Example 6.

Sensitivity of hydraulic head at a point to Cauchy BC head under steady state flow conditions

0. Forward model

Governing equation:

$$K\,b\,\frac{d^2h}{dx^2} + R = 0 \tag{1}$$
$$\tag{2}$$

Boundary conditions:

$$-K\,b\,\frac{dh(x)}{dx} = 0\,, \qquad\qquad x = 0 \tag{3}$$
$$-K\,b\,\frac{dh(x)}{dx} = C\,[h^* - h(x)]\,, \qquad x = L \tag{4}$$
$$\tag{5}$$

Closed-form solution:

$$\text{Not available} \tag{6}$$
$$\tag{7}$$

Spatial derivatives from differentiation:

$$\text{Not available} \tag{8}$$

In [44]:
```python
from IPython.display import HTML, display
def set_background(color):
    script = (
        "var cell = this.closest('.code_cell');"
        "var editor = cell.querySelector('.input_area');"
        "editor.style.background='{}';"
        "this.parentNode.removeChild(this)").format(color)
    display(HTML('<img src onerror="{}">'.format(script)))
```

In [45]:
```python
from warnings import filterwarnings
filterwarnings("ignore", category=DeprecationWarning)

import numpy as np

K, R, b, L, BC3h, BC3c, ocol = 10., 1e-1/1000., 10., 10000., 1., 1., 5000
X = np.arange(L)
```

1. Direct sensitivity

$$\text{Not available} \tag{9}$$

In [ ]:

2. Perturbation sensitivity

$$\tag{10}$$
$$\frac{\partial h(x')}{\partial h_{\Gamma_3}} \approx \frac{h(x, h_{\Gamma_3} + \Delta h_{\Gamma_3}) - h(x, h_{\Gamma_3})}{\Delta h_{\Gamma_3}} \tag{11}$$
$$\tag{12}$$

2a. Analytical

$$\text{Not available} \tag{13}$$

In [ ]:

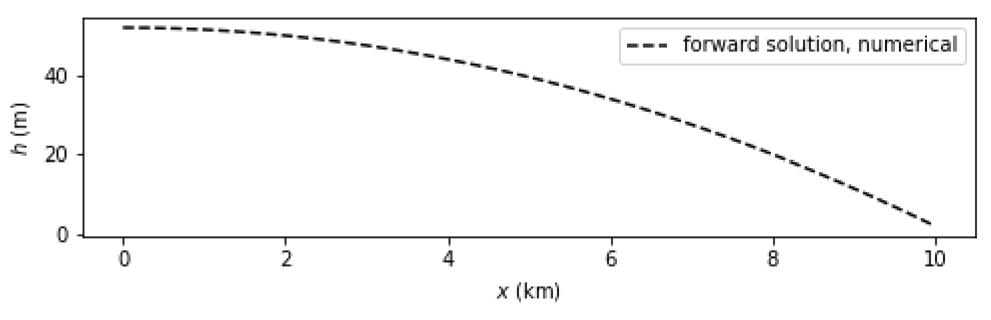
2b. Semi-analytical

$$\text{Not available} \tag{14}$$

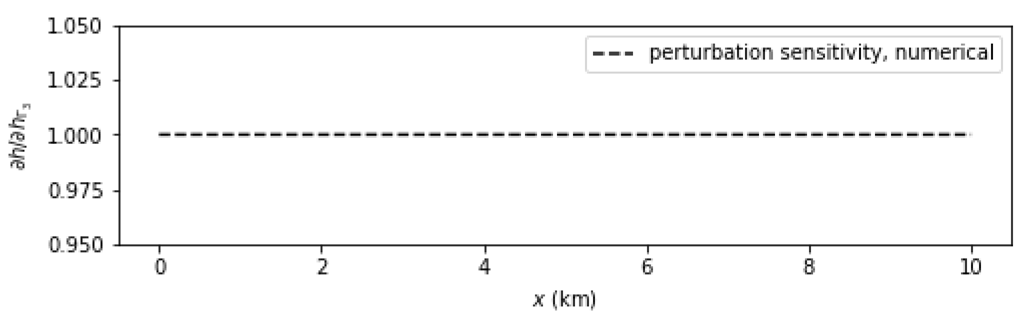
In [ ]:

2c. Numerical

In [46]:
```python
import flopy

dpar = 1e-0
nrow, ncol = 1, int(L)
M0 = flopy.modflow.Modflow(modelname='model', exe_name='../mf2005.exe')
flopy.modflow.ModflowDis(M0, nlay=1, nrow=nrow, ncol=ncol, nper=1, delr=1., delc=1., top=0., botm=-b, steady=Tr
                         perlen=1., nstp=1)
flopy.modflow.ModflowBas(M0, ibound=np.ones([nrow, ncol]), strt=BC3h*np.ones([nrow, ncol], dtype=float))
flopy.modflow.ModflowLpf(M0, hk=K, vka=-999., ss=-999., sy=-999., ipakcb=53)
flopy.modflow.ModflowRch(M0, nrchop=1, rech=R, ipakcb=53)
flopy.modflow.ModflowGhb(M0, stress_period_data={0: [0, 0, ncol-1, BC3h, BC3c]})
flopy.modflow.ModflowPcg(M0, hclose=1e-6, rclose=1e-6)
flopy.modflow.ModflowOc(M0, stress_period_data={(0,0): ['save head', 'save budget']})
M0.write_input()
success, buff = M0.run_model(silent=True)
H0 = flopy.utils.binaryfile.HeadFile('model.hds').get_data()[0,0,:]

%matplotlib inline
import matplotlib as mpl
import matplotlib.pyplot as plt
plt.subplots(figsize=[8,2])
plt.plot(X/1000., H0, 'k--', mfc='none', label='forward solution, numerical')
plt.xlabel('$x$ (km)')
plt.ylabel('$h$ (m)')
plt.legend();
```



In [47]:
```python
M1 = M0
flopy.modflow.ModflowGhb(M1, stress_period_data={0: [0, 0, ncol-1, BC3h+BC3h*dpar, BC3c]})
M1.write_input()
success, buff = M1.run_model(silent=True)
H1 = flopy.utils.binaryfile.HeadFile('model.hds').get_data()[0,0,:]
dhdBC3h = (H1-H0)/(BC3h*dpar)

%matplotlib inline
import matplotlib as mpl
import matplotlib.pyplot as plt
plt.subplots(figsize=[8,2])
plt.plot(X/1000., dhdBC3h, 'k--', mfc='none', label='perturbation sensitivity, numerical')
plt.xlabel('$x$ (km)')
plt.ylabel(r'$\partial h / \partial h_{\Gamma_3}$')
plt.legend()
plt.ylim(0.95, 1.05);
```



In [48]:
```python
print('%.6f'% dhdBC3h[ocol])
```

```
1.000000
```

3. Adjoint sensitivity

$$\frac{\partial h(x')}{\partial h_{\Gamma_3}} = \int_{\Gamma_3} \psi_1^*(x)\,C_{\Gamma_3}\,dx \;=\; \psi_1^*(\Gamma_3)\,C_{\Gamma_3} \tag{15}$$

Governing equation:

$$K\,b\,\frac{d\psi_1^*}{dx} + \frac{1}{2\,K\,b}\delta(x - x') = 0 \tag{16}$$
$$\tag{17}$$

Boundary conditions:

$$\psi_1^*(x) = 0\,, \qquad\qquad x = 0 \tag{18}$$
$$(\text{undefined on } \Gamma_3) \tag{19}$$
$$\tag{20}$$

Closed-form solution:

$$\text{Not available} \tag{21}$$

In [ ]:

3a. Analytical

$$\text{Not available} \tag{22}$$

In [ ]:

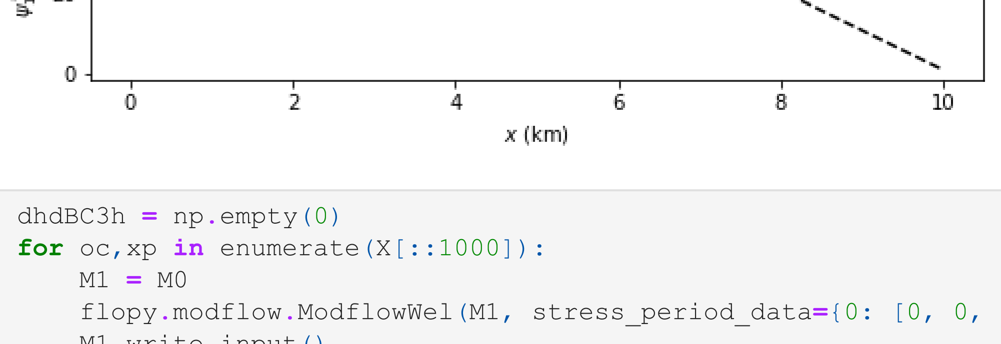
3b. Semi-analytical

$$\text{Not available} \tag{23}$$

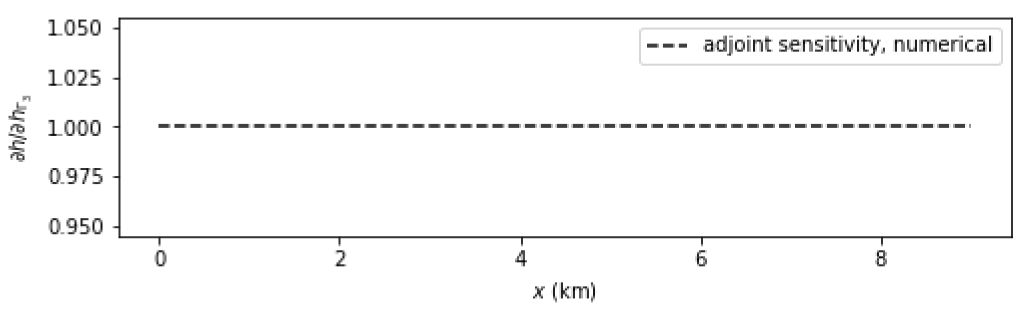
In [ ]:

3c. Numerical

In [49]:
```python
M0 = flopy.modflow.Modflow(modelname='model', exe_name='../mf2005.exe')
flopy.modflow.ModflowDis(M0, nlay=1, nrow=1, ncol=ncol, nper=1, delr=1., delc=1., top=0., botm=-b, steady=True,
                         perlen=1., nstp=1)
flopy.modflow.ModflowBas(M0, ibound=np.ones([nrow, ncol]), strt=BC3h*np.ones([nrow, ncol], dtype=float))
flopy.modflow.ModflowLpf(M0, hk=K, vka=-999., ss=-999., sy=-999., ipakcb=53)
flopy.modflow.ModflowGhb(M0, stress_period_data={0: [0, 0, ncol-1, 0., BC3c]})
flopy.modflow.ModflowWel(M0, stress_period_data={0: [0, 0, ocol, 1.]})
flopy.modflow.ModflowPcg(M0, hclose=1e-6, rclose=1e-6)
flopy.modflow.ModflowOc(M0, stress_period_data={(0,0): ['save head', 'save budget']})
M0.write_input()
success, buff = M0.run_model(silent=True)
A = flopy.utils.binaryfile.HeadFile('model.hds').get_data()[0,0,:]

%matplotlib inline
import matplotlib as mpl
import matplotlib.pyplot as plt
plt.subplots(figsize=[8,2])
plt.plot(X/1000., A, 'k--', mfc='none', label='adjoint solution, numerical')
plt.xlabel('$x$ (km)')
plt.ylabel(r'$\psi^*_1$ (T/$L^2$)')
plt.legend();
```



In [50]:
```python
dhdBC3h = np.empty(0)
for oc,xp in enumerate(X[::1000]):
    M1 = M0
    flopy.modflow.ModflowWel(M1, stress_period_data={0: [0, 0, oc, 1.]})
    M1.write_input()
    success, buff = M1.run_model(silent=True)
    A = flopy.utils.binaryfile.HeadFile('model.hds').get_data()[0,0,:]
    dhdBC3h = np.append(dhdBC3h, A[-1]*BC3c)

%matplotlib inline
import matplotlib as mpl
import matplotlib.pyplot as plt
plt.subplots(figsize=[8,2])
plt.plot(X[::1000]/1000., dhdBC3h, 'k--', mfc='none', label='adjoint sensitivity, numerical')
plt.xlabel('$x$ (km)')
plt.ylabel(r'$\partial h / \partial h_{\Gamma_3}$')
plt.legend();
```



In [51]:
```python
print('%.6f'% dhdBC3h[int(np.where(X[::1000]==float(ocol))[0])])
```

```
1.000000
```

In [ ]: