinking water, water used in the irrigation of short-stemmed plants, etc.) which are largely directed at minimizing risks to human health. [71] Perú has also established guidelines for the quality of domestic WWTP effluent which are aimed at protecting surface water bodies against contamination from treated discharge [70], as well as guidelines for non-domestic wastewater discharged into the domestic sewerage system which are intended to protect against damage to sewers, treatment plants, and other infrastructure. [67] Outside Perú, other arid countries such as Jordan and Israel have set specific standards for reclaimed wastewater reused in irrigation [94], [100], while countries which lead in methods and technologies for wastewater treatment, such as Germany and the USA, have established standards for what seems like every conceivable quality parameter in a myriad of water use and reuse applications, including wastewater reused in irrigation. [5], [114] Finally, international organizations such as the WHO and the Food and Agriculture Organization of the United Nations (FAO) have set their own standards for water quality according to the priorities of their organizations (i.e., protecting human health or supporting global agriculture). [9], [120] But which set of standards is the right one for Chuquitanta? Choosing an appropriate standard for comparison in a project such as the one in Chuquitanta is challenging: too high a standard can mean that "low-tech", low-cost treatment alternatives which would considerably reduce pollutant levels are ruled out in favor of more expensive, high-tech alternatives, just because treatment efficiencies in the former are not good enough to meet sometimes arbitrarily-chosen standards. On the other hand, setting too low a standard can result in treated effluent which still poses human health or environmental risks. One school of thought advocates setting no standards at all for domestic wastewater reused in irrigation other than those which might be required by law, simply focusing instead on the implementation of solutions for the efficient use and reuse of water which minimize extreme risks to human health and groundwater contamination. In a location with a low groundwater table where public access to agricultural areas is restricted, for example, this philosophy would support the direct irrigation of long-stemmed agricultural crops (ex., fruit trees) with raw domestic sewage, with the idea that soil is a better pollutant sink than surface water and that the overall risk to human health is lower and efficient use of water higher if raw sewage is used for agricultural irrigation than if it is dumped untreated into a river or the sea. [56] Because of the high groundwater table, the predominance of short-stemmed agricultural crops and unrestricted access to the fields, this is not a safe option for Chuquitanta, though it is still a thought-provoking idea.

For Chuquitanta, those standards given in Peruvian decree 002-2008-MINAM: "Aprueban los Estánderes Nacionales de Calidad Ambiental para Agua, Categoría 3: Parámetros para Riego de Vegetales de Tallo Bajo" (English: "Approved National Standards for Water Quality, Category 3: Parameters for Irrigation of Short-stemmed Plants") were selected as the "top tier" standards for comparison, in order to aim for the goal that discharge from constructed wetlands chosen for Chuquitanta's water sources be legally compliant for subsequent use in irrigation in Perú. [71] For Cl^-, a range of limit values is given by this decree, but the lower limit value has been chosen as the standard of comparison here because of the sensitivity of wetland functionality to salts. In the case of parameters for which standards were not set in decree 002-2008-MINAM, the somewhat less stringent standards given in Peruvian decree 003-2010-MINAM: "Aprueba Límites Máximos Permisibles para los efluentes de Plantas de Tratamiento de Aguas Residuales Domésticas o Municipales" (English: "Approved Maximum Allowable Limits for Effluent of Domestic or Municipal Wastewater Treatment Plants") were selected as the "second tier," in order to strive that the quality of constructed wetland effluent meets legal requirements set for discharge from conventional treatment plants in Perú. [70] For the three remaining parameters for which no standard was set in either of these Peruvian decrees, namely NH_4-N, P_{tot} and fecal coliforms, standards for the reuse of wastewater in irrigation as established by the Standards Institution of Israel were selected as the "third tier" for comparison, largely because of Israel's similar climate and consequent motivation to keep water quality standards realistic in order to maximize water reuse potential. [100] No standard for comparison is given for TKN; as it is a composite parameter determined as the sum of organic nitrogen, NH_3 and NH_4^+, standards of comparison for TKN are not often established. With the exception of quality standards dictated by decree 002-2008-MINAM, and therefore by law, adherence to the standards shown in Tables 3.2, 3.3, and 3.4 should be strived for but not be an absolute determinant for whether or not to implement a particular treatment system at any of the water sources in Chuquitanta.

4 Applying Water Audit Results for Design Refinement

One of the three goals of this study was to utilize audit results along with the results of the design work completed in Phase III to suggest constructed wetland types and configurations which would be appropriate for use at each of the water sources considered in Phase III, with the goal of treating source water for reuse in irrigation of agriculture or other green areas.

4.1 Overview of wetland types and wetlands in Lima

Wetlands are land that is wet all year. Natural wetlands include swamps, marshes and bogs; they typically occur at low ground and act as natural water collectors. The presence of large amounts of water allows a higher rate of biological activity in wetlands than in most ecosystems, enabling the transformation of pollutants which typically occur in wastewater into essential nutrients or harmless by-products. Constructed wetlands are man-made systems intended to replicate the function of natural wetlands, with regard to both flood protection (i.e., in the form of riparian buffers or retention wetlands) and water treatment (i.e., in the form of treatment wetlands). [47], [119] Numerous studies show that constructed wetlands can successfully reduce organic content and levels of nutrients, suspended solids, microbiological parameters and heavy metals in municipal wastewater under a variety of operating conditions, including in arid climates. As passive systems with long retention times, constructed wetlands need minimal energy for successful operation and do not produce excess sludge or other by-products which require handling other than biomass, which when harvested has a multitude of potential applications for use as fuel, in construction and handicrafts, and when mulched as a means of enriching soil quality. [51], [55] Constructed wetlands can be grouped into two major hydrologic types: free water surface constructed wetlands (FWSW), and subsurface flow constructed wetlands which include both horizontal subsurface flow constructed wetlands (HSSFW), and vertical flow constructed wetlands (VFW). [47] The choice of which wetland type to implement depends mostly on which pollutants are targeted for removal, how much land area is available, the level of wetland management which can be provided and site-specific issues such as soil permeability and the potential for interaction with groundwater. [51]

FWSW contain open water, floating vegetation and emergent plants. They are typically densely vegetated, have a permeable base to allow filtration of water into deeper soil layers, and are shallow enough to allow sunlight to penetrate to the wetland base in order to promote algae growth and photosynthesis. In operation, wastewater is directed into the wetland area and allowed to flow over and infiltrate the bed medium as well as to flow between plant stems and other surface debris. Of the three wetland types, FWSW most closely resemble natural wetlands and as such are characterized by many of the same pros (ex., they offer additional benefits as wildlife habitats or human recreational spaces) and cons (ex., they can act as a breeding ground for insects and may expose humans to water-borne pathogens). To minimize risks to humans, FWSW are typically used only for secondary treatment of high quality wastewater or for tertiary treatment. Because they can tolerate non-continuous inflows and changing water levels, they are often implemented for the treatment of stormwater, and are also frequently used to treat mine drainage and landfill leachate. FWSW are the wetland type which requires the most land area; installation costs are typically comparable to those of conventional treatment plants, though operational costs remain much lower. [47], [51]

HSSFW are gravel, soil or soil/sand beds which are planted with vegetation. They are designed to promote horizontal flow through the subsurface in order to allow water to flow in and around plant roots; when properly operated, water levels in HSSFW remain below the gravel/soil surface. There is typically a liner installed at the wetland base to prevent infiltration to groundwater. Because water remains below bed level, a lower risk of human exposure to pathogens or arthropod-borne diseases is associated with HSSFW than with FWSW; on the other hand, opportunities for wildlife habitat and human recreational space in HSSFW are not as great as in FWSW. HSSFW also require less area than FWSW in order to achieve similar treatment efficiencies, but are generally more expensive to install. HSSFW are typically used for primary treatment before soil infiltration or discharge to surface water, small-scale secondary treatment, or treatment of industrial wastewaters. [47], [51]

VFW follow the same basic principle as HSSFW in that flow is through the subsurface and water levels are maintained below the bed level, but deviate in that the direction of flow is vertical rather than horizontal. Typically, water is “pulse-loaded” at the top surface of the vegetated wetland and allowed to percolate down through several soil layers before being collected in a network of drainage pipes at the bottom of the system. VFW can also be configured for recirculated flow or upward flow depending on treatment goals and system constraints. VFW were originally developed in Europe to provide higher rates of oxygen transfer than possible in HSSFW in order to promote ammonia oxidation, and are thus often used to treat ammonia-reach wastewaters such as landfill leachate and effluent from food processing operations. Conversely, VFW can also be used to block oxygen transport and create anaerobic conditions in lower sediment layers, fostering sulfur chemistry conditions which encourage the removal of heavy metals from industrial and mining effluents. [47] This wetland type has also been successfully used to treat raw sewage and for sludge dewatering, and in one study was even shown to significantly reduce AOX levels in wastewater from a small hospital. [53]

Lima Metropolitana has several constructed wetland facilities for wastewater treatment, as well as two natural coastal wetland areas. Pantanos de Villa is a 244-hectare natural marsh located in flat depression between two hills and the coast in the District of Chorillos. [31] Several water sources feed the swamp, including the Surco "River" (actually a pre-Incan irrigation channel built to direct water from the Rímac River to agricultural areas to the south), infiltration from the Rímac River, and wastewater from settlements on the surrounding hills. In the past, channels connected the wetland with the ocean and enabled regulation of the water level, but with coastal urbanization they were filled in and water levels are now regulated by pumping into the ocean. [72] Additionally, residential development and the construction of a private recreational facility on marsh land has led to a 40% reduction in the wetland's original size. However, the area is now protected by an international treaty (the Ramsar Convention) and is preserved as a sanctuary for waterfowl and for its typical Pacific coastal marsh ecosystem. [75] Evaporation has increased the salinity of wetland water and soil, but vegetation still grows in abundance and is harvested for use. [72] Pantanos de Ventanilla is another natural coastal wetland covering 366 hectares in the Lower Chillón Watershed in the eastern part of the District of Ventanilla in Callao. Though it is located within a regional conservation area, unfortunately it does enjoy the same level of protection as the Pantanos de Villa and has suffered from the effects of informal settlements, illegal poachers, agricultural activities, and waste dumps which infringe on its area. Despite this, the wetland is still recognized as an important migratory stop for birds and a habitat for coastal vegetation, including totora (Schoenoplectus californicus ssp. totora) which is harvested for use by a local handicrafts cooperative. [32], [75]

Several pilot-scale constructed wetlands have been set up by municipalities in Lima Metropolitana or their private partners in recent years to treat domestic wastewater for various purposes. These include a wetland intended to treat water for reuse in the irrigation of 2 hectares of agricultural land in the neighborhood of Oquendo, a wetland at a public school intended to treat school wastewater for partial reuse in the irrigation of its garden, and "micro-wetlands" built at individual houses in the community of Nievería to treat separate blackwater, yellow water and greywater streams as part of an ecological sanitation (ecosan) project. [73] The largest pilot-scale constructed wetlands project in Lima Metropolitana was constructed to provide 0.3 L/s of treated wastewater for irrigation of a park and sports field at the Villa de Oasis slum in the District of Villa el Salvador. The configuration included a primary treatment step for the removal of sand, fats and oils followed by both a VFW treatment step and treatment with a horizontal flow wetland. [74] In general, these initiatives did not succeed (i.e., they suffered operational problems which resulted in either inadequate treatment efficiencies or a complete halt in operations) because of their very small scales and a lack of expertise in planning and maintaining the implemented wetlands. [75] For example, in the case of Villa de Oasis, BOD_5 and fecal coliform levels remained high in plant effluent, likely because wetland retention times were not long enough, and operation of the plant was further hampered by a lack of staff, safety equipment and adequate finances for operation and maintenance. [74] These experiences imply that the success of wetlands initiatives in Lima will likely depend on their implementation on larger scales and with the full support of SEDAPAL.

4.2 Wetland area estimation tool

A simple, Excel-based tool was created to roughly estimate areas required for FWSW, HSSFW, and VFW. The 1990s saw a significant increase in the amount of literature about constructed wetlands and their sizing. Several simple equations were put forth during this period for calculating wetland areas based on plug flow or tanks-in-series models which incorporated inflow and outflow rates, inflow and targeted outflow concentrations of a dimensioning parameter, and first-order areal or volumetric reaction rate constants which considered temperature effects, bed and water depths, internal hydraulics, vegetation types or event parameters. [29] Of course, wetland processes are much more variable and complex than these early models were able to reflect, but in the past two decades their sophistication and applicability to diverse scenarios has increased greatly, benefiting especially from a growing variety of relevant empirical data and better computing capabilities. A more recent method for determining wetland area is discussed in detail in Kadlec (2009) and builds on earlier tanks-in-series models to define the following relationship, known as the P-k-C^* model:

$$\frac{(C_o - C^*)}{(C_i - C^*)} = \frac{1}{\left(1 + \frac{kA}{PQ_i}\right)^P}$$

where C_o denotes the target outflow concentration of a dimensioning parameter (often BOD_5, sometimes NO_3-N, P_{tot} or fecal coliforms if the wetland is designed for specific removal of one of these pollutants, etc.) (mg/L), C_i denotes the inflow concentration of this parameter (mg/L), C^* denotes the background concentration of this parameter (mg/L), k denotes the modified first-order areal constant for this parameter (m/day), A denotes the required wetland area (m^2), P denotes the number of tanks-in-series, and Q_i denotes the inflow rate. [47]

The P-k-C^* model was developed based on assumptions of steady flow, negligible water gains and losses, and concentrations averaged over several nominal detention times. Based on empirical data, Kadlec has developed statistical distributions for k values based on the dimensioning parameter being considered, wetland type (i.e., FWSW, HSSFW, or VFW), and the anticipated inflow concentration of the dimensioning parameter; C^* and P values are also recommended based on these factors. The area estimation tool was developed based on this model using a statistical percentile of 0.90, with BOD_5 as the dimensioning parameter for SCH domestic wastewater and the Puente Piedra WWTP effluent and NO_3-N as the dimensioning parameter for the Chuquitanta irrigation canals and the river (since BOD_5 levels in the latter sources were under the established limit). k, C^*, and P values were subsequently adopted from Tables 8.8 and 8.16 in Kadlec (2009) based on wetland type and inflow concentration of BOD_5 while values of these parameters for NO_3-N were adopted from Kadlec (2012); values will be given as applied in Sections 4.3, 4.4, 4.5 and 4.6. [47], [46] In order to generate more accurate area estimations, the P-k-C^* model can be given additional complexity to account for contributing pollutant removal processes, specifics of internal wetland hydraulics, and other factors affecting wetland performance. However, for the rough early-stage area estimations required here, the basic model described by the equation above is sufficient.

The next sections discuss the wetland configurations which have been recommended for each of the water sources considered in Chuquitanta based on final audit results and the results of design work completed in Phase III. In order to facilitate a rapid overall understanding of the water quality of each source, a graphical display of final audit results for each source has been created based on the data shown in Tables 3.2, 3.3, and 3.4. In these graphics, the standard of comparison for each parameter is indicated with a "+" symbol. It should be noted that for pH, two "+" symbols are used to bookmark an acceptable range of values while the standard value indicated for DO is a lower limit. Where the measured value exceeded the standard, the bar is red; where it remained below the limit, the bar is green. Blue bars indicate that no appropriate standard of comparison was available, while the notation "N.V." means that no value was measured for the particular parameter. Finally, microbiological parameters are abbreviated in the graphics as follows: fecal coliforms (fec), thermotolerant coliforms (ttc), total coliforms (toc), *Escherichia coli* (eco), *Salmonella* (sal), and parasitic worm (helminth) eggs/cysts (pwe).

