Impact of Wastewater Reuse on Plants

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Important considerations

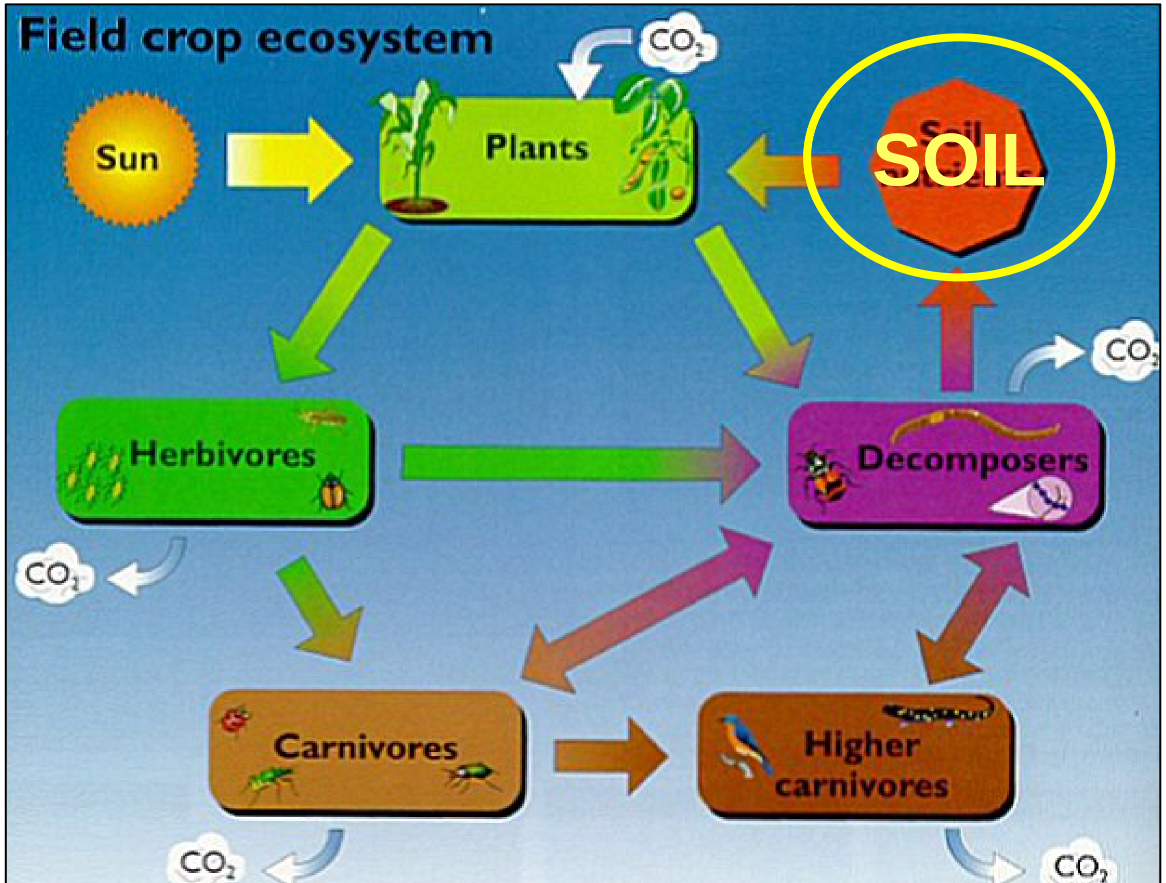
- Health aspects
- Socio-cultural acceptance & reluctance
- Legal aspects, institutional issues, restrictions on use
- Impact on plants, groundwater, environment, etc.
- Technology
- Economic aspects

Needs of Plants

- Soil
- Water
- Nutrients
- Gases (CO_2, O_2)
- Animals: microbial organisms
- Light

Ecosystem of agricultural fields

Plants are part of a complex ecosystem!



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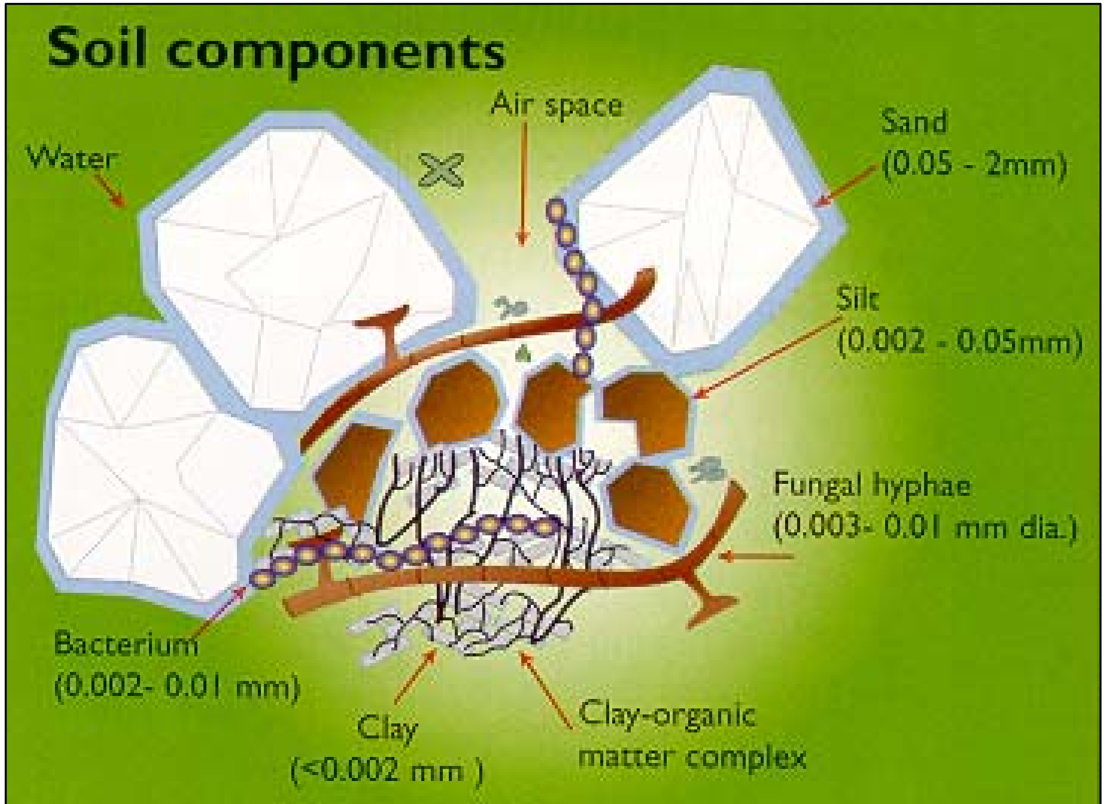
Subsystem: Soil