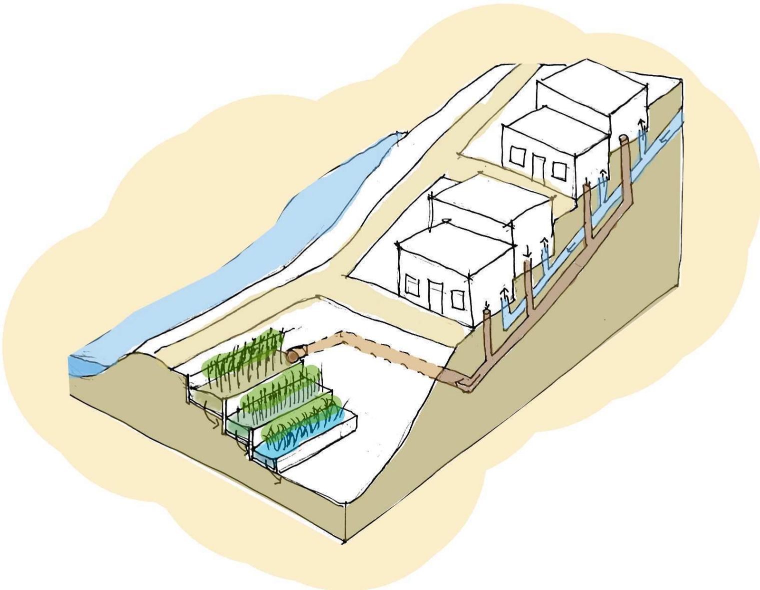


Figure 4.1: Graphical display of Phase III design results for **SCH Domestic Wastewater**. [graphic: ILPÖ]

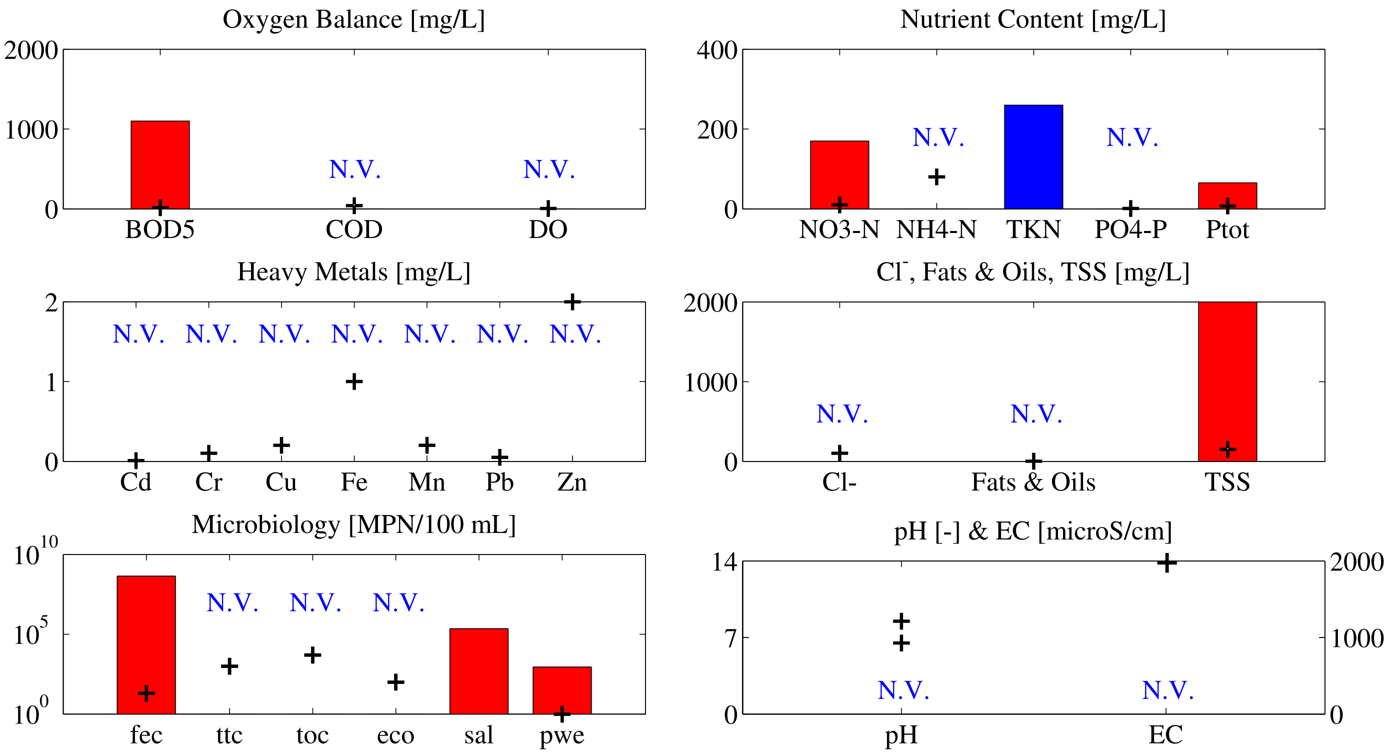


Figure 4.2: Graphical display of final audit results for **SCH Domestic Wastewater**.

4.3 SCH Domestic Wastewater

Student design ideas at the end of Phase III focused on the collection of grey- or blackwater from SCH for transport by gravity to the base of the hill for treatment in a constructed wetland. This system was proposed as a temporary solution until Lima's sewerage network could be expanded to the area. The top of the hill should remain relatively dry, without plans for an irrigated green space in this area (Figure 4.1). Final audit results for combined grey and black domestic wastewater indicate high BOD_5, high nutrient levels, high levels of microbiological parameters, and elevated TSS, as might be expected for untreated wastewater (Figure 4.2).

The recommended technical solution generally supports the design idea and suggests the inclusion of elements from Phase II design results for SCH as well. In the absence of a sewerage system, grey and black wastewater streams in SCH are not combined, which provides an advantage in that treatment methods can be optimized for each stream. Domestic greywater (i.e., water used for bathing, washing and in the kitchen) could be collected either at each household or at multi-household collection points on the hill where solids and grease could be removed on-site using a filter and grease trap or a settling tank. Greywater could then be channeled by gravity through a basic pipe network to the base of the hill for treatment in a VFW with recirculating flow, i.e., a VFW in which water that has vertically passed through a series of soil layers is collected and returned to the top of the system for reapplication to the VFW. A recirculating VFW is recommended in this case because this technology maintains high pollutant removal efficiencies while keeping the land area required to achieve these efficiencies to a minimum. This technology has been successfully implemented in pilot installations at the household and neighborhood scales in Israel for the treatment of domestic greywater for reuse in irrigation, achieving BOD_5 reduction rates of over 95%, TSS removal rates over 90%, and fecal coliform removal rates close to 100%. [35], [99] The recommendation deviates from the graphical representation of the students' ideas (Figure 4.1) in that the proposed constructed wetland would be built on one level, as opposed to along terraces as shown. Further, pipes collecting water from households would carry greywater only and no provision would be included in the design for supplying water for household use via a piped delivery system. Special considerations for the recommended design include the need for a power source to run the pump required to recycle flow throughout the wetland, and that VFW are often subject to problems with bed clogging. There is potential for harvested wetland material to be used either directly for powering the recirculation pump using biogas, or in the production of handicrafts or other materials which might be sold to offset the cost of electricity. Though solar power would not be a good option for powering the pump because skies in the area are cloudy for so much of the year, the possibility for generating hydropower using a water wheel or other simple installation at a nearby irrigation canal branch could also be explored. Bed clogging is the result of the normal activity of microorganisms in wetland soil, but can be minimized by controlling TSS levels in the inflow via adequate pre-treatment, pumping wastewater onto the wetland intermittently, and utilizing wetland plants with well-developed root systems such as totora. In support of student design ideas, wetland effluent could be channeled by gravity for the irrigation of an urban agriculture plot which could be established adjacent to and exclusively for SCH. To some extent, blackwater generated in SCH could be handled by installing ecological sanitation (ecosan) latrines equipped with urine diverting dry toilets (UDDT) to separate urine and feces; urine could be collected and used for direct irrigation of trees and other long-stemmed vegetation while dehydrated human waste could be used for soil enrichment. This has been successfully done within a Sustainable Sanitation Alliance (SuSanA) project carried out in the District of Chorillos in Lima at a school for handicapped children. [39] However, successful implementation of UDDTs in SCH could face challenges related to the larger number of people these facilities would need to serve and because sawdust is required for their successful operation. They may also face some opposition by community members holding out for household sewerage connections and the installation of classic flush-toilets in their homes.

The water quality and quantity data collected for SCH during the audit considers total combined (i.e., black and grey) domestic wastewater. In order to roughly estimate the size of a greywater wetland for the community, it is assumed that 50% of the domestic wastewater from SCH is greywater and that 50% of the BOD_5 in the domestic wastewater comes from greywater [41]; it should be noted however that these percentages are rough estimates largely based on greywater and blackwater composition data collected in developed countries with combined sewerage systems, and that an estimate of 50% greywater is likely higher than is actually the case in SCH (where much lower total quantities of wastewater are produced per capita per day). Based on results shown in Table 3.2, these percentages imply that roughly 24 L/capita/day of domestic greywater is generated in SCH, containing 550 mg/L BOD_5. Using these data, values of k = 554 m/year, C^* = 2.0 mg/L, and P = 2 were determined for VFW from Table 8.16 in Kadlec (2009) [47]; when applied to the tool, these data generate an estimated VFW area of roughly 50 m^2 necessary for the treatment of greywater generated by the 295 people living in SCH.

4.4 Puente Piedra WWTP Effluent

Student design ideas at the end of Phase III were motivated in part by a plan by SEDAPAL to double the Puente Piedra WWTP's capacity to handle a design flow of 1000 L/s, extending current facilities into the riverside zone between the current plant location and the Chillón River in order to accommodate the expansion. The argument was made that because the expanded facility would infringe on the riverside zone

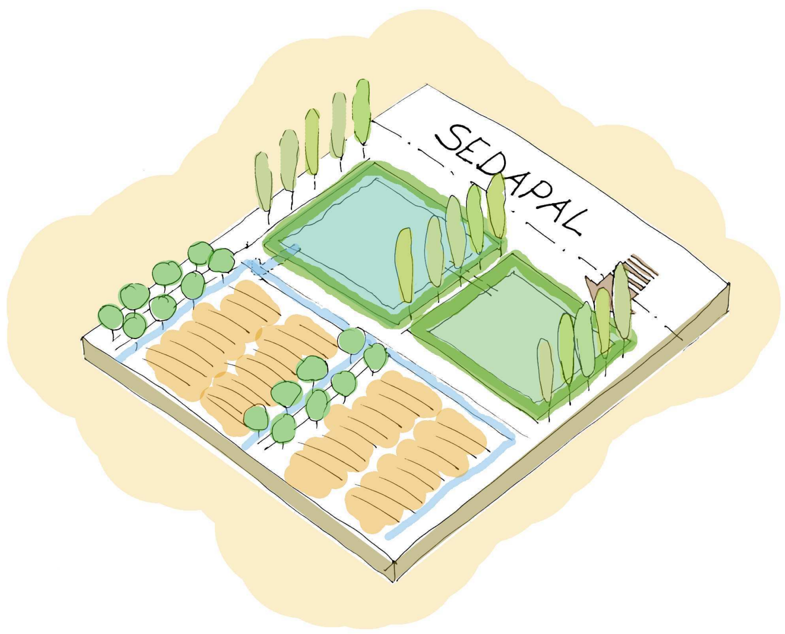


Figure 4.3: Graphical display of Phase III design results for **Puente Piedra WWTP Effluent**. [graphic: ILPÖ]

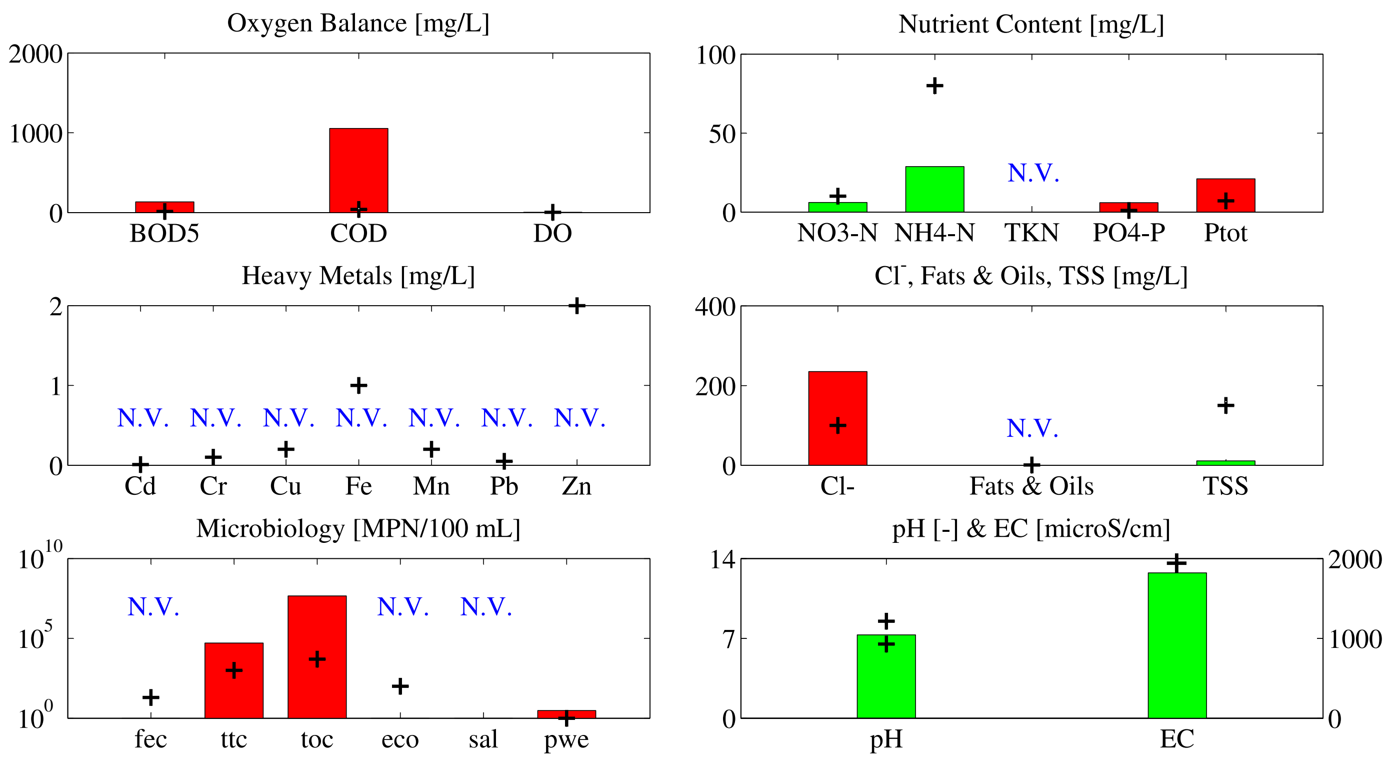


Figure 4.4: Graphical display of final audit results for **Puente Piedra WWTP Effluent**.

designated by ANA as a protected area (i.e., the faja marginal), the new treatment facility should double as a public recreational space. Students envisioned SEDAPAL's new treatment system as a pair or series of lagoons which achieve low-cost, biological (secondary) treatment of the plant's current effluent, but suggested that the final system configuration be developed through a partnership between SMP, SEDAPAL, and Peru's Universidad Nacional de Ingeniería (UNI). They also recommended that a recreational space be designated within the treatment area to incorporate both green space adjacent to the treatment lagoons and parts of the treatment plant which could be made open to the public to provide an opportunity for knowledge-sharing (Figure 4.3). Final audit results indicate high BOD_5 and COD levels, high levels of PO_4-P and P_{tot}, high Cl^-, and high levels of microbiological parameters (Figure 4.4).

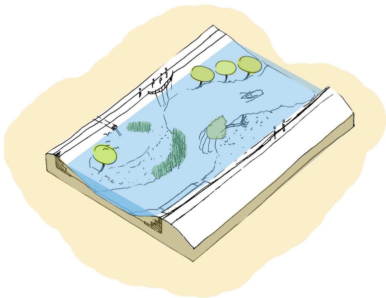
The recommended technical solution is partial treatment of WWTP effluent in a HSSFW which could serve primarily as a stop-gap treatment method while SEDAPAL upgrades and/or expands the Puente Piedra WWTP. After additional treatment in the wetland, the effluent could then be used to irrigate local agriculture as originally intended. HSSFW have been established as effective means of removing organic material and microbiological pollutants from wastewater; BOD_5 reduction efficiencies of up to 80% have been achieved in municipal wastewater undergoing secondary treatment, and COD reduction efficiencies of up to 70% as well as microbiological pollutant removal rates of almost 100% have been achieved in bench-scale HSSFW planted with a mixture of reeds, bulrushes and cattails in China. [52], [117] Unfortunately, HSSFW and constructed wetlands in general do not seem to be particularly efficient at removing nutrients containing PO_4-P. This is due to the fact that PO_4-P tends to adhere to the soil matrix; once the soil is fully saturated, P-removal from waters is typically limited to plant growth periods during which plants take up P from the soil matrix, thereby freeing up space for the adsorption of new PO_4-P from polluted water. However, the ability of HSSFW to reduce PO_4-P and P_{tot} levels in pollutant waters can be increased by utilizing wetland base media with a high P-binding capacity, such as calcium-rich soils and sands. [4] One requirement for properly functioning HSSFW is that TSS concentrations in the inflow should be low to avoid bed clogging; the audit data show that the WWTP does seem to be at least achieving a reasonable level of primary treatment and TSS levels in the effluent are quite low, adding strength to the choice of a HSSFW in this case. This recommendation deviates from the student suggestions in that HSSFW do not look like or function as lagoons. However, this type is preferred to a FWSW (the wetland type most similar to that envisioned in the student design) in this case for several reasons: firstly, the quality of the WWTP effluent is too poor for it to be channeled into an open water treatment lagoon which could successfully be incorporated into a recreational space. The levels of pollutants in the effluent pose too high a risk to humans and have the potential to generate odors or invite vermin which are not likely to welcome human visitors. The better and safer option might be to maintain this polluted water under the ground surface for treatment in a HSSFW, which would still be planted with vegetation that would contribute to an overall greening of the area, even if this space could not be directly accessed by the public. An additional advantage to using a HSSFW rather than a FWSW in this application is that the former requires considerably less land area to achieve the same treatment efficiencies. An educational facility which opened portions of the conventional WWTP to the public and also provided information and limited contact with the HSSFW and its ecosystem, perhaps via a viewing platform or boardwalk, would also be a welcome addition to the site, and perhaps could remain in place alongside a reduced-size wetland after the WWTP had been successfully upgraded.

Based on results shown in Table 3.2 for the Puente Piedra WWTP flow rate and BOD_5 levels, values of k = 107 m/year, C^* = 10.0 mg/L, and P = 3 were determined for HSSFW from Table 8.8 in Kadlec (2009) [47]; when applied to the tool, these data generate an estimated HSSFW area of roughly 8.5 ha necessary for the treatment of the full volume of WWTP effluent. This area is of course quite large. However, the recommendation made here is envisioned as an intermediary solution while SEDAPAL upgrades its plant. With every improvement in the quality of the water flowing into the wetland (i.e., with every reduction in the amount of BOD_5 in the WWTP effluent), the required wetland area gets smaller. It is unlikely that the full area predicted by the tool would be needed for the entire intermediary period, and a smaller area could be used at first to treat some percentage of the WWTP effluent. As the effluent quality improved, the same wetland area could be used to treat more and more of the effluent. The relationships between BOD_5 concentrations in the wetland inflow, flow rate into the wetland, and wetland area can be explored using the wetland area estimation tool.

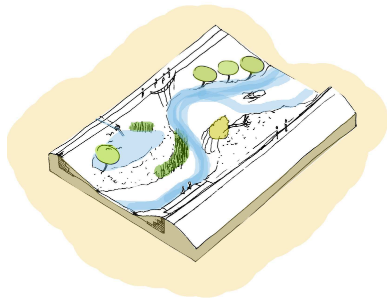
4.5 Chillón River

Student design ideas at the end of Phase III focused on river renaturation via the development of a natural morphology and native bank plantings to encourage the return of local flora and fauna to the river and to provide a space for public recreation. It was also suggested that the flow of the river be supplemented during dry periods using water which now flows into the puquio or with treated WWTP effluent, and that river banks be reinforced to provide flood protection (Figure 4.5). Final audit results indicate elevated NO_3-N levels and high levels of microbiological parameters and most heavy metals (Figure 4.6).

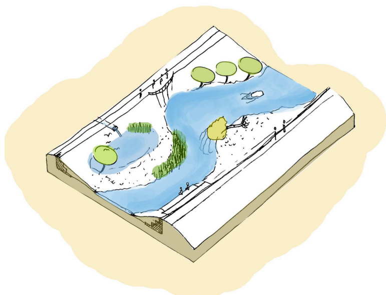
The recommended technical solution generally agrees with the student design ideas in that overall, re-establishing a more natural river morphology and installing native plantings would improve the amount of green space in the area and could have



(a) Chillón River in high flow period



(b) Chillón River in low flow period



(c) Chillón River in average flow period

Figure 4.5: Graphical display of Phase III design results for the **Chillón River**. [graphics: ILPÖ]

some positive effect on river water qualities. For example, totora, a bulrush species which as mentioned above grows in abundance in Pantanos de Ventanilla just across the Chillón River in Callao, might be a good species to introduce to the lower bank areas because of its proven capacity for absorbing heavy metals, though necessary detention times would have to be considered to ensure its effectiveness. [28], [30] However, routing waters from the puquio and/or WWTP into the river channel to supplement river plantings during periods of low flow may pose technical problems related to water qualities, not to mention political and ethical issues. For example, it would not be a good idea to route WWTP effluent into the river if its quality remains low. Or, even if issues surrounding puquio ownership were resolved, AND the community agreed to let the puquio pond dry up, should puquio water really be used during dry periods to keep riverbank plantings alive instead of for the irrigation of agricultural land or multi-purpose green space? Particularly because of its highly variable flow rate, a FWSW might be the best wetland treatment choice for the river, though in order to accommodate the river's maximum average flow of 6250 L/s between Dec. and Apr., the FWSW would be truly huge. Values of $k = 25$ m/year, $C^* = 0$, and $P = 4.4$ were determined for FWSW based on Kadlec (2012) [46]; when these data along with the river's maximum average flow rate and results shown in Table 3.2 for NO_3-N levels in the Chillón River are applied to the tool, they generate an estimated FWSW area of roughly 39 ha necessary for the treatment of

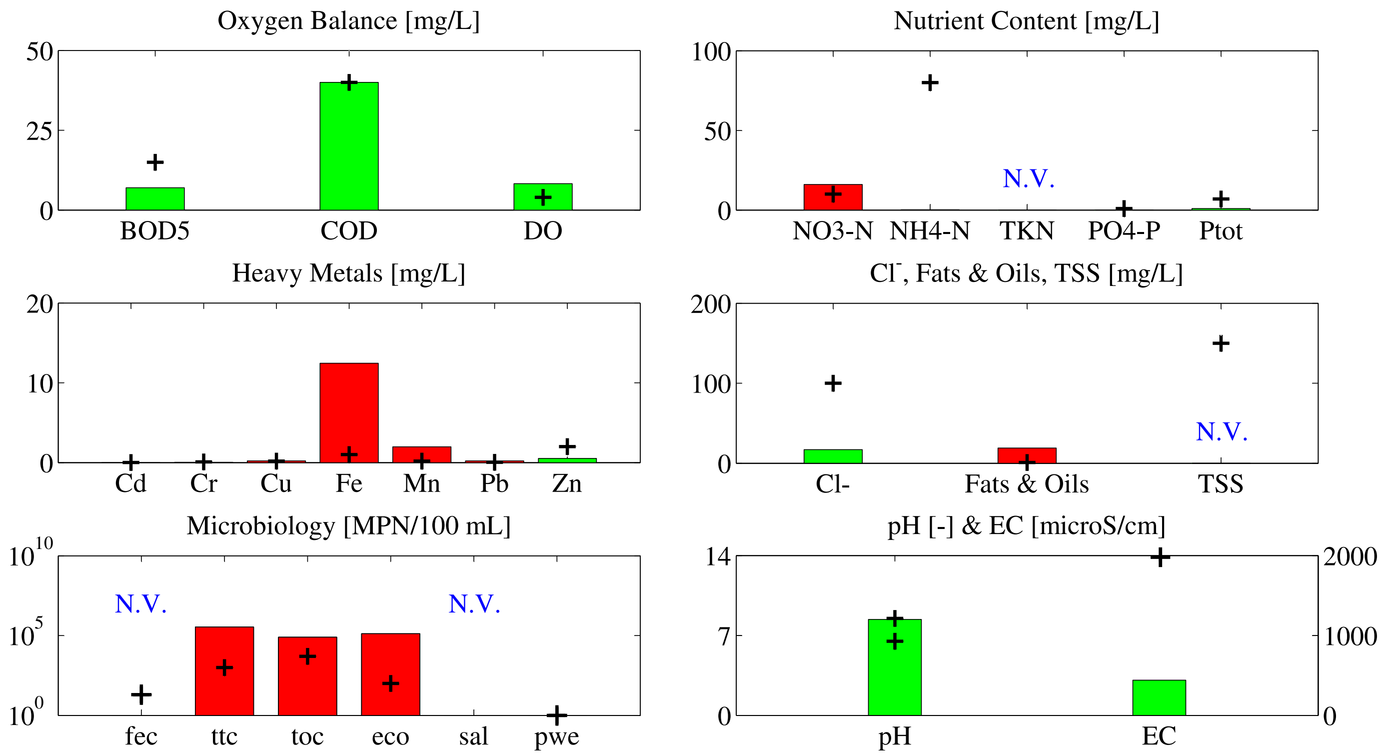


Figure 4.6: Graphical display of final audit results for the **Chillón River**.

river water. Of course, this calculation has been made for the part of the year when river flow volumes are largest. Further, because higher wetland inflow rates require larger wetland treatment areas, steps could be taken to reduce the inflow rates to a FWSW for river water, for example via the implementation of collection basins which could store the full flow of the river and release it to the wetland at a lower rate, or by diverting only a portion of the river's flow to the wetland. But, these are major decisions about a prominent water source and very large land areas which would no doubt have lasting consequences reaching far afield of Chuquitanta. The development of a truly effective and realistic constructed wetland treatment system for implementation with waters from the Chillón River is a major undertaking and beyond the scope of this study.

However, it might be interesting to more deeply explore some of the suggestions made at the end of Phase II design work for the river, which although do not refer to treatment of the river water itself, could be incorporated into a more comprehensive solution for the area. The suggestion was made that a terraced constructed wetland be installed on the settlement-side of the river dike in Chuquitanta as a greening element and a means for domestic greywater treatment. In addition to this, Phase II design results proposed gabions for riverbank reinforcement on the river-side of the dike. It may be possible to

(a) Concrete basin with plantings as constructed wetland "module" [photo: [107]]

(b) Tawantinsuyu agricultural terracing in the southern Peruvian Andes [photo: Julie Oppermann]

Figure 4.7: Greywater treatment and bank reinforcement could be combined on the Chillón River dike by (a) creating a constructed wetland "module" for greywater treatment using reeds or totora planted in concrete basins and (b) arranging the modules in terraces along the river-side of the dike for bank reinforcement, perhaps taking inspiration from the stylings of Incan terracing in southern Perú.

combine these ideas towards the creation of a terraced system of constructed wetland "modules" on the river-side of the dike for combined greywater treatment and bank reinforcement. Greywater could be collected at the top of the dike and treated in a sedimentation tank or with a filter and grease trap to remove solids and oils (as with the system for SCH). From there, it could be channeled into a system of concrete basins planted with Phragmites australis (reed) and/or totora and arranged into terraces on the river-side of the dike (Figure 4.7). The reeds would act to treat the greywater, while their extensive root systems in addition to the mass of the concrete basins could work to help stabilize the bank. Implementation of this system would necessitate either the installation of a pumping system to bring greywater from the settlement to the top of the dike (with the possibility of offsetting electricity costs with harvested biomass, as with the system for SCH) or require that it be carried it up. Also, before this solution could be confidently implemented, the effect of plant roots and infiltration water on dike stability would need to be examined, and an investigation would need to be made into whether or not enough greywater is generated by the settlement adjacent to the dike to maintain the module plantings.

4.6 Chuquitanta Irrigation Canals

Student design ideas at the end of Phase III focused on the installation of canal channels made from natural materials (i.e., not concrete), covering canals where water

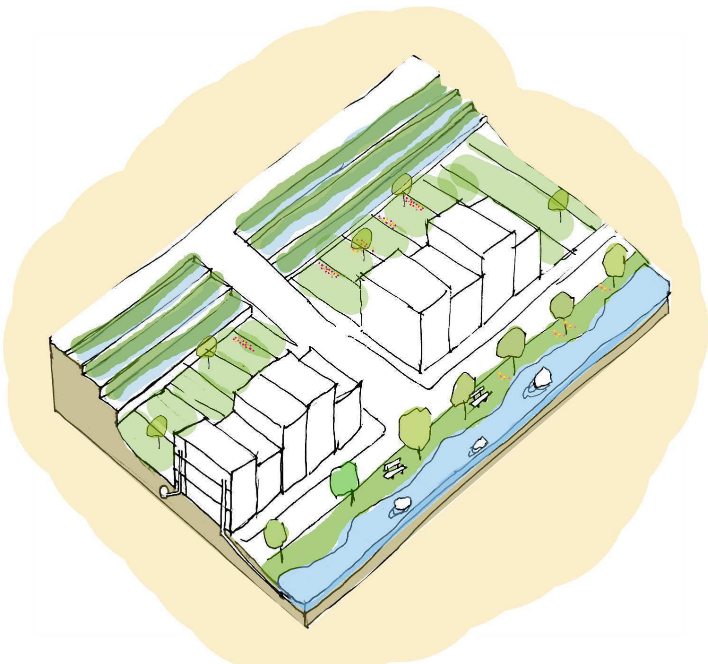


Figure 4.8: Graphical display of Phase III design results for the **Chuquitanta Irrigation Canals**. [graphic: ILPÖ]

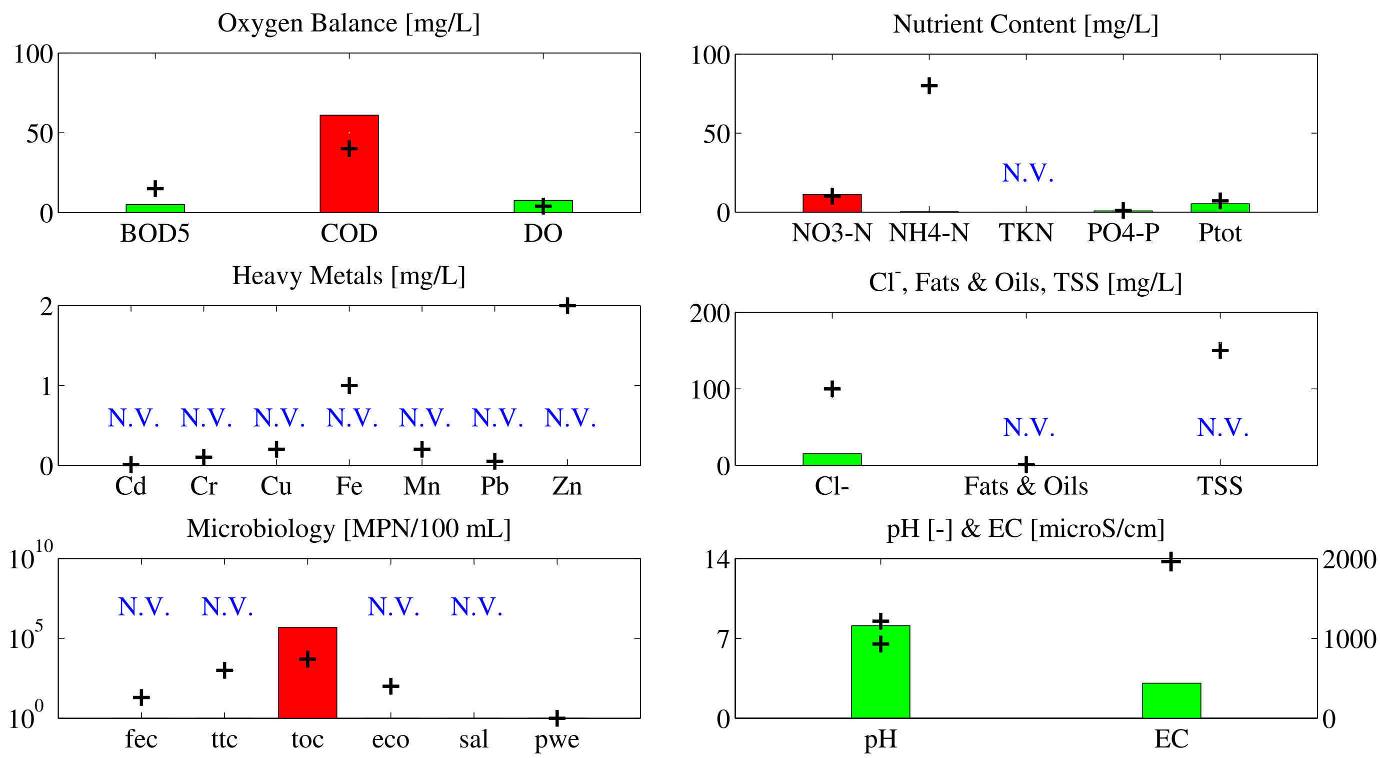


Figure 4.9: Graphical display of final audit results for the **Chuquitanta Irrigation Canals**.

quality remains poor as it moves through settlements in Chuquitanta, and utilizing the canals as "river-like" dual-purpose recreational/constructed wetland areas. They also propose that wetlands treat canal water AND household greywater, and that treated water be used for the irrigation of urban agriculture as well as medians and green strips along local avenues (Figure 4.8). Final audit results indicate high levels of COD, NO_3-N and total coliforms (Figure 4.9).

The recommended technical solution is a FWSW which doubles as a green park. FWSW have been shown to effectively reduce COD, NO_3-N and coliform levels in polluted waters; in two studies from the western USA, FWSW reduced NO_3-N levels in effluent by 80-90% [10], [86], while a study in France revealed FWSW removal efficiencies of over 60% for COD and another in Australia of over 90% for coliforms. [34], [54] Canals could be covered throughout the settlement area, and then outlet into a planted basin forming the FWSW. After treatment, the wetland effluent could be directed back into a "semi-renaturalized" (i.e., lined earthen) canal system outside of the settlement area for subsequent use in agricultural irrigation (lining the canals is likely necessary to prevent water losses to seepage or irrigation). The recommendation deviates from the students' suggestions in that it opts for treatment in a collection basin rather than within the canals themselves. One problem with trying to treat water as it moves freely through a vegetated canal system is that contact time with plants (i.e., detention time) might not be long enough to achieve desired treatment efficiencies. Incorporating basins or some other device for collecting and holding canal water in the planted area makes it much more likely that adequate pollutant removal efficiencies will be reached. With regard to using the FWSW for greywater treatment, it may also be possible and appropriate to install a greywater pre-treatment and piped collection system (as with the system for SCH) in the settlement which outlets to the FWSW. In support of student design ideas, as available, treated FWSW effluent could also be diverted for use in smaller agricultural plots within the settled area or to irrigate road medians.

Values of k = 25 m/year, C^* = 0, and P = 4.4 were determined for FWSW based on Kadlec (2012) [46]; when these data along with the maximum flow rate between Dec. and Apr. of 900 L/s and results shown in Table 3.2 for NO_3-N levels in the Chuquitanta irrigation canals are applied to the tool, they generate an estimated FWSW area of roughly 1 ha necessary for the treatment of the irrigation canal water. This is a large area, but not an unrealistic amount of space in Chuquitanta. However, the advantages of a multi-functional FWSW/recreational green space which incorporates irrigation canal water would have to be weighed against the loss of agricultural land to the installation.

Figure 4.10 shows a summary of Phase III design results, audit results, and the recommended constructed wetland configurations for the source waters in Chuquitanta.

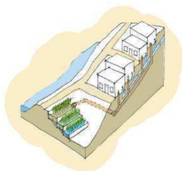
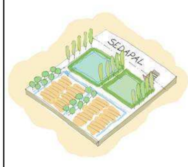
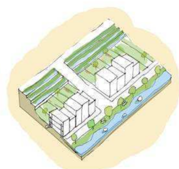
	Domestic WW	WWTP Effluent	Irrigation Water	River Water
AUDIT RESULTS	BOD_5, NO_3-N, P_{tot}, fecal clfms., *Salmonella,* helminth eggs, TSS, TKN, quantity	BOD_5, COD, PO_4-P, P_{tot}, Cl^-, thermotol. clfms., total clfms., helminth eggs, DO, NO_3-N, NH_4-N, TSS, temp., pH, EC, quantity	COD, NO_3-N, total clfms., BOD_5, DO, NH_4-N, PO_4-P, P_{tot}, Cl^-, helminth eggs, temp., pH, EC quantity	NO_3-N, Cd, Cu, Fe, Mn, Pb, fats/oils, thermotol. clfms., total clfms., *E. coli*, BOD_5, COD, DO, NH_4-N, PO_4-P, P_{tot}, Cl^-, temp., pH, EC, Cr, Zn, helminth eggs, quantity
DESIGN RESULTS				
FINAL REC.	recycled vertical flow CW & UDDT	subsurface CW	free surface CW	terraced CW "modules"

Figure 4.10: A summary of final audit and design results as well recommended constructed wetland configurations for the four sources considered.

5 Reflection & Future Outlook

5.1 Auditing the audit

Was the water audit carried out in Chuquitanta a success? The short answer is, yes, it was. The audit achieved the goal of collecting a basic but useful set of water quantity and quality data which informed the design process throughout its early phases and led to the development of robust design alternatives at the end of the preliminary stage. Further, there is potential for continued application of audit results in subsequent design stages and for application of the general auditing methodology developed in this case study to other similar projects. However, the process could certainly be streamlined and optimized so that it goes more smoothly in the future.

Naturally, part of the challenge in carrying out scientific investigations in the developing world is the general unavailability of necessary materials and equipment, and it was expected that both time and money need be reserved for getting water quality testing supplies to Lima. However, the biggest challenge and largest barrier to successfully undertaking the water audit in Chuquitanta described here most definitely lay in the logistics behind getting the Merck Spectroquant® Cell Tests and associated equipment (i.e., the photometer and thermoreactor) to Lima. The choice was made to order the Cell Tests from an international scientific equipment and materials vendor (without a local distribution office in Lima) for shipment to Lima from the United Kingdom, and to carry the photometer and thermoreactor to Lima from Germany as checked baggage. Carrying scientific equipment as checked international baggage proved difficult with regard to the collection and preparation of required accompanying documentation, time spent in the airport at customs waiting for the equipment to be cleared for entry into Perú, and both excess baggage costs and import tariffs. Additionally, the vendor provided extremely disappointing service at almost every stage, taking over two months to prepare and ship what in the end was the wrong materials order to Lima and providing no assistance whatsoever with the customs and import process in Perú. The result was a much higher expenditure of time and money than anticipated. Though the wrong order was filled, luckily it did contain most of the Cell Tests which had been planned for Chuquitanta, with the exception of tests for Total Nitrogen. Information on this parameter would have been useful to the study, but it was not absolutely essential to the integrity of the audit. However, delays in receipt of the Cell Tests were so severe that the author could not carry out the laboratory testing herself; in fact, testing was only made possible through the kindness of Rosa Elena Yaya Beas, director of CITRAR-UNI, who volunteered to conduct the Cell Tests with a team of her students in the author's absence. This gesture was of course a huge help and in the end is what made the collection of many of the audit results possible, but it did require that unanticipated time be spent working with UNI students to train them in the use of the testing equipment and to familiarize them with Cell Test procedures. All of these experiences taken together beg the question: was this all really necessary? In hindsight, maybe not.

For a preliminary stage audit such as the one carried out in Chuquitanta, the colorimetric tests contained in the Aquamerck® Compact Laboratory for Water Testing probably give enough information to be able to guide early design work, and use of the Merck Spectroquant® Cell Tests could most likely be avoided entirely. As described, the results the Compact Laboratory provides are good estimates only, but can be used along with an appropriate standard to provide an adequate level of information at this early stage, i.e., awareness of which specific parameter levels treatment should most urgently be directed at lowering. The Compact Laboratory was transported from Germany to Lima via the USA as carry-on baggage; at airports it was usually necessary to go through an additional screening process and to produce documentation detailing the kit's contents and authorizing it to be carried, but otherwise no other time delays or costs were associated with transporting it to and from Perú. The tests contained in the Compact Laboratory are also fairly easy to use, and after a brief introduction could be successfully carried out by someone without a technical background or specific training. The kit's major disadvantage is that it does not allow the testing of microbiological parameters, which are important indicators of water quality in many parts of the world. However, use of the Compact Laboratory (along with the set of meters and probes utilized throughout the study in Chuquitanta) could be combined with recently developed, portable and easy-to-use field tests for microbiological parameters in order to gain a very good overview of a variety of water quality parameters in the field, entirely avoiding the need for laboratory facilities at preliminary project stages. [64] If more sophisticated results or information about parameters which are harder to accurately test in the field (ex., oxygen content) were needed, then samples could be collected and sent to an approved private laboratory for testing, as successfully done in Phase III of this study for BOD_5, total coliforms and parasitic worm (helminth) eggs/cysts. Though private testing needs to be paid for, when materials and shipping costs as well as import tariffs associated with the materials and equipment necessary for testing at an in-house laboratory like CITRAR-UNI are considered, private testing is probably the cheaper option; with about a two-week wait between dropping samples off at the laboratory and the receipt of results, it is without a doubt the faster option as well.

With all methods utilized to collect information, including testing, accurately and rapidly carrying out a water audit hinges on appropriate and adequate planning which considers the goals of not only the preliminary but also subsequent project phases. Steps carried out during Phase I should be completed as soon as possible in the auditing process to allow ample time for consideration of which parameters are most important to include in the audit and to maximize the amount of information which can be collected through observation, interviews, print sources, and estimation, in order to save time and money by minimizing testing. That being said, it is important to remember than any testing carried out as part of an audit provides only a snapshot in time. If time and resources allow, testing should be repeated when influencing conditions change, ex. during the rainy season if the first round of testing was carried out during the dry season, or over a weekend when residents are at home if the first round of testing was carried out on a weekday, etc. Conducting an appropriately timed second testing round would improve the reliability of audit results greatly. Also, if logistics, time and money allow, it would in some cases be quite helpful to have additional supplementary information about some sources. For instance, in this study it would have been useful to have data about levels of heavy metals in the irrigation canals and AOX in the WWTP effluent.

In this study, final audit results were quantitatively applied to a limited extent in the calculation of land area estimates for the proposed constructed wetland configurations carried out in Chapter 4. However, in subsequent phases of project development as design ideas become more detailed and constructed wetlands more fully dimensioned, there is great potential to apply results even more extensively via the calculation of estimated wetland removal efficiencies for organic content, nitrogen, phosphorus, heavy metals, and other contaminants. It should be noted that the accuracies of estimated land areas determined here and of estimated contaminant removal efficiencies which might be carried out in future project stages are helped immensely through the availability of the more accurate set of results determined using the Cell Tests and through analysis in the private laboratory. Priorities would need to be weighed and decisions made in early audit planning in order to determine if the costs and time expenditure associated with in-house laboratory testing using imported equipment and materials (not recommended) or with sending samples to a private laboratory for analysis (recommended) would be justified in that they would provide more accurate data which could then be constructively applied throughout subsequent project phases.

Finally, the water auditing methodology developed in this study is likely transferable to other similar scenarios, i.e., early-stage design projects which could be helped by a rapid assessment of local water sources. Of course, the choice of parameters which the audit would consider and the methods used to collect information about these parameters would likely differ in other projects. However, the questions considered in choosing parameters and the priority given to methods for information collection (as outlined in Section 2.2) are applicable outside of this case study, as is the general framework for audit execution (as outlined in Section 1.4).

5.2 Are constructed wetlands a good choice for Lima and for incorporation into WP9 prototypes for Chuquitanta?

As described in Section 1.2, shown in Figure 1.8, and illustrated in Chapter 4, constructed wetlands for the treatment of waste- and surface waters for reuse in the irrigation of agricultural and other green spaces are a viable option for Lima and for inclusion in prototypes developed for Chuquitanta in WP9, in particular considering the additional objective of increasing the amount of green area in the metropolitan area. However, it is important to address potential drawbacks to implementing constructed wetlands in this setting which have not yet been discussed, among them the potential for FWSW to act as a vector for mosquitoes and other pests, and that constructed wetlands may remove nutrients from treated waters which might actually benefit agriculture and soil quality via irrigation.

Tropical diseases are not as much of a problem in Lima as in other parts of Perú. Though throughout the country there is some risk of exposure to malaria at elevations below 1500 m [112], the dry climate in Lima and along Perú's southern coast is generally not conducive to mosquito breeding and there is no malaria in this area. For similar reasons, yellow fever, dengue fever, filariasis, arboviral encephalitides and other vector-borne diseases are not considered a problem in Lima Metropolitana. [110] However, populations of mosquitoes and other blood-feeding arthropods can thrive in FWSW when poor construction or operational problems such as clogging lead to the formation of shallow, still pools of low quality water which can serve as a breeding ground for insects. [38] Despite the relatively low risk they pose for spreading disease in Lima, it is important that steps be taken to control mosquito populations in the metropolitan area's constructed wetlands. These might include the strategic removal of vegetation to allow the agitation of wetland water by wind, introducing fish species which prey on mosquito larvae, introducing nematodes and other parasites for which mosquitoes act as a host, or the use of chemical agents to control insect populations. [49] In a well-functioning wetland, mosquito populations will naturally be held in check by fish, birds and insects which eat their larvae. It is certainly possible to achieve this type of healthy balance in wetlands in Lima, as evidenced by a 1996 study of Lima's Pantanos de Villa wetland which found that in reservoirs with high instances of mosquito bioregulators, i.e., species which naturally control mosquito populations, no mosquito larvae were found. [27]

Nutrients in irrigation water such as N, P, K, Mg, S and Ca can actually be beneficial to plant growth and soil quality. Levels of N and P need not be lowered to the same extent in treated waters intended for reuse in irrigation as in treated waters discharged into surface water bodies, where they can cause algal blooms which pose a threat to aquatic plant and animal life. [14] Because they too are composed of plants and soil, constructed wetlands benefit from N and P and may remove these nutrients more efficiently than desired in cases where treated water will be reused in irrigation. Several adjustments can be made to wetland design and operation in order to lower the removal efficiencies of N and P, including shortening hydraulic residence times; choosing plant species which are less efficient at removing nutrients; varying water depths, levels and bed surfaces to control plant colonization; varying operational parameters such as pH, temperature and DO to discourage nutrient uptake by plants; and for P in particular, choosing a wetland substrate material which discourages nutrient adsorption. [4], [51] Of course, the choice of whether or not to make any of these changes would need to be made in consideration of the effects changes might have on removal efficiencies of other parameters. Other options for harnessing the nutrients taken up by wetland plants include harvesting wetland plants, mulching them and mixing them with agricultural soil, or planting wetlands with garden plants or other commercially-viable species to not only achieve desired water treatment efficiencies, but also to harvest and sell as part of a sustainable nursery enterprise operated in conjunction with the wetland. [55], [83]

Additionally, it should again be stressed that proper operation and management of constructed wetland systems is essential if they are to function as intended. Related to this is the selection of wetland plant species in consideration of not only their capacity for removing targeted pollutants, but also the frequency with which they need to be harvested. Before a decision is made about which plants to use in a wetland, a cost-benefit analysis should be carried out which takes into account both harvesting costs and potential financial benefits related to the production of biomass. [49]

5.3 Did technical and design work come together for better outcomes?

Combining technical and design input towards the development of prototypes for water-sensitive ecological infrastructure for Chuquitanta resulted in technically-sound recommendations which strived to remain true to design ideas. Sharing information and ideas throughout preliminary project stages also gave both architecture and engineering students some understanding of the tasks, methods of working and types of result typically attributable to the other, and how we could work together for better results.

However, interaction between technical and design work could be better timed in future projects to optimize outcomes. For example, in this study, preliminary testing carried out during Phase II would have better served student design work completed in the same phase if results had been available to the students slightly earlier, i.e., towards the beginning of the phase, since the students would have had more time to incorporate them into their ideas. It would have also been very helpful to have had interaction with the architecture students during Phase I, on the one hand to learn more about their initial ideas for WSUD in Chuquitanta and Lima in general in order to begin to think about how the audit could serve their development, and on the other hand to give them some introduction to water quality testing and how results might be useful for guiding and shaping their design ideas. Finally, it would have been helpful and interesting to reunite with the students after developing suggestions for constructed wetland configurations which were combined with their Phase III design ideas towards the development of prototypes, in order to have feedback about how well they felt their ideas had been interpreted and honored in the recommendations. In general, however, bringing together design and technical work was a worthwhile objective which brought value to final deliverables, as well as to the overall experience of the author in Lima.

Bibliography

[1] Alvarez, J., Hidalgo, S., Moreno, G., Àvila, J., Reaño, E., Silva, J., Alvarez, C., Diaz, S., and Flores, J. Plan de ordenamiento de la cuenca del río chillón, September 2005.

[2] Andean Air Mail & Peruvian Times Staff. Arid lima among most wasteful cities for water consumption. *Andean Air Mail & Peruvian Times*, September 21, 2010.

[3] Andina. Senamhi: río chillón incrementó en casi 130% su caudal debido a lluvias. *El Comercio*, February 11, 2012.

[4] Arias, C. A. and Brix, H. Phosphorus removal in constructed wetlands: Can suitable alternative media be identified? In Lienard, A., Hrsg., *Wetland Systems for Water Pollution Control IX*, S. 655–661, London, 2005. IWA Publishing.

[5] Arle, J., Blondzik, K., Claussen, U., Duffek, A., Heidemeier, J., Hilliges, F., Hoffmann, A., Koch, D., Leujak, W., Mohaupt, V., Naumann, S., Richter, S., Ringeltaube, P., Schilling, P., Schroeter-Kermani, C., Ullrich, A., Wellmitz, J., and Wolter, R. Wasserwirtschaft in deutschland: Teil 2: Gewässergüte, July 2010.

[6] Autoridad Nacional del Agua, Administración Local de Agua (Chillón, Rímac, Lurín) (ALA-ANA). Puntos criticos en la faja marginal del río chillón, September 2011.

[7] Autoridad Nacional del Agua, Dirección y Administración de Recursos Hídricos, Unidad Administración y Distribución del Agua. Programación y distribución del agua 2008 - 09: Cuenca hidrográfica: Chillón, rímac, lurín, 2009.

[8] Autoridad Nacional del Agua, Sistema de Información de Recursos Hídricos. Disponabilidad hídrica en el perú.

[9] Ayers, R. S. and Westcot, D. W. *Water quality for agriculture.* Food and Agriculture Organization of the United Nations, Rome, 1985.

[10] Beutel, M. W., Newton, C. D., Brouillard, E. S., and Watts, R. J. Nitrate removal in surface-flow constructed wetlands treating dilute agricultural runoff

in the lower yakima basin, washington. *Ecological Engineering*, 35:1538–1546, 2009.

[11] Boman, B. J., Wilson, P. C., and Ontermaa, E. A. Understanding water quality parameters for citrus irrigation and drainage systems, November 2001.

[12] Concejo Metropolitano de Lima. Plan de desarrollo metropolitano de lima-callao 1990-2010 (planmet), 1990.

[13] Consorcio Agua Azul S.A. Perfil de la empresa: Objeto social y plazo de duración, 2009.

[14] Department of Environment and Conservation of New South Wales. *Environmental guidelines: Use of effluent by irrigation*. Department of Environment and Conservation of New South Wales, Sydney [N.S.W.], 2004.

[15] Deutsche Bundesministerium für Bildung und Forschung. Future megacities: Megastädte von morgen.

[16] Dongo-Soria S., D. Desarrollo industrial mira a lurigancho y ventanilla: Urge celeridad en cambios de zonificación. *El Comercio*, S. b10, August 11, 2011.

[17] Ege, M. Lima: Beyond the park: Summer school 2012 booklet, February 20 - March 3, 2012.

[18] El Comercio Staff. En miraflores postergan concesión de nueva planta de tratamiento de parque maría reiche. *El Comercio*, December 28, 2010.

[19] El Comercio Staff. Limeños consumen el doble de agua al día que un suizo o un francés. *El Comercio*, March 22, 2012.

[20] El Comercio Staff. Sedapal pierde s/.300 millones por año debido a robo de agua. *El Comercio*, March 23, 2012.

[21] El Comercio Staff. Pantanos de villa regarán nueva costa verde sur: Cada segundo se pierden 300 litros de agua dulce. *El Comercio*, S. a11, May 13, 2011.

[22] El Comercio Staff. Afirman que hay agua suficiente pero no se usa con eficiencia: Voz de especialistas desde el congreso mundial en brasil. *El Comercio*, S. b19, September 27, 2011.

[23] Encinas Carranza, P., Hrsg. *Reporte ambiental de Lima y Callao, 2010: Evaluación de avances a 5 años del informe GEO*. Universidad Científica del Sur, Fondo Editorial, Lima and Perú, primera edición. Auflage, 2010.

[24] Engineers Australia. An overview of australian runoff quality: A guide to water sensitive urban design.

[25] Fernández-Maldonado, A. M. Expanding networks for the urban poor: Water and telecommunications services in lima, peru. *Geoforum*, 39:1884–1896, 2008.

[26] Flores, A. and Salazar, E. De espaldas a la prevención. *El Comercio*, S. a3, February 18, 2010.

[27] García Ávila, I., Vivar Guzmán, R., Quezada Márquez, J., and Huamán Mayta, P. Insectos acuáticos biorreguladores de larvas de mosquito presentes en los "pantanos de villa", lima, perú. *Revista Cubana de Medicina Tropical*, 48(3), 1996.

[28] Garcia Moreno, M. *Transport of Arsenic and Heavy Metals to Lake Poopó, Bolivia: Natural Leakage and Anthropogenic Effects.* Dissertation, Lunds Universitet, Lund and Sweden, December 18, 2006.

[29] Gearheart, R., Finney, B., Lang, M., Anderson, J., and Lagacé, S. Free water surface wetlands for wastewater treatment: A technology assessment, June 1999.

[30] General Secretariat of the Organization of American States, Unit of Sustainable Development and Environment. *Source Book of Alternative Technologies for Freshwater Augmentation in Latin America and the Caribbean.* IETC Technical Publication Series. United Nations Environment Programme - International Environmental Technology Centre (IETC), Osaka/Shiga and Japan, 1997.

[31] Gil Villacres, F. M. Los pantanos de villa.

[32] Gobierno Regional del Callao, Gerencia Regional de Recursos Naturales y Gestión del Medio Ambiente. Pamphlet: Area de conservación regional humedales de ventanilla.

[33] Grau, M. Lima: una ciudad que se deshidrata. *El Comercio*, S. a10, March 20, 2011.

[34] Greenway, M. The role of constructed wetlands in secondary effluent treatment and water reuse in subtropical and arid australia. *Ecological Engineering*, 25:501–509, 2005.

[35] Gross, A., Shmueli, O., Ronen, Z., and Raveh, E. Recycled vertical flow constructed wetland (rvfcw): A novel method of recycling greywater for irrigation in small communities and households. *Chemosphere*, 66:916–923, 2007.

[36] Grupo Técnico Estratégico de la Cuenca del Chillón, Perú. Evaluación de puntos criticos de contaminación en la cuenca baja del río chillón, July 22, 2004.

[37] Health Canada, Healthy Environments and Consumer Safety Branch, Water Quality and Health Bureau. Guidelines for canadian drinking water quality:

Guideline technical document: Bacterial waterborne pathogens: Current and emerging organisms of concern, February 2006.

[38] Heinrich, K. and Heinrich, S. *Kleinkläranlagen-Handbuch.* Mironde-Verl., Niederfrohna/Sachsen, 1 Auflage, 2008.

[39] Hoffmann, H., Rüd, S., and Schöpe, A. Case study of sustainable sanitation projects: Blackwater and greywater reuse system, April 14, 2009.

[40] Huapalla Pajares, H. Perfil de proyecto: Mejoramiento ambiental del río chillón - tramo callao, 2008.

[41] Imhof, B. and Mühlemann, J. Greywater treatment on household level in developing countries: A state of the art review, February 2005.

[42] Instituto Nacional de Estadistica e Informatica del Perú (INEI). Perfil sociodemográfico de la provincia de lima, 2007.

[43] Instituto Nacional de Estadistica e Informatica del Perú (INEI). Perú: Anuario de estadísticas ambientales, 2011.

[44] Instituto Nacional de Recursos Naturales del Perú, Administración Técnica del Distrito Riego Chillón-Rímac-Lurín. Evaluación integral de recursos hídricos: Monitoreo de la calidad de aguas superficiales - río chillón, 2003.

[45] IPES - Promoción del Desarrollo Sostenible. El gobierno peruano aprueba política para la promoción del uso de aguas residuales tratadas para riego.

[46] Kadlec, R. H. Constructed marshes for nitrate removal. *Critical Reviews in Environmental Science and Technology*, 42(9):934–1005, 2012.

[47] Kadlec, R. H. and Wallace, S. D. *Treatment wetlands.* CRC Press, Boca Raton and FL, 2 Auflage, 2009.

[48] Kahn, H. D., Du, J., and Stralka, K. Estimated per capita water ingestion and body weight in the united states: An update: Based on data collected by the united states department of agriculture's 1994–1996 and 1998 continuing survey of food intakes by individuals, October 2004.

[49] Kivaisi, A. K. The potential for constructed wetlands for wastewater treatment and reuse in developing countries: a review. *Ecological Engineering*, 16(4):545–560, 2001.

[50] La Republica Staff. Quieren evitar seguir regando jardines con agua potable. *La Republica*, October 19, 2011.

[51] Lee, C.-g., Fletcher, T. D., and Sun, G. Review: Nitrogen removal in constructed wetland systems. *Engineering in Life Sciences*, 9(1):11–22, 2009.

[52] Li, J., Wen, Y., Zhou, Q., Xingjie, Z., Li, X., Yang, S., and Lin, T. Influence of vegetation and substrate on the removal and transformation of dissolved organic matter in horizontal subsurface-flow constructed wetlands. *Bioresource Technology*, 99:4990–4996, 2008.

[53] Li, Z., Li, M., Li, Y., and Prospere, A. Experimental study on treatmental efficiency of wastewater from small hospital by vertical flow constructed wetland. In Institute of Electrical and Electronic Engineers, Inc. (IEEE), Hrsg., *Proceedings*, Piscataway and NJ, 2009. IEEE.

[54] Mandi, L., Houhoum, B., Asmama, S., and Schwartzbrod, J. Wastewater treatment by reed beds: An experimental approach. *Water Resources*, 30(9):2009–2016, 1996.

[55] Masi, F. Water reuse and resources recovery: the role of constructed wetlands in the ecosan approach. *Desalination*, 247:28–35, 2009.

[56] McElhinney, K. J. Irrigation water quality standards for developing countries, July 19, 2012.

[57] McElhinney, K. J., Nemcova, E., and Poblet, R. Irrigation and water management practices in chuquitanta, March 7, 2012.

[58] Meier M. Q., M. Cutervo: primer parque nacional del perú cumple medio siglo de olvido: Fundado el 8 de septiembre de 1961, hoy las invasiones y la tala ilegal lo amenazan. *El Comercio*, S. a16, September 5, 2011.

[59] Mejía, C. Inauguran planta de tratamiento de aguas servidas en el río chillón: Beneficiará a más de 150 mil habitantes de 15 asentamientos humanos. *Diario Expreso*, November 9, 2002.

[60] Méndez Vega, J. P. and Marchán Peña, J. Diagnóstico situacional de los sistemas de tratamiento de aguas residuales en las eps del perú y propuestas de solución, 2008.

[61] Mendívil, V. R. Planta taboada comenzará a tratar aguas residuales en agosto del 2012: Tratará desagües de 27 distritos de lima y callao que actualmente se vierten al océano. *El Comercio*, S. a12, October 1, 2011.

[62] Merck KGaA. Aquamerck compact laboratory for water testing 1.11151.0001 manual.

[63] Merck KGaA. Photometer sq 118 manual, 2000.

[64] Metcalf, R. H. and Onsager Stordal, L. A practical method for rapid assessment of the bacterial quality of water: A field-based guide, 2010.

[65] Ministerio de Salud del Perú, Dirección General de Salud Ambiental. Río chillón 2010, June 24, 2011.

[66] Ministerio de Salud del Perú, Dirección General de Salud Ambiental, Dirección de Ecología y Protección del Ambiente. Cuenca del río chillón: Calidad sanitaria, September 2011.

[67] Ministerio de Vivienda Construcción y Saneamiento del Perú. Aprueban valores máximos admisibles (vma) de las descargas de aguas residuales no domésticas en el sistema de alcantarillado sanitario: 021-2009-vivienda.

[68] Ministerio de Vivienda Construcción y Saneamiento del Perú. Lineamientos de política para la promoción del tratamiento para el reuso de las aguas residuales domésticas y municipales en el riego de areas verdes urbanas y periurbanas: 176-2010-vivienda.

[69] Ministerio de Vivienda Construcción y Saneamiento del Perú. Plantas de tratamiento de aguas residuales: Norma os.090.

[70] Ministerio del Ambiente del Perú. Aprueba límites máximos permisibles para los efluentes de plantas de tratamiento de aguas residuales domésticas o municipales: 003-2010-minam.

[71] Ministerio del Ambiente del Perú. Aprueban los estánderes nacionales de calidad ambiental para agua: 002-2008-minam.

[72] Miranda Sara, L. and Molina, R. T. Pantanos de villa, April 12, 2011.

[73] Moscoso, J. and Alfaro, T. Panorama de experiencias de tratamiento y uso de aguas residuales en lima metropolitana y callao, April 2008.

[74] Moscoso, J. and Alfaro Abanto, T. Estudios de caso de experiencias de tratamiento y uso de aguas residuales en la ciudad de lima, perú, September 2008.

[75] Moscoso Cavallini, J. C. Estudio de opciones de tratamiento y reuso de aguas residuales en lima metropolitana, 2011.

[76] Moscoso Cavallini, J. C. Riego de las áreas verdes en lima metropolitana, December 14, 2011.

[77] Municipalidad de San Martin de Porres. Estudio de pre-inversión a nivel de prefactabilidad: Construcción de defensas ribereñas en la margen izquierda del río chillón, October 2008.

[78] Municipalidad de San Martin de Porres. Sistema distrital de riego de áreas verdes de san martin de porres, October 2011.

[79] Nelson, M., Cattin, F., Tredwell, R., Depuy, G., Suraja, M., and Czech, A. Why there are no better systems than constructed wetlands to treat sewage water: Advantages, issues and challenges, 2007.

[80] Oelrichs, A. and Gänsbauer, L. Atlas: Cuenca baja del río chillón: Estrategia de infrastructura ecológica por la cuenca baja del río chillón, May 2012.

[81] Organización de las Naciones Unidas para la Educación, la Ciencia y la Cultura, Programa Hidrológico Internacional. Balance hídrico superficial del perú a nivel multianual, 2006.

[82] Pacheco Caldas, R. Demographic and water usage statistics, February 24, 2012.

[83] Polomski, R. F., Bielenberg, D. G., Whitwell, T., Taylor, M. D., Bridges, W. C., and Klaine, S. J. Differential nitrogen and phosphorus recovery by five aquatic garden species in laboratory-scale subsurface-constructed wetlands. *HortScience*, 43(3):868–874, 2008.

[84] Pontificia Universidad Católica del Perú (PUCP). "la gente piensa que el gras verde y las lindas flores son ecología, pero no lo son", March 16, 2012.

[85] Ramón, R. Es obsoleto sistema para vigilar los vertimientos mineros a ríos. *El Comercio*, S. a10, June 28, 2011.

[86] Reilly, J. F., Horne, A. J., and Miller, C. D. Nitrate removal from a drinking water supply with large free-surface constructed wetlands prior to groundwater recharge. *Ecological Engineering*, 14:33–47, 2000.

[87] Representative from the Municipalidad de San Martin de Porres. Proyecto complementario de sensibilización social y participación ciudadana para el diseño conceptual del parque ecológico municipal del dsmp, 2011.

[88] Rodríguez, L. Lima puede ser verde. *El Comercio*, S. 4, November 30, 2011.

[89] Rodríguez, S. ¿qué parques necesitamos? *Publimetro*, S. 6, March 30, 2012.

[90] Chamorro de Rodríguez, G. and Arboleda Orozco, J. F. Comportamiento del año hidrológico 2007/08: Cuenca de los ríos rímac - chillón - lurín, October 2008.

[91] Salazar Vega, E. Crece riesgo en ribera del chillón: Acumulación de basura estrecha cauce del río. *El Comercio*, S. a8, February 22, 2011.

[92] San Martin de Porres Gerente de Servicios Públicos y Medio Ambiente. Distribución de red de canales y compuertas.

[93] Sandoval, W. Falta solo medio km para acabar túnel transandino de olmos: Megaproyecto podría estar operativo en julio del 2012. *El Comercio*, S. a12, October 12, 2011.

[94] Seder, N., Vallentin, A., and Abdel-Sattar, Z. Irrigation water quality guidelines, November 2006.

[95] Servicio de Agua Potable y Alcantarillado de Lima (SEDAPAL). Planta de tratamiento de aguas residuales "puente piedra".

[96] Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI). Monitoreo de la calidad de agua de los ríos rímac, chillón y lurín, 2007.

[97] Silberner, J. Watching peru's oceans for cholera cues, February 25, 2008.

[98] Silva Nole, L. Agua llega de a pocos en lima norte: Sedapal reparará redes en el distrito de comas y otras zonas. *El Comercio*, S. a2, April 30, 2011.

[99] Sklarz, M. Y., Gross, A., Yakirevich, A., and Soares, M. I. M. A recirculating vertical flow constructed wetland for the treatment of domestic wastewater. *Desalination*, 246:617–624, 2009.

[100] Standards Institution of Israel. Guidelines for treated wastewater reuse (draft), April 2010.

[101] Statistisches Landesamt Baden-Württemberg. Statistische berichte baden-württemberg: Bevölkerung und erwerbstätigkeit, July 20, 2011.

[102] Steinmetz, H. and Krampe, J. Wastewater technology lecture notes: Part 2: Wastewater treatment, WS 2009.

[103] Stokman, A., Poblet, R., and Nemcova, E. Implementing the ecological park of the future: Green, productive, inclusive, sustainable, 2011.

[104] Subirana Abanto, K. "buscamos la buena gestión del agua". *El Comercio*, S. a14, March 22, 2010.

[105] Sustainable Water and Wastewater Management in Urban Growth Centres Coping with Climate Change - Concepts for Lima Metropolitana (Perú) (LiWa). Liwa (lima water).

[106] Sustainable Water Management for the Cities of the Future (SWITCH) Lima. Switch: Local demonstrations for global change: Lima: Optimizing water management to combat urban poverty, December 2008.

[107] Swiss Welfare Organisation (SWO). Gesundes stadtquartier als modell - comunidad saludable modelo: Cono norte - lima, armenviertel von collique-comas.

[108] Torres, F. Hay hasta 87 zonas críticas en las cuencas de los ríos rímac, chillón y lurín. *El Comercio*, February 3, 2009.

[109] Unger, M., Vollherbst, T., Vera, J., and Grimm, F. Lima: eine stadt trocknet aus, July 24, 2010.

[110] United States Centers for Disease Control and Prevention (CDC). Health information for travelers to peru, June 25, 2012.

[111] United States Central Intelligence Agency (CIA). The world factbook: Perú, June 25, 2012.

[112] United States Department of Defense, Office of the Deputy Under Secretary of Defense for Environmental Security. Disease vector ecology profile: Perú, December 1998.

[113] United States Environmental Protection Agency (EPA). Water: Monitoring & assessment: Chapter 5: Water quality conditions, March 6, 2012.

[114] United States Environmental Protection Agency, Office of Wastewater Management, Municipal Support Division, United States Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory, Technology Transfer and Support Division, and United States Agency for International Development (USAID). Guidelines for water reuse, September 2004.

[115] Universität Stuttgart, Institut für Landschaftsplanung und Ökologie (ILPÖ). Beyond the park summer school flyer, February 2012.

[116] Universität Stuttgart, Institut für Landschaftsplanung und Ökologie (ILPÖ). Taller para la elaboración de la estrategia de infraestructura ecológica de lima metropolitana: Integración a los procesos de planificación y gestión, November 18, 2011.

[117] Vymazal, J. and Kröpfelová, L. Removal of organics in constructed wetlands with horizontal sub-surface flow: A review of the field experience. *Science of the Total Environment*, 407:3911–3922, 2009.

[118] Wirth, N. *Wastewater Re-use in Lima Metropolitana: A Concept for an Integrated and Sustainable Water and Wastewater Management.* Dissertation, Hochschule Emden/Leer, Emden and Germany, August 31, 2010.

[119] Wissing, F. and Hofmann, K. *Wasserreinigung mit Pflanzen.* Ulmer, Stuttgart, 2 Auflage, 2002.

[120] World Health Organization. *Guidelines for the safe use of wastewater, excreta and greywater: Policy and regulatory aspects*, Band 1. World Health Organization, Geneva, 3 Auflage, 2006.

[121] Wright, C. P. Water audits: Guidelines and worksheets, July 1993.

[122] WTW Wissenschaftlich - Technische Werkstätten GmbH. Bedienungsanleitung zum ph 91.

[123] WTW Wissenschaftlich - Technische Werkstätten GmbH. Lf 330/set lf 340/set instruction manuals, June 1997.

[124] WTW Wissenschaftlich - Technische Werkstätten GmbH. Oxi 323/set oxi 325/set instruction manuals, June 2000.

[125] Zenteno Tupiño, E., Romero Hernández, C., Muñante Valenzuela, J. G., Vargas Coca, G., Arellano Laos, J. L., and Silva Álvarez, J. Estudio integral de los recursos hídricos en la cuenca del río chillón: Inventario de fuentes de agua subterránea en el valle del río chillón, January 2004.

[126] Zolezzi Chocano, M., Tokeshi Gusukuda Shirota, J., and Noriega Jugo, C. *Densificación Habitacional: Una Propuesta de Crecimiento para la Cuidad Popular*. Sinco Editores S.A.C., 2005.

A “Lima: Beyond the Park” Summer School Announcement

desierto | río estacional | paisajismo | agua | ecología | valle | parque | desarrollo urbano | áreas agrícolas | reciclaje | periferia urbana | zonas arqueológicas

BEYOND THE PARK
MÁS QUE UN PARQUE

TALLER DE VERANO
SUMMER SCHOOL
20.2 - 3.3 - 2012
CHUQUITANTA,
SAN MARTIN DE PORRES, LIMA

¿Cómo puede un parque combinar procesos ecológicos naturales, la experiencia cultural del agua en la ciudad y al mismo tiempo apoyar el buen funcionamiento de la infraestructura del agua en Lima? ¿Cómo revertir la degradación del paisaje de una ciudad en el desierto con contrastes urbanos extremos como Lima? Y ¿cómo diseñar espacios verdaderamente ecológicos que combinen diversas funciones y tenga en cuenta el ciclo urbano del agua, entorno, comunidades y necesidades diferentes?

How can a river park combine natural ecological processes, the cultural experience of water in the city and, at the same time, support the proper functioning of Lima's water infrastructure system? How to revert the landscape degradation of a desert city with extreme urban contrast like Lima? And how to design real ecological spaces which combine different functions and consider the urban water cycle, the surroundings, the communities and different needs?

Instituto de Planificación del Paisaje y Ecología (ILPÖ), Alemania
Centro de Investigación de la Arquitectura y la Ciudad-CIAC, Perú
Proyecto LiWa (Lima Water): http://www.lima-water.de/
Blog de estudiantes: http://limabeyondthepark.wordpress.com/
Contacto: rp@ilpoe.uni-stuttgart.de

Coupling nature, culture and water infrastructure in Lima
Lima is the world's second largest city in a desert. Water supply is mainly from its seasonal rivers that are shaping green valleys in the mountainous desert and flat areas. However, due to fast uncontrolled urbanisation, water extraction and sewage disposal, these rivers are loosing their vital function of serving as green infrastructure for the metropolitan area. Additionally the areas along the rivers have developed in an informal way, reason why there is an urgent need to recover those areas and to integrate them into the open space system to benefit a desert city which lacks green areas. Therefore, during the summer school we will develop strategies for an ecological river park along Chillon river that are not simply based on a park image design - but on a park performance design. Additionally, we will study the urban water cycle and the best way to integrate it into the open space in the city, thus introducing new concepts for the generation of public places with a water sensitive approach.

Conectando naturaleza, cultura e infraestructura del agua en Lima I Lima es la segunda ciudad más grande del mundo ubicada en un desierto. El suministro de agua proviene principalmente de ríos estacionales que dan forma a los valles verdes en el desierto montañoso y áreas planas. Sin embargo, debido al descontrolado proceso de urbanización, extracción de agua y eliminación de aguas residuales y otros problemas, estos ríos están perdiendo su función vital de servir como infraestructura verde ecológica para el área metropolitana. Además, las áreas a lo largo de los ríos se han desarrollado de manera informal, razón por la cual existe una urgente necesidad de recuperar esas áreas con el fin de integrarlos en el sistema de espacios abiertos para beneficiar a una ciudad en el desierto, que carece de áreas verdes. Por lo tanto dentro de la escuela de verano vamos a desarrollar estrategias para un parque ribereño sobre el río Chillón, que no se basa simplemente en un diseño estético de parque pero que busca el mayor rendimiento en el diseño. Para ellos se estudiará el ciclo urbano del agua y la mejor manera de integrarlo en los espacios abiertos en la ciudad introduciendo nuevos conceptos para la generación de espacios públicos considerando el agua.

Universität Stuttgart | ILPÖ | Sto Stiftung | LiWa | CIAC – CENTRO DE INVESTIGACIÓN DE LA ARQUITECTURA Y LA CIUDAD | PONTIFICIA UNIVERSIDAD CATÓLICA DEL PERÚ

B Detailed Testing Procedures: Aquamerck® Compact Laboratory for Water Testing

7.75764.0002-xxxxxxxxxx msp.

November 2011

1.08024.0001

Aquamerck®

Ammonium Test

NH_4^+

1. Method

Colorimetric determination with color card and sliding comparator
Ammonium nitrogen (NH_4-**N**) occurs partly in the form of ammonium ions and partly as ammonia. A pH-dependent equilibrium exists between the two forms. In strongly alkaline solution ammonium nitrogen is present almost entirely as ammonia, which reacts with a chlorinating agent to form monochloramine. This in turn reacts with thymol to form a blue indophenol derivative. The ammonium concentration is measured **semiquantitatively** by visual comparison of the color of the measurement solution with the color fields of a color card.

2. Measuring range and number of determinations

Measuring range / color-scale graduation [1]	Number of determinations
0.2 - 0.4 - 0.6 - 1 - 2 - 3 - **5** **mg/l NH_4^+**	50
0.16 - 0.31 - 0.47 - 0.8 - 1.6 - 2.3 - **3.9** **mg/l NH_4-N**	

[1] for conversion factors see section 8

3. Applications

This test measures both ammonium ions and dissolved ammonia.

Sample material:
Groundwater and surface water, seawater
Drinking water
Wastewater
Aquarium water (freshwater and seawater)
Nutrient solutions for fertilization
Soils and food after appropriate sample pretreatment

4. Influence of foreign substances

The determination is not interfered with by the substances usually contained in the sample materials stated above.
Amines are measured at the same time.

5. Reagents and auxiliaries

Please note the warnings on the packaging materials!
The test reagents are stable up to the date stated on the pack when stored closed at +15 to +25 °C.

Package contents:
1 bottle of reagent NH_4-1
1 bottle of reagent NH_4-2
1 bottle of reagent NH_4-3
1 graduated 5-ml plastic syringe
2 test tubes with screw caps
1 sliding comparator
1 color card

Other reagents and accessories:
Universal indicator strips pH 0 - 14, Cat. No. 109535
Sodium hydroxide solution 1 mol/l TitriPUR®, Cat. No. 109137
Sulfuric acid 0.5 mol/l TitriPUR®, Cat. No. 109072
Ammonium standard solution CertiPUR®, 1000 mg/l NH_4^+, Cat. No. 119812

Flat-bottomed tubes for Aquamerck® tests (12 pcs), Cat. No. 114902

6. Preparation

- **The pH must be within the range 4 - 13.**
  Adjust, if necessary, with sodium hydroxide solution or sulfuric acid.
- Filter turbid samples.

7. Procedure

	Measurement sample	**Blank**	
Rinse both test tubes several times with the pretreated sample.			
Pretreated sample (**20 - 30 °C**)	5 ml	5 ml	Inject into the test tube with the syringe.
Reagent NH_4-1	12 drops[1]	-	Add and mix.
Reagent NH_4-2	1 level blue microspoon (in the cap of the NH_4-2 bottle)	-	Add, close the tube, and shake **vigorously until the reagent is completely dissolved**.
Leave to stand for 5 min.			
Reagent NH_4-3	4 drops[1]	-	Add and mix.
Insert the test tubes into the sliding comparator as shown in the diagram and place the comparator on the color card as indicated by the latter.			
Leave to stand for 7 min.			
Slide the comparator along the color scale until the closest possible color match is achieved between the two open tubes when viewed from above. Read off the result in mg/l NH_4^+ or NH_4-N from the color card indicated by the pointed end of the sliding comparator.			

[1] **Hold the bottle vertically while adding the reagent!**

Notes on the measurement:

- The measured value indicates the content of "total ammonium". This consists - depending on the pH of the water to be tested (**prior to** the addition of the reagents!) - of ammonium ions and free ammonia in the following percentage ratios:

pH	Ammonium ions %	Free ammonia %
6	100	0
7	99	1
8	96	4
9	75	25
10	22	78

  Ammonia, which is toxic e.g. for fish, is stable only in alkaline waters (high pH). In acidic waters (pH lower than 7) virtually only ammonium ions are present. **For this reason, the pH of the water to be tested should always be measured additionally to the determination of ammonium.**
- If the color of the measurement solution is equal to or more intense than the darkest color on the scale, repeat the measurement using **fresh**, diluted samples until a value of less than 5 mg/l NH_4^+ is obtained.
  Concerning the result of the analysis, the dilution must be taken into account:

Result of analysis = measurement value x dilution factor

8. Conversions

Units **required** =	units **given** x	conversion factor
mg/l NH_4-**N**	**mg/l NH_4^+**	0.776
mg/l NH_4^+	mg/l NH_4-**N**	1.29

9. Method control

To check test reagents, measurement device, and handling:
Dilute the ammonium standard solution with distilled water to 2 mg/l NH_4^+ and analyze as described in section 7.
Additional notes see under **www.merck-chemicals.com/qa**.

10. Notes

- Reclose the reagent bottles immediately after use.
- Rinse the test tubes and the syringe **with distilled water only**.
- **Information on disposal can be obtained under the Quick Link "Waste Disposal Advice" at www.merck-chemicals.com/test-kits.**

July 2011

1.11170.0001

Aquamerck®

Nitrate Test

NO_3^-

1. Method

Colorimetric determination with colour card and sliding comparator
Nitrate ions are reduced to nitrite ions that react in acidic solution with sulfanilic acid to form a diazonium salt. This reacts with a benzoic acid derivative to form an orange-yellow azo dye. The nitrate concentration is measured **semiquantitatively** by visual comparison of the colour of the measurement solution with the colour fields of a colour card.

2. Measuring range and number of determinations

Measuring range / colour-scale graduation [1]	Number of determinations
10 - 25 - 50 - 75 - 100 - 125 - **150** **mg/l NO_3^-**	200
2.3 - 5.6 - 11 - 17 - 23 - 28 - **34** **mg/l NO_3-N**	

[1] for conversion factors see section 8

3. Applications

Sample material:
Groundwater, drinking water, and surface water (also humin-containing samples)
Industrial water
Wastewater
Food and animal fodder after appropriate sample pretreatment
Soils and fertilizers after appropriate sample pretreatment
This test is **not suited** for seawater.

4. Influence of foreign substances

This was checked in solutions with 100 mg/l NO_3^-. The determination is not yet interfered with up to the concentrations of foreign substances given in the table.

Concentrations of foreign substances in mg/l							
Al^{3+}	**10**	**Fe^{3+}**	**1**	**S^{2-}**	**1**	**Cl_2**	**1**
Ca^{2+}	100	Mg^{2+}	100	SiO_3^{2-}	100	**EDTA**	**10**
Cl^-	1000	Mn^{2+}	100	SO_3^{2-}	100	**Cationic surfactants** [1]	**10**
Cr^{3+}	**1**	Na^+	100	SO_4^{2-}	1000	Anionic surfactants [2]	100
$Cr_2O_7^{2-}$	**1**	NH_4^+	100	Zn^{2+}	100	**Oxidizing agents (H_2O_2)**	**10**
Cu^{2+}	**10**	**NO_2^-**	**3**				
F^-	**10**	PO_4^{3-}	100				
Fe^{2+}	**10**	Polyphosphates	100				

[1] tested with N-cetylpyridinium chloride
[2] tested with Na-dodecyl hydrogen sulfate

5. Reagents and auxiliaries

Please note the warnings on the packaging materials!

The test reagent is stable up to the date stated on the pack when stored closed at +15 to +25 °C.

Package contents:
2 bottles of reagent NO_3-1
1 graduated 5-ml plastic syringe
2 test tubes with screw caps
1 sliding comparator
1 colour card

Other reagents and accessories:
Merckoquant® Nitrate Test, Cat. No. 110020,
measuring range 10 - 500 mg/l NO_3^- (2.3 - 113 mg/l NO_3-N)
Universal indicator strips pH 0 - 14, Cat. No. 109535
Sodium hydroxide solution 1 mol/l TitriPUR®, Cat. No. 109137
Sulfuric acid 0.5 mol/l TitriPUR®, Cat. No. 109072
Nitrate standard solution CertiPUR®, 1000 mg/l NO_3^-, Cat. No. 119811

Flat-bottomed tubes for Aquamerck® tests (12 pcs), Cat. No. 114902

6. Preparation

- Check the nitrate content with the Merckoquant® Nitrate Test.
  Samples containing more than 150 mg/l NO_3^- must be diluted with distilled water.
- **The pH must be within the range 4 - 10.**
  Adjust, if necessary, with sodium hydroxide solution or sulfuric acid.
- Filter turbid samples.

7. Procedure

Rinse both test tubes several times with the pretreated sample.

	Measurement sample	Blank	
Pretreated sample (**15 - 25 °C**)	5 ml	5 ml	Inject into the test tube with the syringe.
Reagent NO_3-1	2 level green microspoons (in the cap of the NO_3-1 bottle)	-	Add, close the tube tightly, and **shake vigorously for 1 min**.

Insert the test tubes into the sliding comparator as shown in the diagram and place the comparator on the colour card as indicated by the latter.

Leave to stand for 5 min.

Slide the comparator along the colour scale until the closest possible colour match is achieved between the two open tubes when viewed from above.
Read off the result in mg/l NO_3^- or NO_3-N from the colour card indicated by the pointed end of the sliding comparator or, if necessary, estimate an intermediate value.

Notes on the measurement:

- If the colour of the measurement solution is equal to or more intense than the darkest colour on the scale, repeat the measurement using **fresh**, diluted samples until a value of less than 150 mg/l NO_3^- is obtained.
  Concerning the result of the analysis, the dilution (see also section 6) must be taken into account:

  Result of analysis = measurement value x dilution factor

- Any black residues that may occur are due to the reaction mechanism and do not falsify the measurement results in any way.

8. Conversions

Units **required**	=	units **given**	x	conversion factor
mg/l NO_3-**N**		**mg/l NO_3^-**		0.226
mg/l NO_3^-		mg/l NO_3-**N**		4.43

9. Method control

To check test reagent, measurement device, and handling:
Dilute the nitrate standard solution with distilled water to 100 mg/l NO_3^- and analyze as described in section 7.
Additional notes see under **www.merck-chemicals.com/qa**.

10. Notes

- Reclose the reagent bottle immediately after use.
- Rinse the test tubes and the syringe **with distilled water only**.
- **Information on disposal can be obtained under the Quick Link "Waste Disposal Advice" at www.merck-chemicals.com/test-kits.**

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1.08025.0001

Aquamerck®

Nitrite Test NO_2^-

1. Method

Colorimetric determination with color card and sliding comparator
In acidic solution nitrite ions react with sulfanilic acid to form a diazonium salt, which in turn reacts with N-(1-naphthyl)ethylenediamine dihydrochloride to form a red-violet azo dye. The nitrite concentration is measured **semiquantitatively** by visual comparison of the color of the measurement solution with the color fields of a color card.

2. Measuring range and number of determinations

Measuring range / color-scale graduation[1]	Number of determinations
0.025 - 0.050 - 0.075 - 0.10 - 0.15 - 0.2 - 0.3 - **0.5 mg/l NO_2^-**	200
0.0076 - 0.015 - 0.023 - 0.030 - 0.046 - 0.06 - 0.09 - **0.15 mg/l NO_2-N**	

[1] for conversion factors see section 7

3. Applications

Sample material:
Groundwater and surface water, seawater
Drinking water
Fish waters
Aquarium water (freshwater and seawater)

4. Reagents and auxiliaries

Please note the warnings on the packaging materials!
The reagents in the test are stable up to the date stated on the pack when stored closed at +15 to +25 °C.

Package contents:
2 bottles of reagent NO_2-1
1 bottle of reagent NO_2-2
1 graduated 5-ml plastic syringe
2 test tubes with screw caps
1 sliding comparator
1 color card

Other reagents and accessories:
Universal indicator strips pH 0 - 14, Cat. No. 109535
Sodium hydroxide solution 1 mol/l TitriPUR®, Cat. No. 109137
Sulfuric acid 0.5 mol/l TitriPUR®, Cat. No. 109072
Nitrite standard solution CertiPUR®, 1000 mg/l NO_2^-, Cat. No. 119899

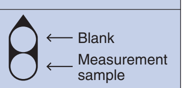
Flat-bottomed tubes for Aquamerck® tests (12 pcs), Cat. No. 114902

5. Preparation

- **The pH must be within the range 2 - 10.**
  Adjust, if necessary, with sodium hydroxide solution or sulfuric acid.
- Filter turbid samples.

6. Procedure

Rinse both test tubes several times with the pretreated sample.			
	Measurement sample	**Blank**	
Pretreated sample (**15 - 25 °C**)	5 ml	5 ml	Inject into the test tube with the syringe.
Reagent NO_2-1	5 drops[1]	-	Add, close the tube, and mix.
Reagent NO_2-2	1 level grey microspoon (in the cap of the NO_2-2 bottle)	-	Add, close the tube, and shake **vigorously until the reagent is completely dissolved**.
Insert the test tubes into the sliding comparator as shown in the diagram and place the comparator on the color card as indicated by the latter.			
Leave to stand for 1 min.			
Slide the comparator along the color scale until the closest possible color match is achieved between the two open tubes when viewed from above. Read off the result in mg/l NO_2^- or NO_2-N from the color card indicated by the pointed end of the sliding comparator.			



[1] **Hold the bottle vertically while adding the reagent!**

January 2012

Note on the measurement:

If the color of the measurement solution is equal to or more intense than the darkest color on the scale, repeat the measurement using **fresh**, diluted samples until a value of less than 0.5 mg/l NO_2^- is obtained.

Concerning the result of the analysis, the dilution must be taken into account:

Result of analysis = measurement value x dilution factor

7. Conversions

Units **required** =	units **given** x	conversion factor
mg/l NO_2-**N**	**mg/l NO_2^-**	0.304
mg/l NO_2^-	mg/l NO_2-**N**	3.28

8. Method control

To check test reagents, measurement device, and handling:
Dilute the nitrite standard solution with distilled water to 0.2 mg/l NO_2^- and analyze as described in section 6.
Additional notes see under **www.merck-chemicals.com/qa**.

9. Notes

- Reclose the reagent bottles immediately after use.
- Rinse the test tubes and the syringe **with distilled water only**.
- **Information on disposal can be obtained under the Quick Link "Waste Disposal Advice" at www.merck-chemicals.com/test-kits.**

April 2011

Aquamerck®

1.08027.0001

pH Test

pH

1. Definition

The pH of dilute aqueous solutions is defined as the negative logarithm of the hydrogen ion concentration in mol/l:

pH = -lg (H^+ concentration)

Solutions are characterized as acidic, neutral, or alkaline according to their pH:

Solution	pH	H^+ concentration in mol/l
acidic	**< 7**	$> 10^{-7}$
neutral	**7**	10^{-7}
alkaline, basic	**> 7**	$< 10^{-7}$

2. Method

Colorimetric determination with colour card and sliding comparator
An indicator solution changes colour depending on the pH. The pH value is measured **semiquantitatively** by visual comparison of the colour of the measurement solution with the colour fields of a colour card.

3. Measuring range and number of determinations

Measuring range / colour-scale graduation	Number of determinations
pH 4.5 - 5.0 - 5.5 - 6.0 - 6.5 - 7.0 - 7.5 - 8.0 - 8.5 - **9.0**	400

4. Applications

The pH determination using indicator solutions is also suited for weakly buffered water samples.

Sample material:
Groundwater, drinking water, and surface water
Fish waters
Aquarium water
Boiler water

5. Reagents and auxiliaries

Please note the warnings on the packaging materials!
The test reagent is stable up to the date stated on the pack when stored closed at +15 to +25 °C.

Package contents:
2 bottles of reagent pH-1
1 graduated 5-ml plastic syringe
2 test tubes with screw caps
1 sliding comparator
1 colour card

Other reagents and accessories:
Buffer solution pH 7.00 CertiPUR®, Cat. No. 109407

Flat-bottomed tubes for Aquamerck® tests (12 pcs), Cat. No. 114902

6. Preparation

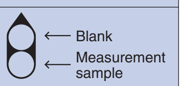
Filter turbid samples.

7. Procedure

Rinse both test tubes several times with the pretreated sample.

	Measurement sample	**Blank**	
Pretreated sample (**15 - 25 °C**)	5 ml	5 ml	Inject into the test tube with the syringe.
Reagent pH-1	2 drops[1]	-	Add and mix.

Insert the test tubes into the sliding comparator as shown in the diagram and place the comparator on the colour card as indicated by the latter.



Slide the comparator along the colour scale until the closest possible colour match is achieved between the two open tubes when viewed from above.

Read off the pH from the colour card indicated by the pointed end of the sliding comparator or, if necessary, estimate an intermediate value.

[1] **Hold the bottle vertically while adding the reagent!**

Note on the measurement:

If the colour of the measurement solution corresponds to the lowest or highest value on the scale, the actual pH value may lie outside the measuring range.

8. Method control

To check test reagent, measurement device, and handling:
Analyze the buffer solution pH 7.00 as described in section 7.
Additional notes see under **www.merck-chemicals.com/qa**.

9. Notes

- Reclose the reagent bottle immediately after use.
- Rinse the test tubes and the syringe **with distilled water only**.
- **Information on disposal can be obtained under the Quick Link "Waste Disposal Advice" at www.merck-chemicals.com/test-kits.**

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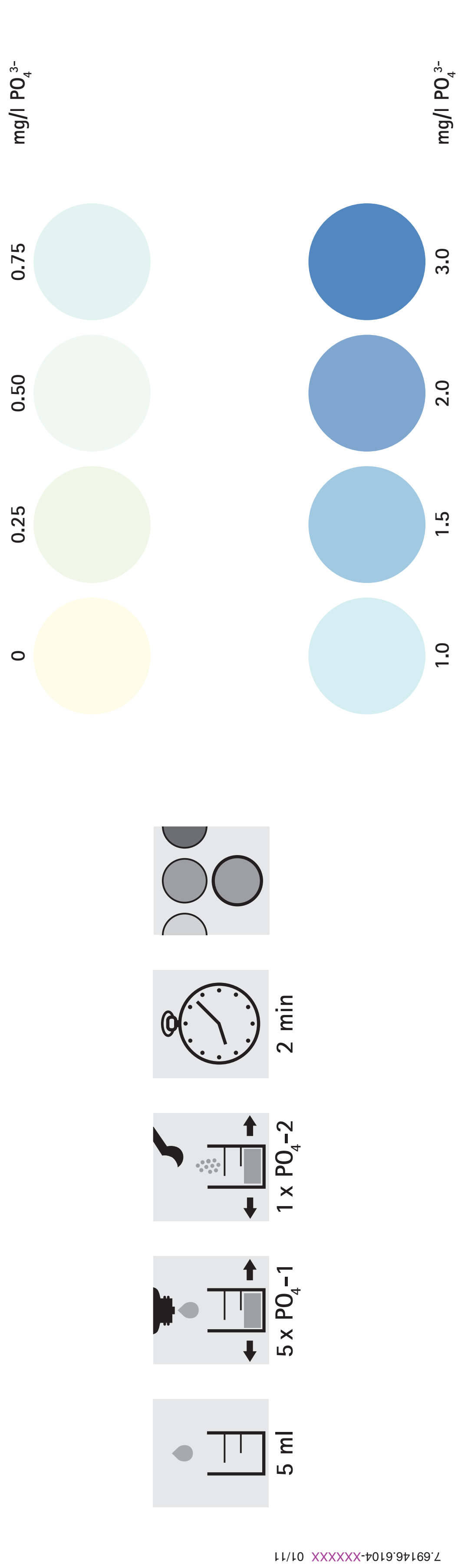


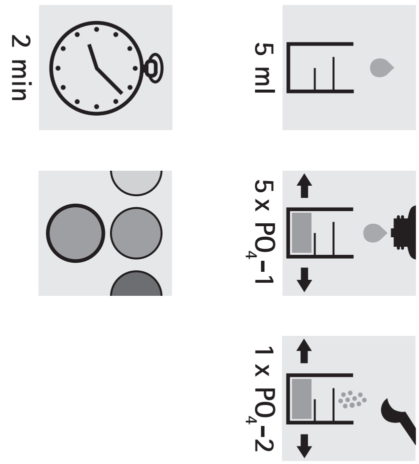
7.69146.6104-XXXXXX 01/11

Phosphate Test
in freshwater and seawater

Phosphat-Test
in Süß- und Seewasser

Test Phosphates
dans les eaux douces et l'eau de mer

Test Fosfatos
en agua dulce y agua de mar



Store at +15 °C to +25 °C.
Conserver de +15 °C à +25 °C.
Lagern bei +15 °C bis +25 °C.
Almacenar entre +15 °C y +25 °C.

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Aquamerck®
Phosphate Test
0.25 - 3 mg/l PO_4^{3-}

1.14661.0001
100 Tests

C Detailed Testing Procedures: Merck Spectroquant® Cell Tests

April 2011

1.14558.0001

Spectroquant®

Ammonium Cell Test

NH_4^+

1. Method

Ammonium nitrogen (NH_4-**N**) occurs partly in the form of ammonium ions and partly as ammonia. A pH-dependent equilibrium exists between the two forms. In strongly alkaline solution ammonium nitrogen is present almost entirely as ammonia, which reacts with hypochlorite ions to form monochloramine. This in turn reacts with a substituted phenol to form a blue indophenol derivative that is determined photometrically.
The method is analogous to EPA 350.1, APHA 4500-NH_3 D, ISO 7150/1, and DIN 38406 E5.

2. Measuring range and number of determinations

Measuring range	Number of determinations
0.20 - 8.00 mg/l NH_4-N	25
0.26 - 10.30 mg/l NH_4^+	

For programming data for selected photometers see the website.

3. Applications

This test measures both ammonium ions and dissolved ammonia.

Sample material:
Groundwater and surface water, seawater
Drinking water
Wastewater
Nutrient solutions for fertilization
Soils and food after appropriate sample pretreatment

4. Influence of foreign substances

This was checked in solutions containing 4 and 0 mg/l NH_4-N. The determination is not yet interfered with up to the concentrations of foreign substances given in the table.

Concentrations of foreign substances in mg/l or %					
Al^{3+}	1000	**Mn^{2+}**	**10**	EDTA	1000
Ca^{2+}	250	Ni^{2+}	25	**Primary amines[1)]**	**0**
Cd^{2+}	1000	NO_2^-	500	**Secondary amines[2)]**	**10**
CN^-	25	Pb^{2+}	1000	Aminophenols	25
Cr^{3+}	**10**	PO_4^{3-}	250	Aniline	50
$Cr_2O_7^{2-}$	250	**S^{2-}**	**5**	Triethanolamine	1000
Cu^{2+}	25	SiO_3^{2-}	1000	Surfactants[3)]	1000
F^-	1000	Zn^{2+}	50	Na-acetate	10 %
Fe^{3+}	50			NaCl	20 %
Hg^{2+}	50			$NaNO_3$	10 %
Mg^{2+}	50			Na_2SO_4	15 %

Reducing agents interfere with the determination.

[1)] tested with methylamine
[2)] tested with dimethylamine
[3)] tested with nonionic, cationic, and anionic surfactants

5. Reagents and auxiliaries

Please note the warnings on the packaging materials!

The test reagents are stable up to the date stated on the pack when stored closed at +15 to +25 °C.

Package contents:
1 bottle of reagent NH_4-1K (contains granulate + desiccant capsule)
25 reaction cells
1 cell with blank (**white** screw cap); **required only when using the SQ 118 photometer**
1 blue dose-metering cap
1 sheet of round stickers for numbering the cells

Other reagents and accessories:
Universal indicator strips pH 0 - 14, Cat. No. 109535
Sodium hydroxide solution 1 mol/l TitriPUR®, Cat. No. 109137
Sulfuric acid 0.5 mol/l TitriPUR®, Cat. No. 109072
Spectroquant® CombiCheck 10, Cat. No. 114676
Ammonium standard solution CRM, 0.400 mg/l NH_4-N, Cat. No. 125022
Ammonium standard solution CRM, 1.00 mg/l NH_4-N, Cat. No. 125023
Ammonium standard solution CRM, 2.00 mg/l NH_4-N, Cat. No. 125024
Ammonium standard solution CRM, 6.00 mg/l NH_4-N, Cat. No. 125025

Pipette for a pipetting volume of 1.0 ml

6. Preparation

At the first use **replace the black screw cap of the reagent bottle NH_4-1K by the blue dose-metering cap**.
Hold the reagent bottle **vertically** and, at each dosage, press the slide **all the way** into the dose-metering cap. **Before each dosage** ensure that the slide is **completely retracted**.
Reclose the reagent bottle with the black screw cap at the end of the measurement series, since the function of the reagent is impaired by the absorption of atmospheric moisture.

- Analyze immediately after sampling.
- Samples containing more than 8.00 mg/l NH_4-N must be diluted with distilled water. Alternatively, it is also possible to use the Spectroquant® Ammonium Cell Tests Cat. No. 114544 (measuring range 0.5 - 16.0 mg/l NH_4-N) or 114559 (measuring range 4.0 - 80.0 mg/l NH_4-N).
- **The pH must be within the range 4 - 13.**
  Adjust, if necessary, with sodium hydroxide solution or sulfuric acid.
- Filter turbid samples.

7. Procedure

Pretreated sample (**20 - 30 °C**)	1.0 ml	Pipette into a reaction cell (**20 - 30 °C**), close the cell, and mix.
Reagent NH_4-1K	1 dose	Add, close the cell tightly, and shake **vigorously until the reagent is completely dissolved.**
Leave to stand for 15 min (reaction time), then measure the sample in the photometer.		

Notes on the measurement:

- For photometric measurement the cells must be clean.
  Wipe, if necessary, with a clean dry cloth.
- Measurement of turbid solutions yields false-high readings.
- Ammonium-free samples turn yellow on addition of reagent NH_4-1K.
- The pH of the measurement solution must be within the range 11.5 - 11.8.
- The colour of the measurement solution remains stable for at least 60 min after the end of the reaction time stated above.
- In the event of ammonium concentrations exceeding 500 mg/l, other reaction products are formed and false-low readings are yielded. In such cases it is advisable to conduct a plausibility check of the measurement results by diluting the sample (1:10, 1:100).

8. Analytical quality assurance

recommended before each measurement series
To check the photometric measurement system (test reagent, measurement device, handling) and the mode of working, the ammonium standard solutions CRM, 0.400 mg/l NH_4-N, Cat. No. 125022, 1.00 mg/l NH_4-N, Cat. No. 125023, 2.00 mg/l NH_4-N, Cat. No. 125024, and 6.00 mg/l NH_4-N, Cat. No. 125025 or Spectroquant® CombiCheck 10 can be used. Besides a **standard solution** with 4.00 mg/l NH_4-N, CombiCheck 10 also contains an **addition solution** for determining sample-dependent interferences (matrix effects).
Additional notes see under **www.merck-chemicals.com/qa**.

Characteristic quality data:

In the production control, the following data were determined in accordance with ISO 8466-1 and DIN 38402 A51:

Standard deviation of the method (mg/l NH_4-N)	± 0.042
Coefficient of variation of the method (%)	± 1.0
Confidence interval (mg/l NH_4-N)	± 0.10
Number of lots	39

Characteristic data of the procedure:

Sensitivity: Absorbance 0.010 A corresponds to (mg/l NH_4-N)	0.04
Accuracy of a measurement value (mg/l NH_4-N)	max. ± 0.19

For quality and batch certificates for Spectroquant® test kits see the website.

9. Notes

- Reclose the reagent bottle immediately after use.
- Rinse glassware ammonium-free with distilled water. **Do not use detergent!**
- **Information on disposal can be obtained under the Quick Link "Waste Disposal Advice" at www.merck-chemicals.com/test-kits.**

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1.14730.0001

Chloride Cell Test

Cl^-

1. Method

Chloride ions react with mercury(II) thiocyanate to form slightly dissociated mercury(II) chloride. The thiocyanate released in the process in turn reacts with iron(III) ions to form red iron(III) thiocyanate that is determined photometrically.
The method is analogous to EPA 325.1 and APHA 4500-Cl^- E.

2. Measuring range and number of determinations

Measuring range	Number of determinations
5 - 125 mg/l Cl^-	25

For programming data for selected photometers / spectrophotometers see the website.

3. Applications

Sample material:
Groundwater, surface water, and seawater (after dilution)
Drinking water and mineral water
Industrial water
Wastewater and percolating water

4. Influence of foreign substances

This was checked in solutions containing 70 and 0 mg/l Cl^-. The determination is not yet interfered with up to the concentrations of foreign substances given in the table.

Concentrations of foreign substances in mg/l or %							
Ag^+	**5**	Cu^{2+}	500	NH_4^+	1000	**Free chlorine**	**10**
Al^{3+}	100	F^-	100	Ni	100	Surfactants[2)]	1000
Br^-	**5**	Fe^{3+}	250	NO_2^-	100	Na-acetate	1 %
Ca^{2+}	1000	**Hg^{2+}**	**10**	Pb^{2+}	500	$NaNO_3$	20 %
Cd^{2+}	500	**I^-**	**10**	PO_4^{3-}	100	Na_2SO_4	1 %
CN^-	**0.5**	K^+	1000	**S^{2-}**	**0.5**[1)]		
Cr^{3+}	500	Mg^{2+}	500	SiO_3^{2-}	1000		
$Cr_2O_7^{2-}$	250	Mn^{2+}	1000	Zn^{2+}	500		

[1)] In cases of higher concentrations, eliminate sulfide ions by adding hydrogen peroxide (1 drop of Perhydrol® per 10 ml of sample).

[2)] tested with nonionic, cationic, and anionic surfactants

5. Reagents and auxiliaries

Please note the warnings on the packaging materials!
The test reagents are stable up to the date stated on the pack when stored closed at +15 to +25 °C.

Package contents:
1 bottle of reagent Cl-1K
25 reaction cells
1 cell with blank (**white** screw cap); **required only when using the SQ 118 photometer**
1 sheet of round stickers for numbering the cells

Other reagents and accessories:
Hydrogen peroxide 30 % H_2O_2 (Perhydrol®) for analysis EMSURE®, Cat. No. 107209
Universal indicator strips pH 0 - 14, Cat. No. 109535
Ammonia solution 25 % for analysis EMSURE®, Cat. No. 105432
Nitric acid Titrisol® for 1 mol/l, Cat. No. 109966
Spectroquant® CombiCheck 10, Cat. No. 114676 or
Spectroquant® CombiCheck 20, Cat. No. 114675

Pipettes for pipetting volumes of 0.50 and 1.0 ml

6. Preparation

- Analyze immediately after sampling.
- **The pH must be within the range 1 - 12.**
  Adjust, if necessary, with dilute ammonia solution or nitric acid.
- Filter turbid samples.

7. Procedure

Reagent Cl-1K	0.50 ml	Pipette into a reaction cell and mix.
Pretreated sample **(10 - 30 °C)**	1.0 ml	Add with pipette, close the cell, and mix.
Measure the sample in the photometer.		

April 2011

Notes on the measurement:
- For photometric measurement the cells must be clean.
  Wipe, if necessary, with a clean dry cloth.
- Measurement of turbid solutions yields false-high readings.
- The pH of the measurement solution must be approx. 1.
- The colour of the measurement solution remains stable for 30 min. (After 60 min the measurement value would have increased by 5 %.)

8. Analytical quality assurance

recommended before each measurement series
Spectroquant® CombiCheck 10 or 20 can be used for this purpose.
These articles contain a **standard solution** with 25 mg/l Cl^- (CombiCheck 10) or, respectively, 60 mg/l Cl^- (CombiCheck 20) for checking the photometric measurement system (test reagents, measurement device, handling) and the mode of working and also an **addition solution** for determining sample-dependent interferences (matrix effects).
Additional notes see under **www.merck-chemicals.com/qa**.

Characteristic quality data:
In the production control, the following data were determined in accordance with ISO 8466-1 and DIN 38402 A51:

Standard deviation of the method (mg/l Cl^-)	± 1.3
Coefficient of variation of the method (%)	± 2.2
Confidence interval (mg/l Cl^-)	± 3
Number of lots	25

Characteristic data of the procedure:

Sensitivity: Absorbance 0.010 A corresponds to (mg/l Cl^-)	1
Accuracy of a measurement value (mg/l Cl^-)	max. ± 5

For quality and batch certificates for Spectroquant® test kits see the website.

9. Notes

- Reclose the reagent bottle immediately after use.
- **The test reagents must not be run off with the wastewater!**
  Information on disposal can be obtained under the Quick Link "Waste Disposal Advice" at www.merck-chemicals.com/test-kits.

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September 2011

1.14895.0001

COD Cell Test

COD

USEPA approved for wastewater

1. Definition

The COD (chemical oxygen demand) expresses the amount of oxygen originating from potassium dichromate that reacts with the oxidizable substances contained in 1 l of water under the working conditions of the specified procedure.

1 mol $K_2Cr_2O_7$ is equivalent to 1.5 mol O_2
Results are expressed as mg/l COD (= mg/l O_2)

2. Method

The water sample is oxidized with a hot sulfuric solution of potassium dichromate, with silver sulfate as the catalyst. Chloride is masked with mercury sulfate. The concentration of unconsumed yellow $Cr_2O_7^{2-}$ ions is then determined photometrically.
The method corresponds to ISO 15705 and is analogous to EPA 410.4 and APHA 5220 D.

3. Measuring range and number of determinations

Measuring range	Number of determinations
15 - 300 mg/l COD	25

For programming data for selected photometers see the website.

4. Applications

This test measures organic and inorganic compounds oxidizable by dichromate. Exceptions: some heterocyclic compounds (e.g. pyridine), quaternary nitrogen compounds, and readily volatile hydrocarbons.

Sample material:
Groundwater and surface water
In-process controls
Wastewater

5. Influence of foreign substances

This was checked in solutions with a COD of 150 mg/l. The determination is not yet interfered with up to the concentrations of foreign substances given in the table.

Concentrations of foreign substances in mg/l or %					
Cl^-	2000	SO_3^{2-}	25	H_2O_2	10
Cr^{3+}	75			$NaNO_3$	10 %
CrO_4^{2-}	**5**			Na_2SO_4	10 %
NO_2^-	**10**			Na_3PO_4	10 %

6. Reagents and auxiliaries

Please note the warnings on the packaging materials!
Store the pack protected from light! The test reagents are stable up to the date stated on the pack when stored closed at +15 to +25 °C.

Package contents:
25 reaction cells
1 sheet of round stickers for numbering the cells

Other reagents and accessories:
Merckoquant® Chloride Test, Cat. No. 110079,
measuring range 500 - ≥3000 mg/l Cl^-
Spectroquant® CombiCheck 60, Cat. No. 114696
COD standard solution CRM, 100 mg/l COD, Cat. No. 125029
COD standard solution CRM, 200 mg/l COD, Cat. No. 125030

Pipette for a pipetting volume of 2.0 ml
Thermoreactor

7. Preparation

- Analyze immediately after sampling.
- Homogenize the samples.
- Check the chloride content with the Merckoquant® Chloride Test. Samples containing more than 2000 mg/l Cl^- must be diluted with distilled water **prior to** determining the COD.

8. Procedure

Suspend the bottom sediment in the reaction cell by swirling.		
Pretreated sample	2.0 ml	**Carefully** allow to run from the pipette down the inside of the tilted reaction cell onto the reagent (**Wear eye protection! The cell becomes hot!**).
Tightly attach the screw cap to the cell.		
In all subsequent steps the cell must be held only by the screw cap!		
Vigorously mix the contents of the cell.		
Heat the cell at 148 °C in the preheated thermoreactor for 120 min. Remove the hot cell from the thermoreactor and allow to cool in a test-tube rack. **Do not cool with cold water!**		
Wait 10 min, swirl the cell, and return to the rack for complete cooling to room temperature (cooling time at least 30 min).		
Measure in the photometer.		

Notes on the measurement:

- For photometric measurement the cells must be clean. Wipe, if necessary, with a clean dry cloth.
- Measurement of turbid solutions yields false-low readings.
- The measurement value remains stable over a long term.
- When using the SQ 118 photometer, a blank must be prepared for each test package according to the procedure described above (as per measurement sample, but with distilled water instead of sample).

9. Analytical quality assurance

recommended before each measurement series
To check the photometric measurement system (test reagent, measurement device, handling) and the mode of working, the COD standard solutions CRM, 100 mg/l COD (Cat. No. 125029) and 200 mg/l COD (Cat. No. 125030) or Spectroquant® CombiCheck 60 can be used. Besides a **standard solution** with 250 mg/l COD, CombiCheck 60 also contains an **addition solution** for determining sample-dependent interferences (matrix effects).
Additional notes see under **www.merck-chemicals.com/qa**.

Characteristic quality data:

In the production control, the following data were determined in accordance with ISO 8466-1 and DIN 38402 A51:

Standard deviation of the method (mg/l COD)	± 1.5
Coefficient of variation of the method (%)	± 0.95
Confidence interval (mg/l COD)	± 4
Number of lots	39

Characteristic data of the procedure:

Sensitivity: Absorbance 0.010 A corresponds to (mg/l COD)	2
Accuracy of a measurement value (mg/l COD)	max. ± 8

For quality and batch certificates for test kits see the website.

10. Note

The test reagents must not be run off with the wastewater!
Information on disposal can be obtained under the Quick Link "Waste Disposal Advice" at www.merck-chemicals.com/test-kits.

February 2011

1.14764.0001

Spectroquant®

Nitrate Cell Test

NO_3^-

1. Method

In sulfuric and phosphoric solution nitrate ions react with 2,6-dimethylphenol (DMP) to form 4-nitro-2,6-dimethylphenol that is determined photometrically.
The method is analogous to DIN 38405 D9.

2. Measuring range and number of determinations

Measuring range	Number of determinations
1.0 - 50.0 mg/l NO_3-N	25
4 - 221 mg/l NO_3^-	

For programming data for selected photometers / spectrophotometers see the website.

3. Applications

This test is not suited for the determination in waters with chloride contents exceeding 2000 mg/l and COD values exceeding 1000 mg/l.

Sample material:
Groundwater, drinking water, and surface water
Spring water and well water
Mineral water
Wastewater and industrial water
Nutrient solutions for fertilization
Soils after appropriate sample pretreatment
This test is **not suited** for seawater.

4. Influence of foreign substances

This was checked in solutions containing 25 and 0 mg/l NO_3-N. The determination is not yet interfered with up to the concentrations of foreign substances given in the table.

Concentrations of foreign substances in mg/l or %					
Al^{3+}	1000	Mg^{2+}	1000	EDTA	1000
Ca^{2+}	1000	Mn^{2+}	1000	Surfactants[2)]	1000
Cd^{2+}	500	NH_4^+	1000	**COD (K-hydrogen phthalate)**	**1000**
Cl^-	**2000**	Ni^{2+}	1000	**Organic substances (glucose)**	**1000**
CN^-	100	**NO_2^-**	**10**[1)]	Na-acetate	20 %
Cr^{3+}	1000	Pb^{2+}	250	NaCl	0.5 %
$Cr_2O_7^{2-}$	**100**	PO_4^{3-}	1000	Na_2SO_4	20 %
Cu^{2+}	1000	SiO_3^{2-}	500		
F^-	1000	SO_3^{2-}	100		
Fe^{3+}	250	Zn^{2+}	1000		
Hg^{2+}	250				

1) In cases of higher concentrations, eliminate nitrite ions acc. to section 6.
2) tested with nonionic, cationic, and anionic surfactants

5. Reagents and auxiliaries

Please note the warnings on the packaging materials!
The test reagents are stable up to the date stated on the pack when stored closed at +15 to +25 °C.

Package contents:
1 bottle of reagent NO_3-1K
25 reaction cells
1 cell with blank (**white** screw cap); **required only when using the SQ 118 photometer**
1 sheet of round stickers for numbering the cells

Other reagents and accessories:
Merckoquant® Chloride Test, Cat. No. 110079,
measuring range 500 - >3000 mg/l Cl^-
Merckoquant® Nitrite Test, Cat. No. 110007,
measuring range 2 - 80 mg/l NO_2^- (0.6 - 24 mg/l NO_2-N)
Amidosulfuric acid for analysis EMSURE®, Cat. No. 100103
Acilit® indicator strips pH 0 - 6.0, Cat. No. 109531
Sulfuric acid 25 % for analysis EMSURE®, Cat. No. 100716
Merckoquant® Nitrate Test, Cat. No. 110020,
measuring range 10 - 500 mg/l NO_3^- (2.3 - 113 mg/l NO_3-N)
Spectroquant® CombiCheck 80, Cat. No. 114738
Nitrate standard solution CRM, 2.50 mg/l NO_3-N, Cat. No. 125037
Nitrate standard solution CRM, 15.0 mg/l NO_3-N, Cat. No. 125038
Nitrate standard solution CRM, 40.0 mg/l NO_3-N, Cat. No. 125039

Pipettes for pipetting volumes of 0.50 and 1.0 ml

6. Preparation

- Analyze immediately after sampling.
- Check the chloride content with the Merckoquant® Chloride Test.
  Samples containing more than 2000 mg/l Cl^- must be diluted with distilled water.
- Check the nitrite content with the Merckoquant® Nitrite Test.
  If necessary, eliminate interfering nitrite ions. The stated amounts apply for nitrite contents of up to 100 mg/l:
  To 10 ml of sample add approx. 50 mg of amidosulfuric acid and dissolve.
  The pH of this solution must be within the range 1 - 3. Adjust, if necessary, with sulfuric acid.
- Check the nitrate content with the Merckoquant® Nitrate Test.
  Samples containing more than 50.0 mg/l NO_3-N (221 mg/l NO_3^-) must be diluted with distilled water.
- Filter turbid samples.

7. Procedure

Pretreated sample **(5 - 25 °C)**	0.50 ml	Pipette into a reaction cell. **Do not mix contents!**
Reagent NO_3-1K	1.0 ml	Add with pipette (**Wear eye protection! The cell becomes hot!**). Close the cell **tightly** and mix. **The cell must be held only by the screw cap!**
Leave the hot cell to stand for 10 min (reaction time). Do not cool with cold water! Measure the sample in the photometer.		

Notes on the measurement:

- For photometric measurement the cells must be clean.
  Wipe, if necessary, with a clean dry cloth.
- Measurement of turbid solutions yields false-high readings.
- The colour of the measurement solution remains stable for 30 min after the end of the reaction time stated above. (After 60 min the measurement value would have increased by 5 %.)

8. Analytical quality assurance

it is recommended prior to each measurement series
To check the photometric measurement system (test reagents, measurement device, handling) and the mode of working, the nitrate standard solutions 125037, 125038, and 125039 or Spectroquant® CombiCheck 80 can be used. Besides a **standard solution** with 25.0 mg/l NO_3-N, CombiCheck 80 also contains an **addition solution** for determining sample-dependent interferences (matrix effects).
Additional notes see under **www.merck-chemicals.com/qa**.

Characteristic quality data:

In the production control, the following data were determined in accordance with ISO 8466-1 and DIN 38402 A51:

Standard deviation of the method (mg/l NO_3-N)	± 0.25
Coefficient of variation of the method (%)	± 0.9
Confidence interval (mg/l NO_3-N)	± 0.6
Number of lots	22

Characteristic data of the procedure:

Sensitivity: Absorbance 0.010 A corresponds to (mg/l NO_3-N)	0.3
Accuracy of a measurement value (mg/l NO_3-N)	max. ± 1.0

For quality and batch certificates for Spectroquant® test kits see the website.

9. Notes

- Reclose the reagent bottle immediately after use.
- **For information on disposal/return for disposal please contact your local Merck organization or Merck dealer.**

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1.14543.0001

April 2011

Spectroquant®

Phosphate Cell Test

P

for the determination of orthophosphate and total phosphorus

USEPA approved for drinking water and wastewater

1. Method

In sulfuric solution orthophosphate ions react with molybdate ions to form molybdophosphoric acid. Ascorbic acid reduces this to phosphomolybdenum blue (PMB) that is determined photometrically.
The method is analogous to EPA 365.2+3, APHA 4500-P E, and DIN EN ISO 6878.

2. Measuring range and number of determinations

Measuring range	Number of determinations
0.05 - 5.00 mg/l PO_4-P	25
0.2 - 15.3 mg/l PO_4^{3-} **0.11 - 11.46 mg/l P_2O_5**	

For programming data for selected photometers / spectrophotometers see the website.

3. Applications

This test measures only orthophosphate. Samples must be decomposed by digestion before total phosphorus can be measured (see section 6).

Sample material:
Groundwater and surface water, seawater
Drinking water
Wastewater
Nutrient solutions for fertilization
Soils after appropriate sample pretreatment
Food after appropriate sample pretreatment

4. Influence of foreign substances

This was checked in solutions containing 2 and 0 mg/l PO_4-P. The determination is not yet interfered with up to the concentrations of foreign substances given in the table.

Concentrations of foreign substances in mg/l or %							
Ag^+	1000	F^-	50	Pb^{2+}	25	EDTA	1000
AsO_4^{3-}	**0.2**	Fe^{3+}	1000	**S^{2-}**	**2.5**	Surfactants[1)]	100
Ca^{2+}	1000	**Hg^{2+}**	**10**	SiO_3^{2-}	1000	COD (K-hydrogen	
Cd^{2+}	1000	Mg^{2+}	1000	SO_3^{2-}	1000	phthalate)	150 [2)]
CN^-	1000	Mn^{2+}	1000	Zn^{2+}	1000	Na-acetate	1 %
Cr^{3+}	1000	NH_4^+	1000			NaCl	5 %
$Cr_2O_7^{2-}$	**5**	Ni^{2+}	500			$NaNO_3$	10 %
Cu^{2+}	250	NO_2^-	1000			Na_2SO_4	10 %

Reducing agents interfere with the determination.

[1)] tested with nonionic, cationic, and anionic surfactants

[2)] **A higher COD may impair the efficacy of the digesting mixture in the determination of total phosphorus and thus result in false-low readings. Up to a maximum of 300 mg/l COD, this can be avoided by adding 2 doses of reagent P-1K instead of 1.**

5. Reagents and auxiliaries

Please note the warnings on the packaging materials!

The test reagents are stable up to the date stated on the pack when stored closed at +15 to +25 °C.

Package contents:
1 bottle of reagent P-1K
1 bottle of reagent P-2K
1 bottle of reagent P-3K
25 reaction cells
1 cell with blank (**white** screw cap); **required only when using the SQ 118 photometer**
1 green dose-metering cap
1 blue dose-metering cap
1 sheet of round stickers for numbering the cells

Other reagents and accessories:
Merckoquant® Phosphate Test, Cat. No. 110428,
measuring range 10 - 500 mg/l PO_4^{3-} (3.3 - 163 mg/l PO_4-P)
Universal indicator strips pH 0 - 14, Cat. No. 109535
Sulfuric acid 0.5 mol/l TitriPUR®, Cat. No. 109072
Spectroquant® CombiCheck 10, Cat. No. 114676
Phosphorus (total) standard solution CRM, 0.400 mg/l PO_4-P, Cat. No. 125046
Phosphorus (total) standard solution CRM, 4.00 mg/l PO_4-P, Cat. No. 125047
Hydrochloric acid 25 % for analysis EMSURE®, Cat. No. 100316

Pipette for a pipetting volume of 5.0 ml
Thermoreactor

6. Preparation

At the first use **replace the black screw caps of the reagent bottles P-1K and P-3K by the corresponding dose-metering caps:**
Reagent P-1K: green dose-metering cap
Reagent P-3K: blue dose-metering cap
Hold the respective reagent bottle **vertically** and, at each dosage, press the slide **all the way** into the dose-metering cap. **Before each dosage** ensure that the slide is **completely retracted**.
Reclose the reagent bottles with the black screw caps at the end of the measurement series, since the function of the reagents is impaired by the absorption of atmospheric moisture.

- Analyze immediately after sampling.
- **Digestion for the determination of total phosphorus (Wear eye protection!):**

Pretreated sample	5.0 ml	Pipette into a reaction cell.
Reagent P-1K	1 dose[1)]	Add, **close the cell tightly**, and mix.
Heat the cell at 120 °C[2)] in the preheated thermoreactor for 30 min. Allow the closed cell to cool to room temperature in a test-tube rack. **Do not cool with cold water!**		

[1)] in the case of high COD values: 2 doses

[2)] A digestion temperature of 100 °C may result in false-low readings (e. g. in the case of polyphosphates).

- Check the phosphate content with the Merckoquant® Phosphate Test. Samples containing more than 5.00 mg/l PO_4-P must be diluted with distilled water **prior to** digestion. Alternatively, it is also possible to use the Spectroquant® Phosphate Cell Test Cat. No. 114729 (measuring range 0.5 - 25.0 mg/l PO_4-P).
- **The pH must be within the range 0 - 10.**
  Adjust, if necessary, with sulfuric acid.
- Filter turbid samples.

7. Procedure

Pretreated sample (**10 - 35 °C**)	5.0 ml	Pipette into a reaction cell and mix or - after digestion for total phosphorus - shake the tightly closed cell vigorously after cooling.
Reagent P-2K[1)]	5 drops[2)]	Add, close the cell tightly, and mix.
Reagent P-3K[1)]	1 dose	Add, close the cell tightly, and shake **vigorously until the reagent is completely dissolved**.
Leave to stand for 5 min (reaction time), then measure the sample in the photometer.		

[1)] In the case of high chloride contents, it is recommended to switch the sequence of the reagents P-2K and P-3K.

[2)] **Hold the bottle vertically while adding the reagent!**

Notes on the measurement:

- For photometric measurement the cells must be clean.
  Wipe, if necessary, with a clean dry cloth.
- Measurement of turbid solutions yields false-high readings.
- The pH of the measurement solution must be within the range 0.80 - 0.95.
- The colour of the measurement solution remains stable for at least 60 min after the end of the reaction time stated above.

8. Analytical quality assurance

recommended before each measurement series
To check the photometric measurement system (test reagents, measurement device, handling) and the mode of working, the phosphorus (total) standard solutions 125046 and 125047 (for the determination of total phosphorus) or Spectroquant® CombiCheck 10 can be used. Besides a **standard solution** with 0.80 mg/l PO_4-P, CombiCheck 10 also contains an **addition solution** for determining sample-dependent interferences (matrix effects).
Additional notes see under **www.merck-chemicals.com/qa**.

Characteristic quality data:

In the production control, the following data were determined in accordance with ISO 8466-1 and DIN 38402 A51:

Standard deviation of the method (mg/l PO_4-P)	± 0.024
Coefficient of variation of the method (%)	± 1.0
Confidence interval (mg/l PO_4-P)	± 0.04
Number of lots	36

Characteristic data of the procedure:

Sensitivity: Absorbance 0.010 A corresponds to (mg/l PO_4-P)	0.02
Accuracy of a measurement value (mg/l PO_4-P)	max. ± 0.06

For quality and batch certificates for Spectroquant® test kits see the website.

9. Notes

- Reclose the reagent bottles immediately after use.
- Use only phosphate-free detergents to rinse glassware. Otherwise fill with hydrochloric acid (approx. 10 %) and leave to stand for several hours.
- **Information on disposal can be obtained under the Quick Link "Waste Disposal Advice" at www.merck-chemicals.com/test-kits.**

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