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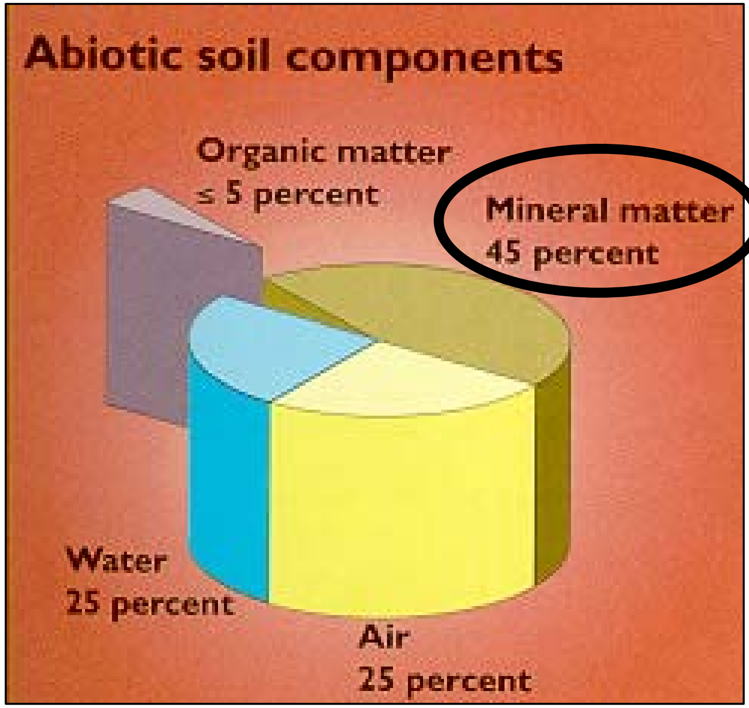
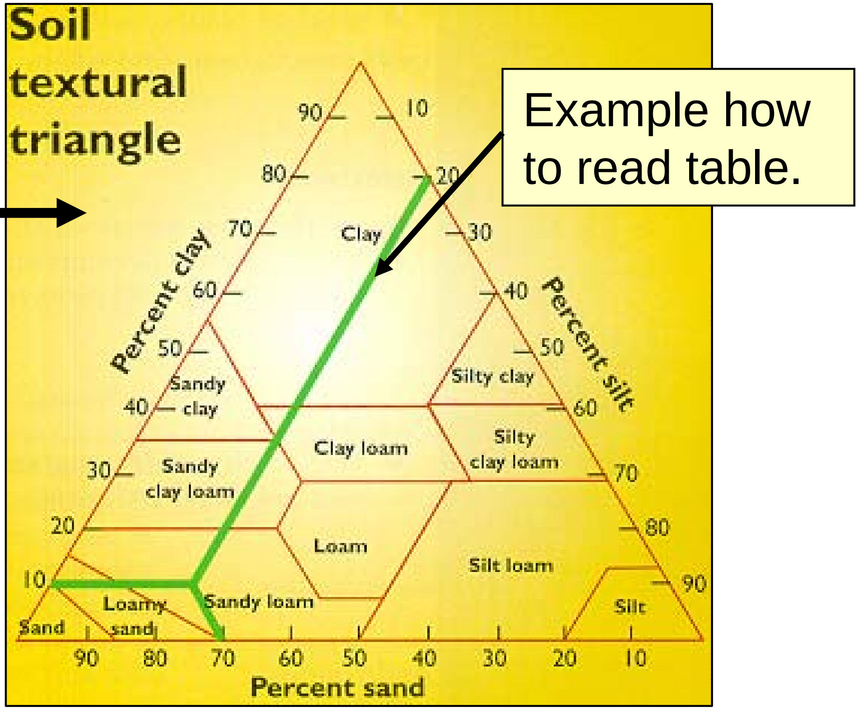
Components can be classified into:

- biotic
- abiotic

Subsystem: Soil

ABIOTIC





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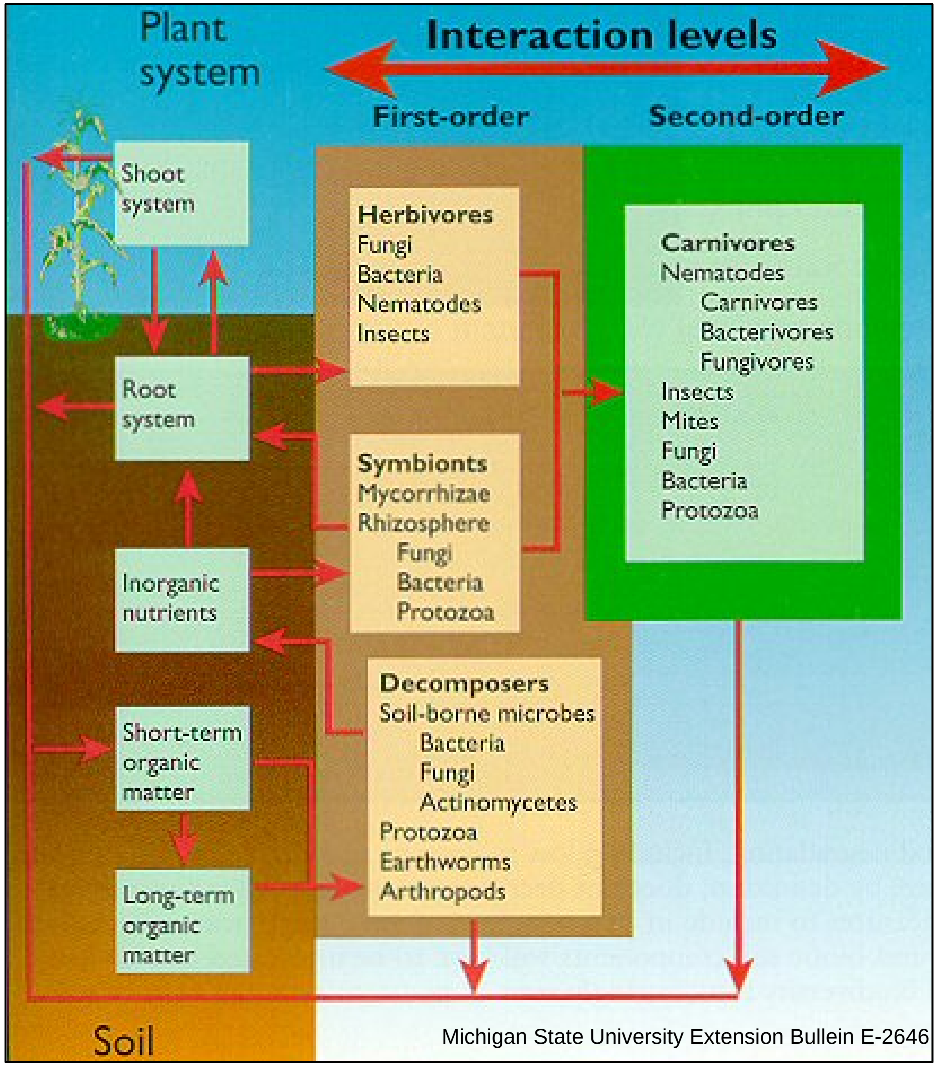
Subsystem: Soil

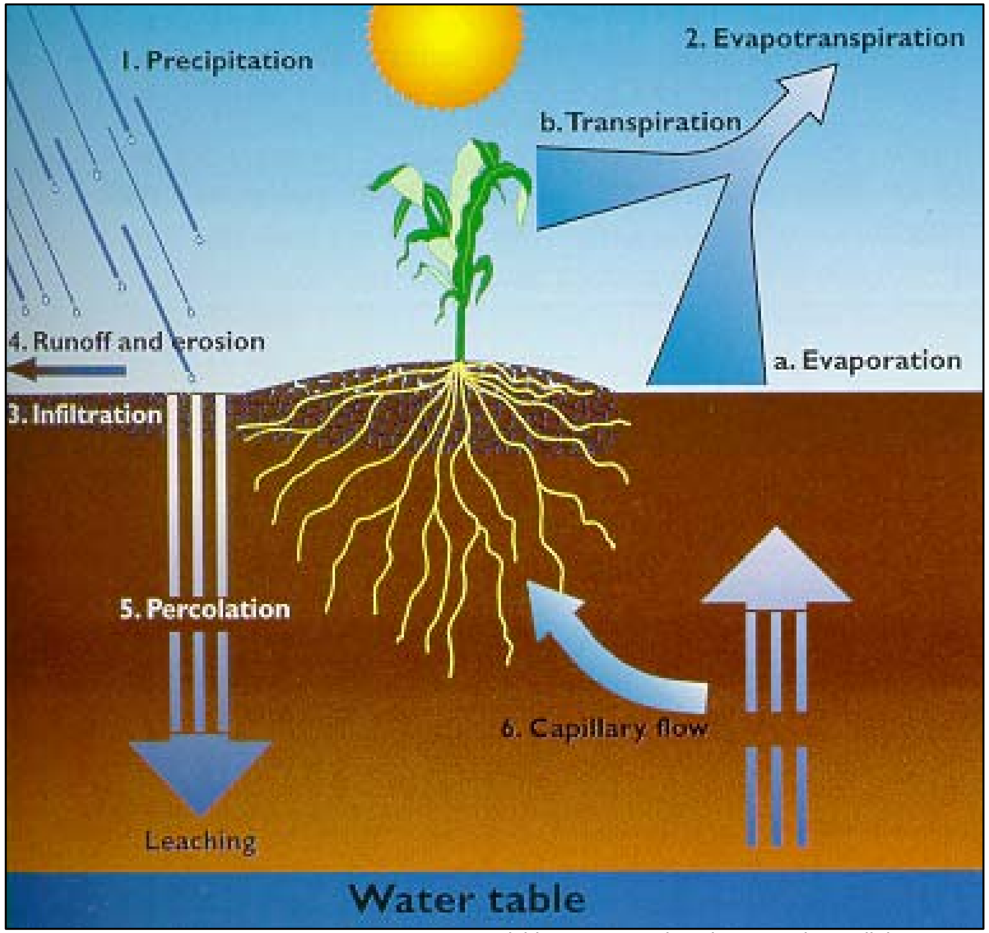
BIOTIC

- First order:
  - Herbivores
  - Symbionts
  - Decomposer
- Second order:
  - Carnivores

Soil-Plant Interactions



Subsystem: Water



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Nutrients

- Non-mineral nutrients:
  largest amount used, derived from CO_2 and H_2O
- Mineral nutrients:
  taken up from soil through roots:
  - Macronutrients
  - Micronutrients / trace elements

Nutrients

Plants need 16 essential nutrients:

- macro-nutrients

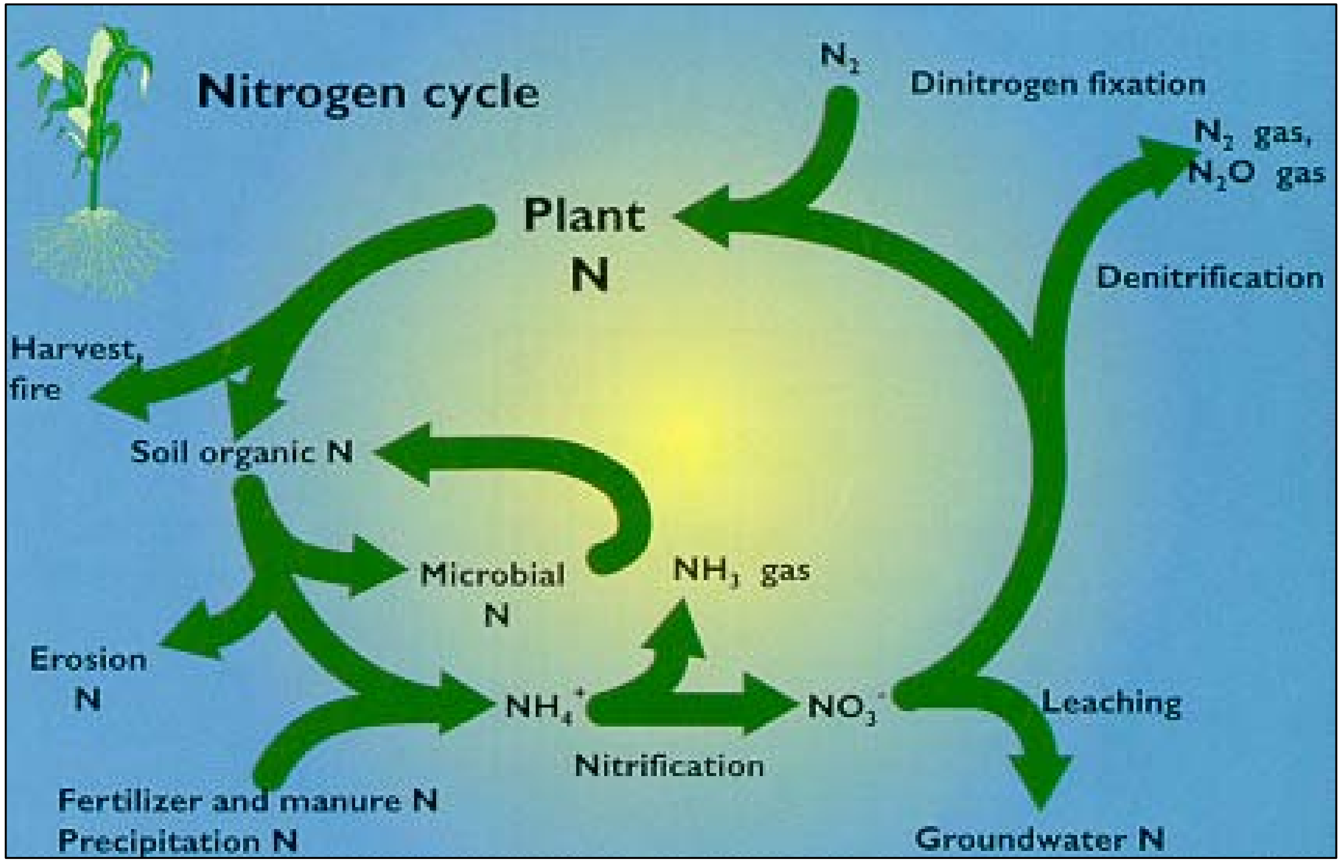
Element:	Form of uptake:
H	Water (H_2O)
C	Carbon dioxide (CO_2), Hydrogen Carbonate (HCO_3^-)
O	Oxygen (O_2), Carbon dioxide (CO_2)
N	Nitrate (NO_3^-), Ammonia (NH_4^+), (NH_3, NO_x, N_2)
P	Phosphates ($H_2PO_4^-$, HPO_4^{2-})
S	Sulphate (SO_4^{2-}), (Sulphate dioxide (SO_2))
K	K^+
Mg	Mg^{2+}
Ca	Ca^{2+}

Most important to fertilise! **N P K**

- micro-nutrients

Element:	Form of uptake:
B	Hydroboronoxides ($H_2BO_3^-$, ($B(OH)_4^-$), Boric acid (H_3BO_3))
Cl	Cl^-, (HCl)
Mn	Mn^{2+}
Fe	Fe^{2+}, Fe^{3+}
Cu	Cu^{2+}
Zn	Zn^{2+}
Mo	Molybdate (MoO_4^{2-})

Nitrogen



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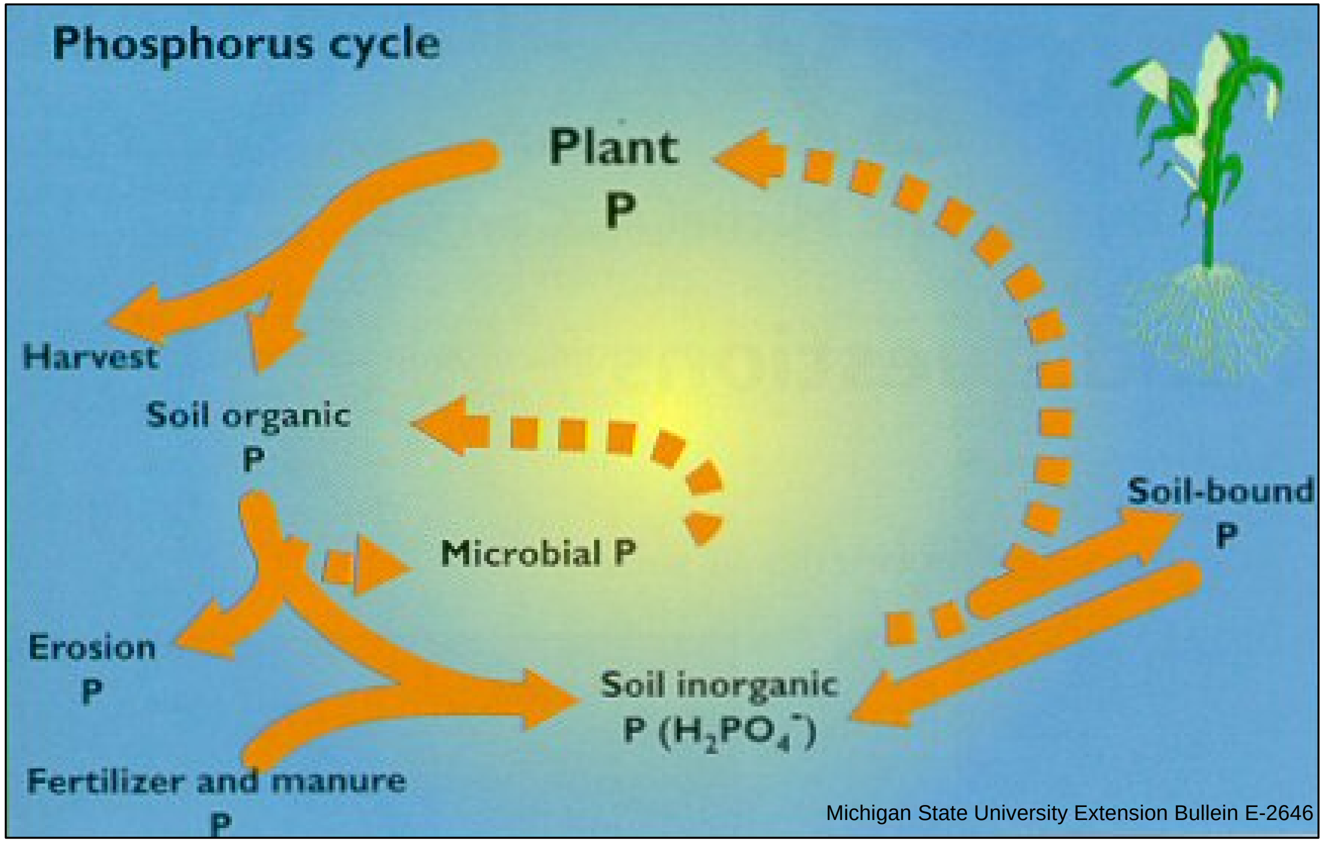
Phosphorus



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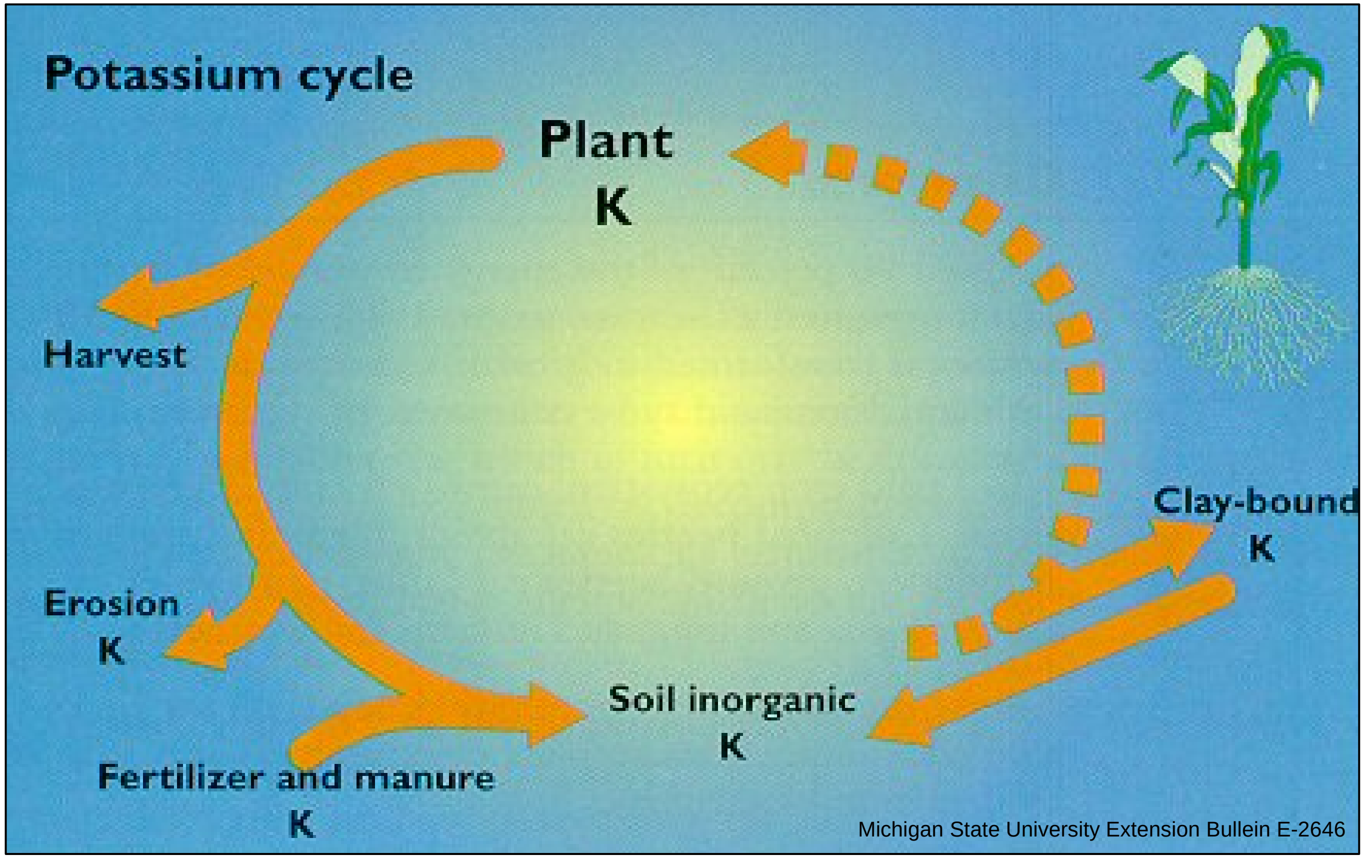
Potassium


Potassium cycle
Plant
K
Harvest
Erosion
K
Clay-bound
K
Soil inorganic
K
Fertilizer and manure
K
Michigan State University Extension Bullein E-2646

Needs covered by wastewater

- **Soil**
- **Water**
- **Nutrients**

Possible to cover with wastewater!

- Gases (CO_2, O_2)
- Animals: microbial organisms
- Light

Not covered but also not applied through humans.

Implementations

IMWI, 2004

Field irrigated with wastewater, Pakistan

IMWI, 2004

Watercourse carrying municipal effluents to fields near Haroonabad, Pakistan

Near East Region

- 14% of world area
- 10% of world population
- 3.5% of total precipitation
- 2.2% of annual internal renewable water resources

FAO, 2002

Deficiency level of renewable water resources is below $500m^3$/capita*y.

Reuse in NER now

- Direct reuse
  - irrigation and fertilisation purposes in agriculture and landscape management
- Indirect reuse
  - recharge of groundwater aquifers (to control over-drafts and salt intrusion in coastal areas)

Situation NER

- WW treatment is seen as more and more important, in aspects of reuse as well
- Kuwait, Jordan, the Gulf States, Saudi Arabia, and Cyprus included ww as important water resource in their national strategies and action plans
- Large share of ww not treated
- Parts of it used uncontrolled (although for production of food crops eaten raw)

FAO, 2002

Situation NER

Country	WASTEWATER PRODUCTION (million m^3/y)		
	Produced wastewater	**Treated wastewater**	**Reused wastewater**
Cyprus	50	16	23
Iraq		425	
Jordan	300	69	58
Lebanon	350	4	2
Malta	32.8	9.3	6
Syria	825	550	550
Turkey	2840	100	50

FAO

Situation NER

Major limitations

- High costs for treatment and management of reclaimed water
- Unclear policies, institutional conflicts, lack of regulatory framework
- Additional training and capacity strengthening needed
- Sometimes limitations in man power

FAO, 2002

Fatwa

- ”Wastewater does not become pure by treatment or disinfection, while it becomes more than pure when it gets transfer from the liquid phase to the gaseous phase and back again to its liquidity status.”

Mufti of the Kingdom of Jordan (5/10/03)

- ”Reclaimed water can be used for ablution and drinking if it is sufficiently and appropriately treated to ensure good health.“

Council of Leading Islamic Scholars in Saudi Arabia (1978)

Fatwa

- ”Impure water could be purified by the modern filtering techniques that are the best and most efficient methods for purification. Therefore, this Council believes that such water will be totally pure and it may be used for ritual purification and drinking as long as there are no negative consequences on health. If drinking is to be avoided, it is merely for reasons of public health and safety, not due to any ramifications of Islamic law.”

Scholars Council of the Kingdom of Saudi Arabia States, 1978

Treatment

Degrees of conventional treatment:

- Preliminary: removal of coarse solids and other large fragments from raw wastewater.
- Primary: removal of settable organic & inorganic solids and floating materials.
- Secondary: removal of the residual organic and suspended solids.
- Tertiary and/or advanced: removals of specific constituents like nutrients and heavy metals. Disinfection is often used to reduce microbiological constituents.

Quality criteria for reuse

- Salinity
- Alkalinity (due to high Na concentrations)
- Specific ion toxicity (often Na, Cl, B)
- Trace metals / heavy metals
- Pathogens
- Nutrient content
- Others...

Salinity

Electrical Conductivity of irrigation water (dS/m and mg/l)*					
<2 **<1280**	**2-3** **1280-1920**	**3-4** **1920-2560**	**4-5** **2560-3200**	**5-7** **3200-4480**	**>7** **>4480**
Citrus, Apples, Peach, Grapes, Strawberry, Potato, Pepper, Carrot, Onion, Beans, Corn	Fig, Olives, Broccoli, Tomato, Cucumber, Cantaloupe, Watermelon, Spinach, Vetch, Sudan grass, Alfalfa	Sorghum, Groundnut, Rice, Beets, Tall fescue	Soybean, Date palm, Harding grass, Trefoil, Artichokes	Safflower, Wheat, Sugar beet, Rye grass, Barley grass, Bermuda grass, Sudax	Cotton, Barley, Wheat grass

*1dS/m = 640 mg/l

FAO, 2000

Salinity

To overcome the problem:

- Select crops with high tolerance
- Select salt tolerant crops with the ability to absorb high amounts of salts
- Irrigation system
- Scheduling of irrigation (amount and frequency are crucial)
- Leaching
- Soil polymers and/or other soil conditioners
- Drainage

Trace metals - Heavy metals

Essential trace metals for plants:

- Copper
- Manganese
- Molybdenum
- Nickel
- Zinc
- Iron

Trace metals - Heavy metals

Most important heavy metals regarding potential hazards and occurrence in contaminated soils:

- Arsenic
- Cadmium
- Copper
- Chromium
- Mercury
- Lead
- Zinc

Trace metals - Heavy metals

TRACE METAL = HEAVY METAL

Trace metals and heavy metals are often the same elements. It is just a **QUESTION OF AMOUNT** what they are for plants and the whole environment.

Trace metals - Heavy metals

"Question of amount" for plants depends of:

- Type of plant
- Growing stage
- Time of input
- Interval of inputs
- Used part
- etc.

Trace metals - heavy metals

Recommended limits for trace elements in reclaimed water use for irrigation:

Constituent	Long-term use (mg/l)[b]	Short-term use (mg/l)[c]
Arsenic	0.10	2.0
Cadmium	0.01	0.05
Copper	0.2	5.0
Iron	5.0	20.0
Lead	5.0	10.0
Manganese	0.2	10.0
Molybdenum	0.01	0.05
Nickel	0.2	2.0
Zinc	2.0	10.0

[a] For water used continuously on all soils

FAO, 2000

[b] For water used for a period of up to 20 years on fine - textured neutral or alkaline soils

TM/HM - Situation NER

In general, heavy metals and trace elements should not be considered as pressing or serious problem in NER for two main reasons:

- The concentration of heavy metals in municipal wastewater is low due to low heavy industry activities.
- The soils of NER have mostly high $CaCO_3$ rates and pH above 7, which inactivate the heavy metals and reduce their mobility and availability to crops. HM become unavailable.

TM/HM - Situation NER

Therefore:

- HM in treated wastewater under calcareous soil conditions is not considered as problem and no particular management is required.
- Under acid conditions (just few cases) HM could be a problem and measures are recommended.

TM/HM - Situation NER

Recommended measures:

- Liming (use of calcium carbonate). In this way soil pH is increased and thus solubility of HMs is reduced.
- Avoid using acid fertilizers.
- Select crops tolerant to certain HMs.
- Select crops having no bio-magnification characteristics → accumulation of certain heavy metals by specific crops and/or parts of the crop.

Link: ww - plants

Nutrient contents

	Total N	P	K
Faeces	5-7	3-5.4	1-2.5
Urine	15-19	2.5-5	3-4.5
Nightsoil	10.4-13	2.7-5	2-3.5
Cow manure	0.3-2	0.1-0.7	0.3-1.2
Pig manure	4-6	3-4	2-3
Plant residues	1-11	0.5-2.8	1-11

IMT, NLH

Pathogens of main concern

- Bacteria: Coliforms: Echerichia, Balmonella, Klebsiella, Enterococcus, Citrobacter
- Virus: Poliovirus, Hapatitis A and E, Norwalk virus, Rotavirus, Echovirus
- Protozoa: Cryptosporidium parvum, Giardia lamblia, Entamoeba histolytica, Cyclospora cayetanensis, Gnathostoma spinigerum

Pathogens

This leads to the following illnesses:

- Hepatitis
- Typhoid
- Dysentery
- Cholera
- Cryptosporidiosis
- Giardiasis
- Malnutrition
- Death...

Pathogen removal during sewage treatment

		Enteric virus	Salmonella	Giardia	Cryptosporidium
Concentration in raw sewerage*		10^5-10^6	10^3-10^5	10^4-10^5	10^2-10^5
Infectious dose*		1-10^1	10^1-10^8	< 20	1-10^1
Primary treatment[a]	% removal	50-98.3	95.8-99.8	27-64	0.7
	No. remaining/l	1700-500000	160-3360	72000-146000	
Secondary treatment[b]	% removal	53-99.92	98.65-99.996	45-96.7	
	No. remaining/l	80-470000	3-1075	6480-109500	
Secondary treatment[c]	% removal	99.983-99.9999998	99.99-99.999999995	98.5-99.99995	2.7[d]
	No. remaining/l	0.007-170	0.000004-7	0.099-2.951	

* number per litre.

[a] Primary sedimentation and disinfection.

[b] Primary sedimentation, trickling filter or activated sludge, and disinfection.

[c] Primary sedimentation, trickling filter or activated sludge, disinfection, coagulation, filtration, and disinfection.

[d] Filtration only.

Data from Crook (1998), Yates (1994), Robertson et al. (1995), Enriquez et al. (1995), Modore et al. (1987), Feachem et al. (1983)

Pathogen removal

Two main steps:

- Come into contact with surfaces
- Interact with those surfaces

Pathogen removal

Come into contact with surfaces through:

- Diffusion:< 2 microns
- Sedimentation: 2-10 microns
- Physical straining: > 10 microns

Pathogen removal

Interact with those surfaces:

- Sorption: Bonding-ionic/covalent, precipitation-hydroxyl formation, bridging-biopolymers, polysaccharides, etc.
- Coagulation: Electrostatic forces, Van der Waals forces, hydrophobic forces

Pathogen survival

Type of Pathogen	Survival time in days			
	In faeces, nightsoil and sludge	In fresh water and sewage	In the soil	On crops
Viruses *Enteroviruses*	< 100 (< 20)	< 120 (< 50)	< 100 (<20)	< 60 (<15)
Bacteria Faecal Coliforms *Salmonella* spp. *Shigella* spp. *Vibrio cholerae*	 < 90 (<50) < 60 (< 30) < 30 (<10) < 30 (< 5)	 < 60(< 30) < 60 (< 30) < 30 (< 10) < 30 (< 10)	 < 70 (< 20) < 70 (< 20) - < 20 (< 10)	 < 30 (< 15) < 30 (<15) < 10 (< 5) < 5 (< 2)
Protozoa *Entamoeba histolytica cysts*	< 30 (< 15)	< 30 (< 15)	< 20 (< 10)	< 10 (< 2)
Helminths *Ascaris lumbricoides eggs*	Many months	Many months	Many months	< 60 (< 30)

Figures in brackets show the usual survival time.

Mara and Cairncross, 1988

Nutrients

- Suspended solids,
- Colloidal solids,
- Dissolved solids:

1. Are present in wastewater
2. Contain macro- and micro-nutrients, which are essential for crop nutrition.

Nutrients

One problem can be that the nutrient content of ww exceeds plant needs and thus:

- pose a potential source for groundwater pollution.
- cause excessive vegetative growth.
- plants mature delayed or uneven.
- reduce quality of the irrigated crops.

Calculation of nutrients present in the treated effluent as part of the overall fertilisation program is necessary.

In this respect wastewater analysis is required at least once at the beginning of the growing season.

Nutrients

Fertilisation potential through wastewater:

	N	P	K
Nutrient concentration (mg/l)	40	10	30
Yearly nutrients (kg/ha) added through application of 10000m^3 water/ha	400	100	300

FAO, 2000

These application rates supply sufficient or even more of N required by agricultural crops and also most of P and K.

Nutrient uptake

Fertiliser uptake in % as influenced by the irrigation system:

Irrigation system*	Nitrogen	Phosphorus	Potassium
Furrow	40 – 60	10 – 20	60 – 75
Sprinkler	60 – 70	15 – 25	70 – 80
Microirrigation	75 - 85	25 - 35	80 - 90

*The values refer to good designed and operated irrigation systems

FAO, RNEA, 1992

Nutrient uptake

Nutrients required by selected crops for canopy formation and fruit production

Crop	N	P	K	P_2O_5	K_2O
Tomato					
Canopy (kg/ha)	95	12	108	27	130
Fruits (kg/ton)	1.80	0.17	3.13	0.38	3.75
Eggplant					
Canopy (kg/ha)	105	13	113	30	135
Fruits (kg/ton)	1.96	0.17	3.2	0.40	3.8
Lettuce (kg/ha)	115	14	160	32	192
Banana					
Canopy (kg/ha)	250	26	800	60	1000
Fruits (kg/ton)	2.0	0.22	5.0	0.5	6.0
Citrus					
Canopy (kg/ha)	85	8	90	18	108
Fruits (kg/ton)	1.44	0.19	1.53	0.44	1.84

FAO, Papadopoulos, 2000

Others

- Clogging of sprinkler, mini-sprinkler and drip irrigation systems. The most serious problems occur with drip systems. Filtration is required → more attendance needed!
- Plugging through slimes, bacteria, algae, and suspended solids etc. in the sprinkler head, emitter orifice or supply line.

Biological quality criteria

This criteria is generally expressed in the guidelines of WHO (World Health Organisation).

The WHO divides into 3 categories of different reuse conditions:

- A: Irrigation of crops likely to be eaten uncooked, sports fields, public parks.
- B: Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees.
- C: Localised irrigation of crops in category B if exposure of workers and the public does not occur.

Biological quality criteria

Category	Person / group exposed	Nematodes (eggs/kg)	Fecal coliforms (No/100g)
A	Workers, Consumers, Public	≤ 1	≤ 1000
B	Workers	≤ 1	No standard recommended.
C	None	Not relevant.	Not relevant.

WHO, 1989

WHO guidelines

- need right balance between maximising public health benefits and still allowing for the beneficial use of scarce resources
- need to be adapted to the local social, economic and environmental conditions
- should be co-implemented with other health interventions: hygiene promotion, provision of adequate drinking water and sanitation, other primary health-care measures

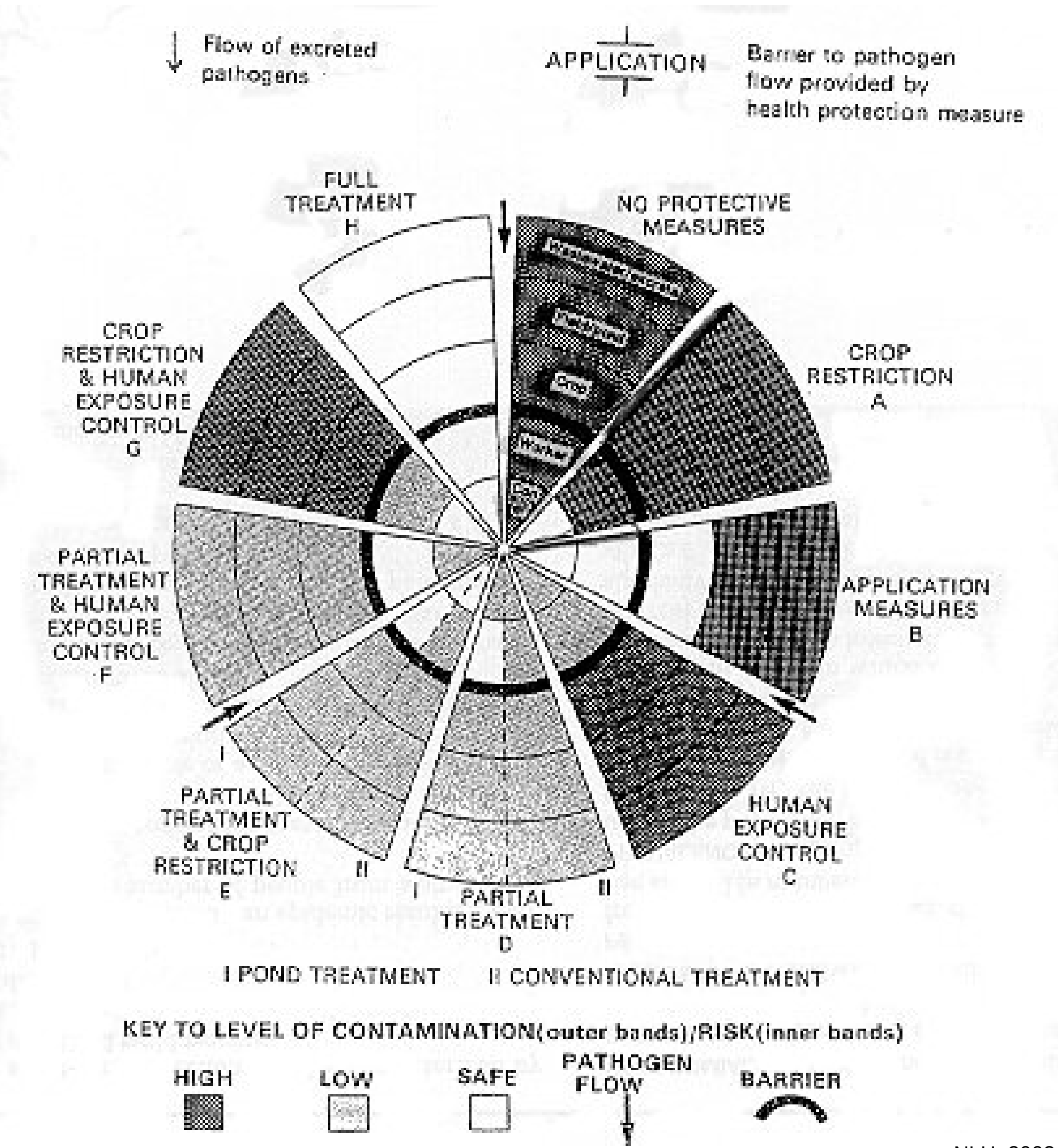
WHO guidelines

- Were published in 1989.
- Are currently under revision with expected publication in 2004.
  - 2^{nd} edition, Vol. 1 and 2
  - technical report, 2^{nd} edition
- Online available: http://www.who.int/water_sanitation_health/wastewater/en/
  - Executive summary of the 1989 guidelines
  - Analysis of wastewater for use in agriculture
- Full guidelines can be ordered via WHO homepage.

Risk assess-ment

Explanation circles (out → in):

- wastewater/excreta
- field/pond
- crop
- worker
- consumer



NLH, 2003

Risk assessment

IMWI, 2004

Wastewater pumping station near Hanoi

People bathing and washing in the Ganges, India.

Earth Island Institute, 2004

IMWI, 2004

A farmer wades through a homemade diversion canal, which carries wastewater to his fields, Pakistan

Risk assessment

Differentiation between actual and potential risks!

An actual risk only exists, when all of these conditions are fulfilled:

- Either an infectious dose exists or pathogens multiplies to this dose.
- The infective dose reaches the human host.
- The host becomes infected.
- The infection causes disease or further transmission.

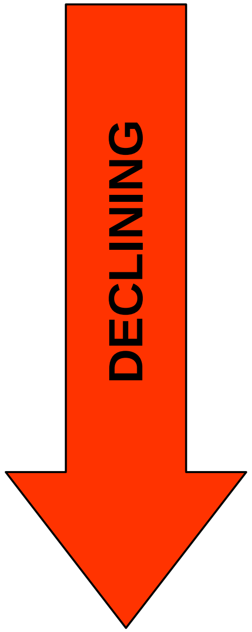
Risk assessment

Risk assessment process:

- 1. Hazard identification
- 2. Exposure assessment
- 3. Dose-Response assessment
- 4. Risk characterisation

Risk

Declining potential to transmit pathogens irrespectively of irrigation method and wastewater quality used:



Vegetables eaten raw

Vegetables eaten cooked

Ornamentals raised for sale

Trees producing fruits (eaten raw without peeling)

Lawns in amenity areas of unlimited access to public

Trees producing fruits eaten raw after peeling

Table grapes

Lawns and other trees in amenity areas of limited access

Fodder crops

Trees producing nuts and other similar trees

Industrial crops

Irrigation systems

1. Surface methods → traditional

- Flood irrigation (by border or basin), wetting almost all the land surface
- Hose-basin irrigation. The water is delivered by hose
- Furrow irrigation, wetting only part of the ground surface.

Irrigation


USGS, 2004

Traditional spray irrigation


USGS, 2004

Farmland in USA being irrigated by a large spray-irrigation system

Irrigation systems

2. Pressurised irrigation methods

- Sprinklers: sprinklers of high capacity, ordinary mini-sprinklers, and sprayers.
- Drip: point or localised irrigation system.
- Subsurface irrigation: yet used with wastewater, may provide the best health protection.
- Bubbler irrigation: localised irrigation technique with regulated flow.

Irrigation

Aquatechnik, 2004

Sprinkler

Aquatechnik, 2004

Drip

Microsprinkler implemented for vegetables

Hammer, 2003

Irrigation systems

Factors influencing choice of system:

- Foliar wetting and consequent leaf damage resulting in poor yield
- Salt accumulation in the root zone with repeated applications
- Ability to maintain high soil-water potential
- Suitability to handle brackish water without significant yield loss
- Economic aspects (investment costs, running costs...)
- Maintenance and operation
- etc.

Irrigation systems

Due to the facts mentioned, to stay within the WHO guidelines, and to keep risks low:

Not every crop can be irrigated with every irrigation system
(and every type of wastewater)!

Irrigation of fruit trees

Before and after

Guayaba plantation in Cuba.

Irrigation of flowers

Hammer, 2003

Hammer, 2003

Hammer, 2003

Control measures

- Wastewater reuse guidelines
  - national
  - WHO
  - Fatwa for reclaimed water
- Monitoring and control of wastewater quality
- Control of storage, transport, and distribution facilities
- Control of crops
- Control of workers